

COMPARISON OF VARIOUS NUMERICAL WEATHER PREDICTION MODELS FOR MONITORING OF IN-FLIGHT STATIC PRESSURE MEASUREMENTS

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Abstract

This study deals with the evaluation of a technique to monitor the altitude indication of airborne aircraft air data systems on the basis of different meteorological numerical weather prediction models. Within the framework of this analysis, flight experiments with the Airbus A320-232 ('Advanced Technology Research Aircraft', ATRA) and a Dassault Falcon 20-E5 of the German Aerospace Center (DLR) have been conducted to compare the meteorological data used with reference pressure measurements. The evaluation of the assessed technique shows good levels of agreement with established high accuracy pressure measurements of low measurement uncertainty that are also used for the calibration of pitot-static-systems. Based on the findings, conceptual proposals are considered for the operational use of the discussed methodology to monitor static pressure measurements of air data systems.

1. DEFINITIONS

φ	Latitude
λ	Longitude
h	Geometric altitude
A320	Airbus A320-232
ALT	Altitude
ASE	Altimetry System Error
ATRA	Advanced Technology Research Aircraft
DGPS	Differential Global Positioning System
DLR	German Aerospace Center
FA20	Dassault Falcon 20-E5
GNSS	Global Navigation Satellite System
HMU	Height Monitoring Unit
ICAO	International Civil Aviation Organization
NWP	Numerical Weather Prediction
SBAS	Satellite Based Augmentation System
TC	Trailing Cone
TP	Test Point
UTC	Coordinated Universal Time

2. INTRODUCTION

In times of sustained growth of air traffic across the world and the associated close vertical separation of the aircraft involved, the accuracy and reliability of barometric altimeters that are used on-board becomes more and more

important. Established methods for monitoring their performance provide recurrent overflights of so called Height Monitoring Units (HMU), which are located on the ground, and are capable of determining the Altimetry System Error (ASE) of individual aircraft. This is defined as the difference between the pressure altitude displayed to the flight crew when referenced to the International Standard Atmosphere ground pressure setting (1013.2 hPa/29.92 inHg) and free stream pressure altitude [1]. To estimate the latter, numerical weather prediction (NWP) models are used together with the multilateration of transponder signals and statistical means, taking the overflights of a variety of different aircraft into account. In order to avoid possible detours, increased track mileage and fuel consumption, this paper is investigating an alternative method to determine the ASE using an on-board GNSS-receiver in combination with NWP models. Instead of taking measurements on a random basis only, this method is also capable of continuously monitoring the ASE of individual aircraft's air data systems.

In this paper, predicted static pressure of various NWP models is compared in reference to pressure measurements taken by two different experimental aircraft of the German Aerospace Center (DLR) during conducted flight experiments. The Advanced Technology Research Aircraft (ATRA), an Airbus A320, and a Dassault Falcon 20-E5 (FA20) were both equipped with a trailing cone (TC) in order to determine the static pressure of the free undisturbed airflow. In this process, the TC represents accurate, state of the art technology to determine the ASE. The experimental vehicles use diverse methods to determine their GNSS position and are therefore associated with different measurement uncertainties. This enables discussions about their overall influence on the accuracy of the method discussed in this paper. These anomalies can be significantly reduced by the application of correction data supplied by a Differential Global Positioning System

(DGPS) that improves the signal travel time measurement taken by the on-board GNSS-receiver. Various NWP models are considered for their use as pressure references, and their accordance with in-flight measurements is compared. In order to gain more representative predicted static pressure data collection from multiple different NWP models, an operational concept was developed, based on the calculation of their arithmetic mean value, which then is used as a reference for the monitoring of the performance of air data systems. Although the standard deviation of varying predicted pressure values is no absolute measure for the accuracy of the forecast, it can still serve as a measure for the consistency of the predictions made by different models with one another. Another advantage of applying this procedure is to minimize the impacts of anomalies created by the output of an individual model.

3. COMPARISON OF DIFFERENT NUMERICAL WEATHER PREDICTION MODELS

In a first step, the model outputs of three different NWP Models (A, B, C) are compared with each other. The intent is to quantify the scale of their relative variations and its implication for the determination of the barometric flight altitude. FIG 1 depicts the difference between the forecasted geometric altitudes h of various pressure levels in relation to the mean forecast altitude \bar{h} of all three NWP. In this example a diurnal cycle with four model outputs (00, 06, 12 and 18 UTC) is shown, using data based on the 21st January 2015 for a latitude $\phi=49.5^\circ$ (North) and longitude $\lambda=12^\circ$ (East). The graphics can indicate relative tendencies between the models; however absolute statements cannot be made as this pre-investigation does not

provide reference data. For the analysis of flight test data, model outputs are compared to measurements of an elaborately calibrated reference system which is further described in section 5.

Although, the mean and standard deviation of varying predicted pressure values are no absolute measure for the accuracy of the forecast, they can still serve as a measure for the consistency of the different models with one another. The comparison reveals that the consistency of the output values is highest for the 06 UTC run in the morning. Here the highest mean deviation of the various models considering all pressure levels is less than 6 feet at this stage. The maximum difference between the mean values of the single models is less than 10 feet.

Noticeable also is the fact that Model B shows a negative difference in altitude compared to the overall average of all three models at low atmospheric air pressure (high altitude region) in all four figures. At high air pressure (lower altitudes) it systematically deviates towards positive values. For the operational use of the discussed method it is worth noting that these differences in the considered data are most pronounced in the very high altitude region at or above approximately FL380 (pressure less than ~200 hPa) and below approximately FL60 (pressure higher than ~800 hPa). Therefore the differences and standard deviations between the models are expected to be less within this range when comparing them to the numbers shown in FIG 1, which take the entire altitude spectrum between approximately sea level and space into account.

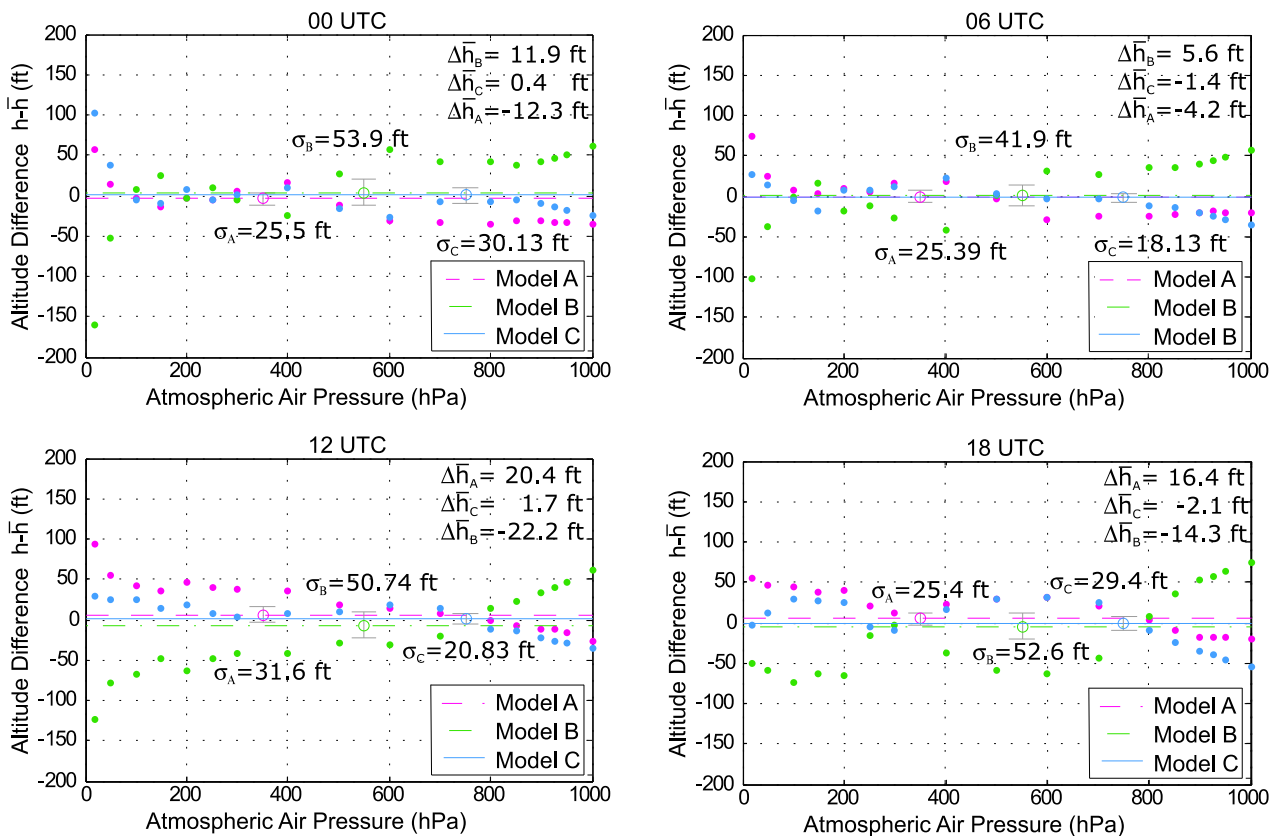


FIG 1. Quantitative comparison of various NWP based on output data for the 21st January 2015 at a latitude of $\phi=49.5^\circ$ and longitude of $\lambda=12^\circ$



FIG 2 Airbus A320-232 D-ATRA with extended trailing cone (lower right corner) [2]

4. FLIGHT TEST TRIALS

4.1. Flight Test Aircraft

As already mentioned in previous sections, two different DLR research aircraft have been used. They are described in the following subsections.

4.1.1. Airbus A320-232 / D-ATRA

The majority of the flight test data have been gathered with the Airbus A320-232 research aircraft (see FIG 2), which was deployed by DLR in late 2008 and serves as a modern and flexible flight test platform. The aircraft is equipped with a GNSS-receiver, capable to process SBAS-signals in order to increase the accuracy.

For a flight test campaign with different flight experiments in summer 2015, the aircraft was furnished with a trailing cone system which was provided by Airbus. This trailing cone system is regularly used by Airbus in their flight test platforms and therefore a well sophisticated and reliable system. It is assumed that the system works as it should, i.e. give an accurate measurement of the ambient atmospheric (static pressure) well clear of the aircraft's fuselage. However, functional check flights have been conducted in order to become familiar with the trailing cone system and to validate its measurements by means of tower fly-by. For this purpose it is necessary to compare static pressure values measured by the trailing cone pressure sensor $p_{s,TC}$ with an independent static reference pressure $p_{s,ref}$. The comparison of the two static pressure values allows the calculation of the static pressure error Δp_s as final result of the trailing cone validation.

$$(1) \quad \Delta p_s = p_{s,TC} - p_{s,ref}$$

The well-established procedure is to perform tower fly-bys at low altitude between 300 ft and 400 ft in order to remain outside the ground effect. Focus has to be put on the precision with which the predefined straight and level flight conditions are stabilized while passing the tower. When the runway approach threshold is reached, the pilot transmits a countdown which is received by the ground station and the test personnel on the ground. The aircraft then flies throughout the predefined test section of 1000 m and ambient pressure and temperature at a known altitude are recorded.

Prior to testing the recently calibrated pressure sensor of the trailing cone on-board the aircraft will be compared

with the precise portable barometer in order to recognize a possible bias. This will be repeated after landing. In addition, a ground block will be performed prior take-off on the runway. The current ambient pressure and temperature obtained from the ground station as well as the measured static pressure of the trailing cone and the geometric altitude are recorded for further evaluation.

The static reference pressure is derived based on altitude measurements using the following formulae [3]:

$$(2) \quad p_{s,ref} = p_{s,TP} \cdot e^{-\frac{g \Delta h_{TP}}{R \cdot T_s}}$$

where $p_{s,TP}$ is the static pressure and T_s the reference temperature both of which are measured on the tower. The letter g stands for the acceleration of gravity and R for the specific gas constant. The altitude difference between the aircraft and the reference static pressure sensor is Δh_{TP} . For the conversion of the measured altitude information into a static pressure value, two approaches are most common. The first one uses absolute measurements of the altitude and static pressure values (see FIG 3) while the second approach is based on relative measurements for the input parameters Δh_{TP} and $p_{s,TP}$.

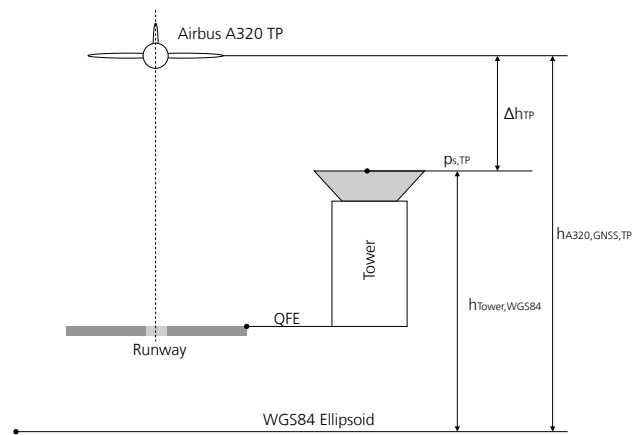


FIG 3 Analysis of tower fly-bys with absolute measurement. Figure modified from [4].

In order to determine the altitude difference Δh_{TP} , both the elevation and the height of the tower must be known. In addition, the barometer used on the tower must be calibrated precisely. For the analysis with relative measure-

ments, both prerequisites are not necessary.

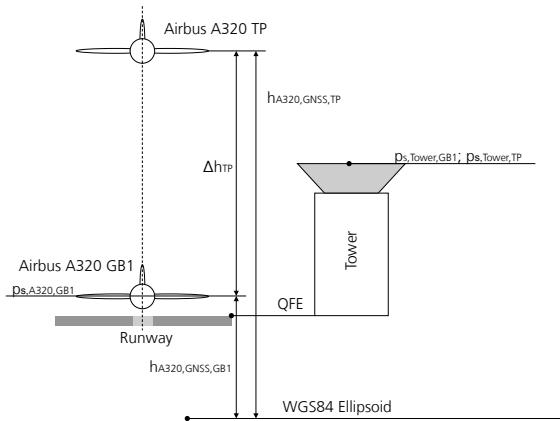


FIG 4 Analysis of tower fly-bys with relative measurement. Figure modified from [4].

A so-called ground block is performed before take-off where the static pressure of the trailing cone sensor and the corresponding altitude are recorded which serve as reference for the tower fly-bys. Any atmospheric pressure changes during the execution of the flights are monitored by the pressure sensor located on the tower. The reference pressure is adjusted accordingly.

However, a malfunction of the used pressure sensors can only be detected by comparing the results of both measurement methods. Only if the results of both methods coincide, a correct validation of the trailing cone system can be assumed. A comprehensive description of both approaches and a thorough discussion of the differences can be found in Ref. [4].

In total, six tower fly-bys were flown in the airspeed regime between 240 and 330 KCAS, corresponding to Mach 0.37 and Mach 0.51 respectively. The high airspeeds at low altitudes were made possible by using the flight test facilities of the Bundeswehr Technical and Airworthiness Center for Aircraft (WTD 61) at Manching Air Base with its military control zone. During the approach, the ground crew transmitted on demand by radio the current ambient pressure and temperature to the aircraft. The numbers were entered into the on-board measurement system which displayed the static pressure error to the flight test crew during every tower fly-by. The online determination of the static pressure error allowed the assessment of the measurement results during each individual flight, and to repeat a test point or terminate the flight test in case of a malfunction. After a successful flight test series, the post-process analysis yields the results illustrated in FIG 5.

The results are as expected, i.e. a negligible difference between both methods and different runs per airspeed. The resulting mean static pressure error for the absolute measurement method is $\bar{p}_{s,rel}=0.036 \text{ hPa}$ compared to the value of $\bar{p}_{s,abs}=-0.024 \text{ hPa}$ for the relative measurement approach. Since both values are very small and with a negligible difference, it is proved that the trailing cone system works as anticipated.

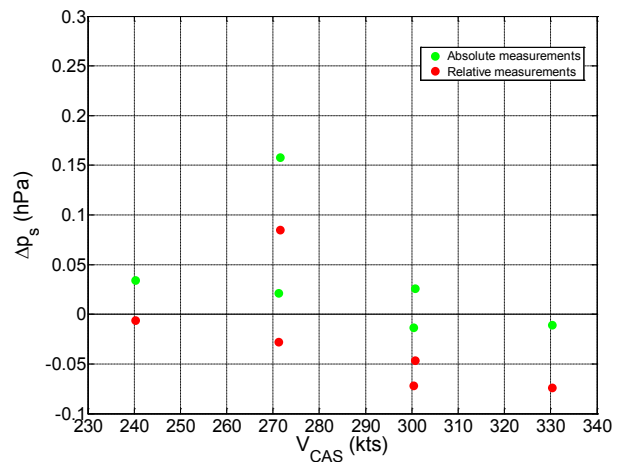


FIG 5 Static pressure error vs. calibrated airspeed

The resulting confidence interval for the true static pressure error Δp_s with a confidence level of 95% was determined correspondingly with Ref. [4] as:

$$(3) \quad -0.46 \text{ hPa} < \Delta p_s < 0.46 \text{ hPa}$$

It includes additional measurement uncertainty components, e.g. coming from the ground based reference pressure sensor, and the GNSS-receiver for the altitude measurement.

For completeness, the static pressure error over the Mach number is shown in FIG 6 below.

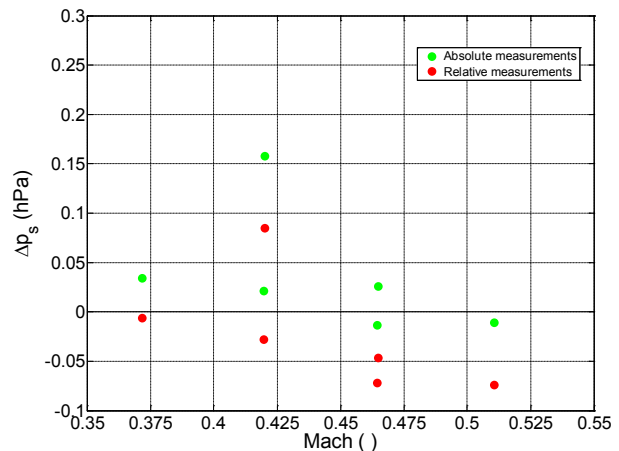


FIG 6 Static pressure error vs. Mach number

Although the flown Mach number is quite high for tower fly-bys of a transport type aircraft, the complete aircraft envelope, with a maximum Mach number of 0.8, can only be covered at higher flight levels. Due to the satisfying results of the tower fly-bys and the regular use of the trailing cone system by Airbus for certification flight test trials, it was decided to skip further test points in higher flight levels in favor of the main focus of the flight test programme described in subsection 4.2.

4.1.2. Dassault Falcon 20-E5 / D-CMET

As a second reference aircraft the DLR Dassault Falcon 20-E5 research aircraft was used. This aircraft had been modified for the use in several fields of research and therefore, it can be operated as a flexible platform provid-

ing the possibility of the installation of different configurations of sensors and measurement equipment.



FIG 7 Dassault Falcon 20-E5 with extended trailing cone [2]

From 2011 Falcon flight test data with trailing cone measurements are available and were recycled for this study. The aircraft configuration was clean, except for the installed trailing cone system. No external under wing carriages or center fuselage containers were installed during the trials. It was decided to perform a functional test flight in order to check the proper function of the trailing cone system by means of tower fly-bys. Details of the validation of the trailing cone system can be obtained from Ref. [4]. The confidence interval for the true static pressure error Δp_s with a confidence level of 95% was determined as:

$$(4) \quad -0.88hPa < \Delta p_s < 1.13hPa$$

These flight test data sets were now used for the comparison of two NWP models.

4.2. Flight Test Programme

Within the flight test campaign of the DLR ATRA, two flights were performed covering the entire A320 flight envelope. In addition the authors were able to use flight test data of additional seven flights of another flight experiment, where again a trailing cone was used during flights in medium or upper airspace.

For all flights two areas were selected. Firstly the airspace over Mecklenburg-West Pomerania with its flat topography close to the Baltic Sea and secondly an airspace over the Allgäu in the proximity of the Alps. Both should take into account the influence of significant different topographies on the numerical weather prediction model. All except one flight were conducted in the first airspace. The FA20 flight tests trials were located in airspaces over Manching Air Base and Northern Bavaria.

For the two dedicated A320 and the FA20 flights, so called racetrack pattern (like holding pattern) were flown in 5,000 ft altitude steps, starting from FL050. The racetrack pattern length was about 2-3 minutes, depending on the airspeed and the available airspace. Both legs were used to measure the static pressure in order to have two legs per barometric altitude for comparison (see FIG 6).

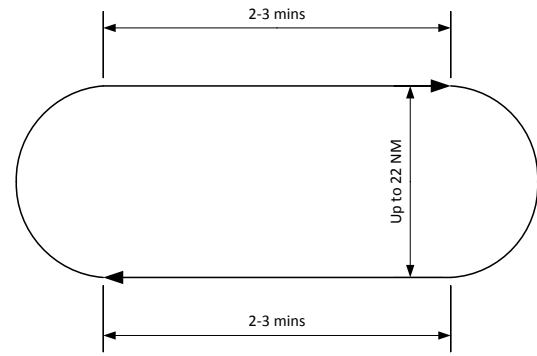


FIG 8 Racetrack pattern

The racetrack pattern has been flown in the following altitudes with the preferred airspeeds shown in TAB 1 below.

Altitude	Calibrated Airspeed	Mach Number
FL390	240 kts	0.777
FL350	240 kts	0.714
FL300	270 kts	0.718
FL250	300 kts	0.717
FL200	300 kts	0.589
FL150	270 kts	0.536
FL100	240 kts	0.435
FL050	240 kts	0.397

TAB 1 Altitudes/Airspeed/Mach Numbers for racetrack patterns

The calibrated airspeeds were chosen to be identical with the airspeeds flown in the tower fly-by trials (cf. 4.1.1) in order to ensure a consistent residual of static pressure error.

5. ANALYSIS OF IN-FLIGHT MEASUREMENTS

To investigate the accuracy of the method described in section 2, data gathered from several flight experiments was considered. In total nine ATRA flights in two different test areas are analyzed; one of them located in the northern part of Germany and the other one in the south.

For this purpose, stabilized flight segments with a defined duration of precisely $t=60s$ are used to compare the mean static pressure predicted by the various NWP models for the respective time of day and location with the mean static pressure measured by the TC. In this context, the term stabilized segment refers to limiting values for the following state variables: An indicated altitude deviation of $\Delta h=\pm 15$ ft, true airspeed of $\Delta V_{TAS}=\pm 5$ kt compared to the mean value of the respective segment and a bank angle of $\phi=\pm 2^\circ$.

Each resulting mean pressure difference is representing the performance of the described method for the given date, time, location and environmental conditions. In order to gain more representative results, multiple segments at the same altitude are used. FIG 7 to FIG 11 show the pressure difference between the static pressure predicted by the NWP models and the TC measurements. In this representation, the average pressure difference of all regarded segments at the same altitude and their standard deviation is displayed as a function of barometric altitude.

In this analysis, the latter can be regarded as a measure for the consistency between the various results obtained by the analysis of single segments.

The local pressure gradient $\frac{dp}{dh}$ decreases with increasing barometric altitude/flight level within the earth's atmosphere. Thus, the pressure difference correlating to a fixed difference in altitude from the reference altitude is dependent on the reference altitude itself and decreases as well. This is caused due to a decreased size of the air column above the reference altitude/flight level at higher levels, putting less weight on the air molecules underneath. A dotted orange line around the mean altitude difference indicates a tube whose width is equal to the standard deviation of the altitude difference.

These differences are based on all analyzed flight segments, irrespective of reference altitude. The resulting curves are computed based on the ICAO International Standard Atmosphere which is used to convert the mean altitude difference and its standard deviation into pressure differences. The diagrams reflect the influence of the previously described altitude dependence due to a changing hydrostatic pressure on the pressure/altitude correlation.

The results for the analysis of Model A are illustrated in FIG 7. The mean value of the pressure difference is 0.07 hPa and its standard deviation is 0.53 hPa. The respective mean altitude deviation is -10.7 ft and the standard deviation is 32.4 ft.

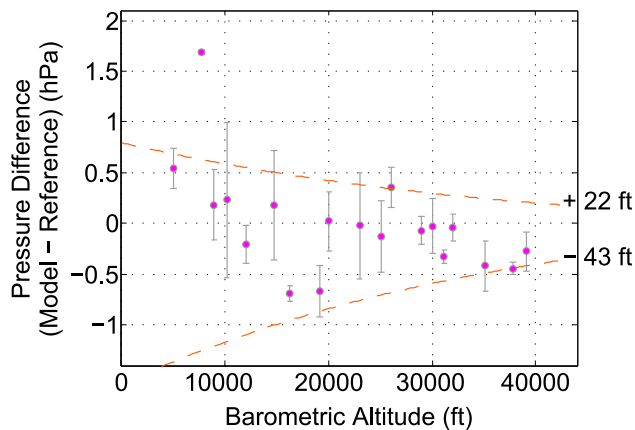


FIG 9 Pressure difference of Model A compared to TC measurements of the ATRA as a function of barometric altitude (nine different flights).

For comparison and to independently verification, FIG 8 shows the results of the same NWP model based on flight experiments conducted on the FA20 aircraft. The pressure difference has a mean value of 0.16 hPa and a standard deviation of 0.30 hPa. The computed mean altitude deviation is 3.2 ft and the standard deviation is 20 ft. It can be seen in this analysis that the variations of the pressure difference are smaller, since the results are based on three flights only which in addition were conducted in one single test area in the south of Germany.

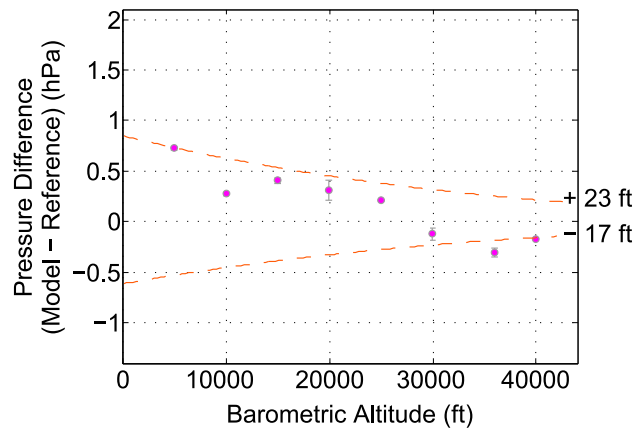


FIG 10 Pressure difference of Model A compared to TC measurements of the FA20 as a function of barometric altitude (three different flights).

Although Model B showed some disagreements with Model A based on data of a single diurnal cycle during the pre-studies (cf. section 3), these findings cannot be confirmed by the analysis of the conducted flight experiments. In fact, the overall performance of Model B agrees with the results of Model A. The mean difference of the Model B pressure predictions compared to the trailing cone measurements are within the range of -0.09 hPa (standard deviation 0.54 hPa) in the case of measurements taken with the ATRA (see FIG 9) and 0.14 hPa (standard deviation 0.35 hPa) for the data coming from the FA20 campaign (FIG 10). The calculated altitude deviations are -10.7 hPa with a standard deviation of 32.2 ft (ATRA) and 3.2 ft with a standard deviation of 17 ft (FA20), respectively.

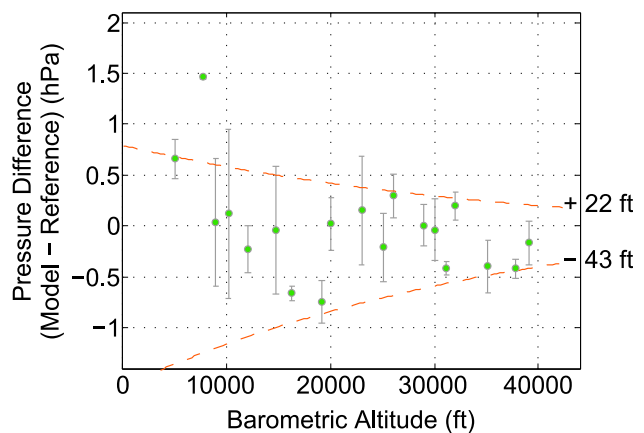


FIG 11 Pressure difference of Model B compared to TC measurements of the ATRA as a function of barometric altitude (nine different flights).

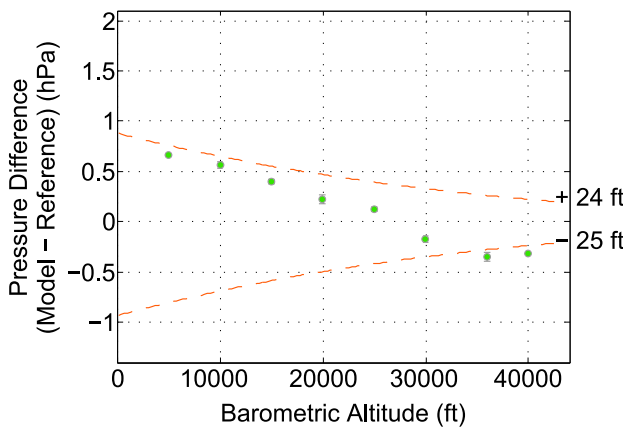


FIG 12 Pressure difference of Model B compared to TC measurements of the FA20 as a function of barometric altitude (three different flights).

Although higher agreements of Model A and C compared to Model A and B were suspected, taking into account the results of the pre-studies (cf. section 3), this analysis reveals an average difference to the trailing cone reference data of 0.39 hPa and a standard deviation of 0.46 hPa for Model C as shown in FIG 11. The respective altitude deviation is 28 ft with a standard deviation of 29 ft.

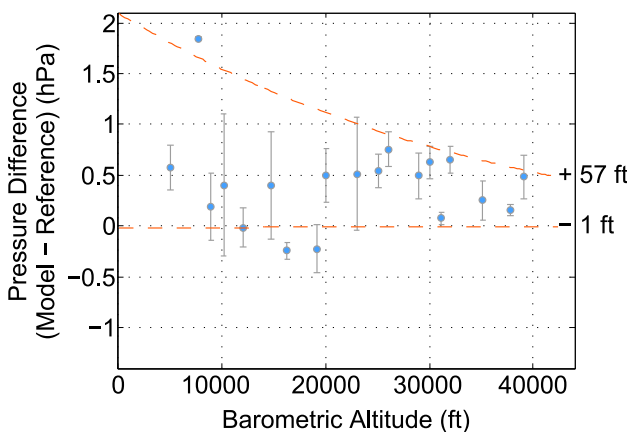


FIG 13 Pressure difference of Model C compared to TC measurements of the ATRA as a function of barometric altitude (nine different flights).

This is almost three times as high as the magnitude of the mean difference reflected by the other two models. Possible reasons for the discrepancy between the pre-investigation and the full analysis are not only caused by the different amount of analyzed data, but also by the examined altitude interval. As the data used in section 3 is based on a single day only, it is less representative for the operational use than the analysis of the flight experiments which were conducted in various test areas, at different dates and under diverse weather conditions. Furthermore, the direct comparison of the NWP models examines the full altitude band that is available from the forecast data whereas the flight envelope of the ATRA limits the data gained during the flight experiments to an altitude band that is of interest for aircraft flying between approximately 5,000 ft and FL400. As the values for the mean and standard deviations determined in section 3 are based on the entire altitude interval which is available from the NWP models, they are not directly comparable to the numbers gained during the flight experiments as they are based on

a tighter altitude interval.

Since Model A shows a negative and Model C a positive mean offset to trailing cone measurements, an improvement in determining the most probable static pressure forecast – based on the data considered in this study – can be achieved by averaging the output values of both models. FIG 12 illustrates the mean values of Model A and C as well as the average value of the two.

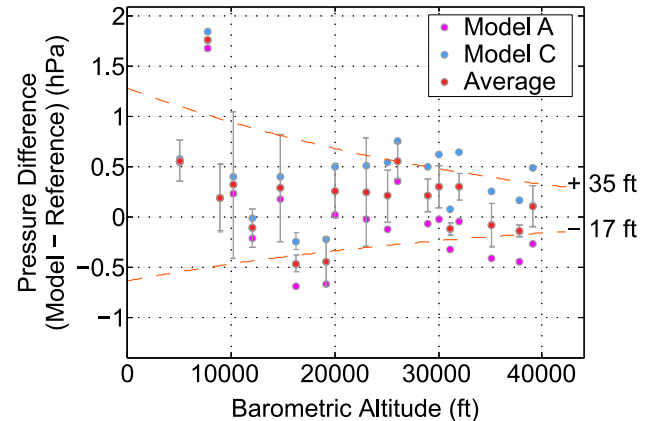


FIG 14 Pressure difference of the 'Twofold Averaging' method based on Model A and C compared to TC measurements of the ATRA as a function of barometric altitude (nine different flights).

This method (here: named 'Twofold Averaging') reduces the mean value difference to +9 ft and the standard deviation to 26 ft, resulting in pressure values that – regarding all measurements in total – lie respectively 1.7 ft for the mean value and 19 ft for the standard deviation closer to the measurements taken by the trailing cone. Instead of using the information of two NWP models only, the 'Threefold Averaging' method additionally includes the output values of Model B when calculating the air pressure. FIG 13 shows the results of the calculated mean values of all three models.

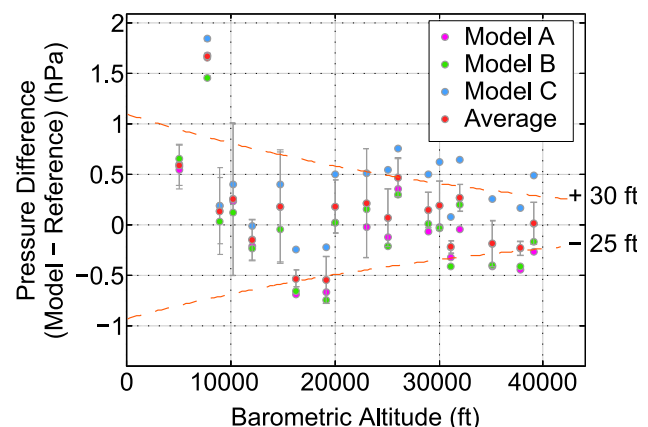


FIG 15 Pressure difference of the 'Threefold Averaging' method based on Model A, B and C compared to TC measurements of the ATRA as a function of barometric altitude (nine different flights).

The overall mean value difference compared to the trailing cone measurements in this case is only +3 ft with a standard deviation of 28 ft.

TAB 2 shows an overview of the results determined by the analysis of the conducted flight experiments.

Model	\bar{p}_s (hPa)	σ_p (hPa)	\bar{h} (ft)	σ_h (ft)
Model A	-0.07	0.53	-10.7	32.4
Model B	-0.09	0.54	-10.7	32.2
Model C	0.39	0.46	28.3	28.8
Model AC	0.16	0.48	8.8	26.1
Model ABC	0.08	0.50	2.3	27.6

TAB 2 Overview of the results

It can be seen that both averaging methods can decrease the standard deviation of the pressure differences, however the mean difference is only slightly improved. A bettering can be observed on the mean and standard deviation of the altitude differences. Because the pressure differences of the various models are differently distributed over the analyzed altitude spectrum, similar results for the evaluated pressure differences can result in diverse altitude deviations. That is caused by the altitude-pressure correlation which is non-linear and determined by the pressure gradient $\frac{dp}{dh}$.

6. IN-FLIGHT LONG-TERM MONITORING

In order to investigate the operational feasibility of this method, four ATRA flights with a flight profile similar to a scheduled airline flight were chosen. The first flight pair was performed in June 2015 from Braunschweig (EDVE) to Paris LeBourget (LFPB) and return, whereas the second flight pair was conducted from Braunschweig (EDVE) to Sevilla (LEZL) and return in November 2015.

During the flight test trials described in section 4 and analyzed in section 5, the reference for the geometric altitude was a high-end GNSS-receiver with SBAS-correction. An airline in-service aircraft is usually not equipped with such kind of GNSS-receiver therefore the standard GPS-Signal of the ATRA was used for the following analysis. The question now asked is, how big are the differences between both altitude reference systems.

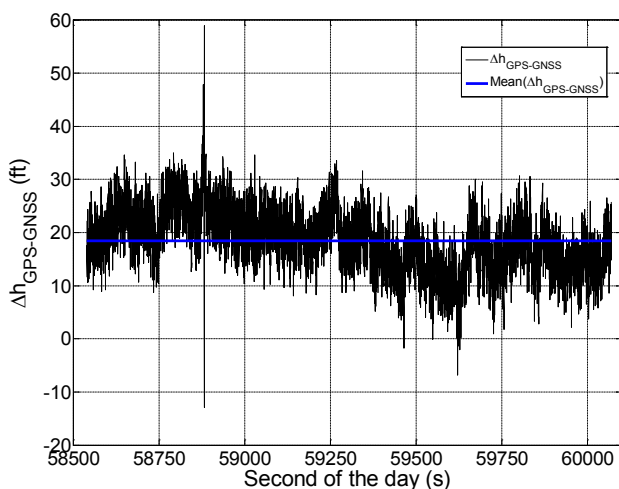


FIG 16 Altitude difference between standard A320 GPS-signal and SBAS-corrected GNSS-signal.

To answer this question, both altitude reference signals have been compared for the four flights. FIG 16 shows the flight from Paris to Braunschweig in cruising flight level (FL350). As indicated by the blue line, the mean altitude difference is about 18.5 ft and the standard deviation (not shown in the figure) reads 5.7 ft. Since the other considered flights yield differences in the same order of magnitude (or even lower), it was decided to accept the un-augmented GPS-signal as an altitude reference.

In the next step, one of the scrutinized NWP models was used to calculate the barometric altitude based on the GPS-altitude. Due to the unavailability of NWP model data, the twofold or threefold method has not been applied. In addition, the altitude reference point was moved from the GPS antenna on the top of the fuselage down to the static pressure sensor in the lower part of the fuselage.

For all flights time periods have been identified between $t=76s$ and $t=5680s$ where the aircraft fulfilled the criteria for a steady and stabilized flight described in section 5. For these time intervals the barometric altitude indicated to the pilot was compared with the barometric altitude obtained from the NWP model. The difference is called Altimetry System Error (ASE) and is shown in FIG 15.

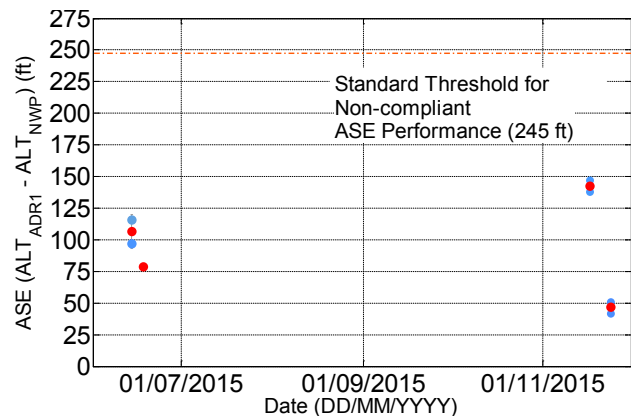


FIG 17 Altimetry System Error (ASE) for four ATRA flights in RVSM airspace in 2015

The blue dots are the mean values per time section and the red dots indicate the average of the mean values of the whole flight, i.e. four red dots in total. In addition, the ± 245 ft Standard Threshold for Non-compliant ASE Performance [1] is plotted by the broken red line. For reasons of clarity, only the positive part of the y-axis is shown, i.e. the limit applies also to negative ASE. It is essential to know, that if an aircraft penetrated the ASE limit of ± 245 ft, a special inspection is required to identify and consolidate the reason.

The visible spread of ASE between the flights is similar to the results which are obtained from the HMU [5]. Also the identified ASE of the ATRA aircraft is well below the non-compliant limit.

7. CONCLUSIONS

The comparison of data from NWP models with in-flight trailing cone pressure measurements of low measurement uncertainty that are also used for the calibration of pitot-

static-systems shows high congruence. This is especially the case because the determined pressure differences of a high number of analyzed flight segments are within the confidence interval of the trailing cone. In some cases the determined pressure difference exceeds this interval.

This can not only be assigned to the quality of the NWP models. Another aspect is the accuracy of the position determination by the use of GNSS, which plays a significant role in computing the static pressure from NWP models. Deviations in the GNSS position from the true position lead to error propagation during the process of determining the static pressure from NWP models. This is because NWP models provide the air pressure as a function of position and altitude and therefore rely on an accurate position determination. To achieve the highest degree of accuracy, it is recommendable to post-process the GNSS data used in order to correct for atmospheric disturbances that affect the accuracy of the position determination.

The discussed method is based on NWP analysis data which is available only every 6 hours only. Thus, a linear interpolation method is used to calculate the static pressure for flight measurements that were taken in between two of these time steps. For non-linear time courses of atmospheric variables as they occur for example for the case of a sudden passage of frontal weather, deviations from the in-flight measurements are expected. Generally, it is anticipated for the method discussed to be most precise near time steps of model-outputs.

Finally, the practical use of this method was investigated for flights which have a flight profile similar to scheduled flights. It was shown that the ASE obtained on the basis of NWP models yield satisfying results with a low spread. Therefore the presented method can be assumed to be generally suited to monitor air data systems, independent of a limited number of HMU ground stations. In addition, this method allows the monitoring of all barometric altitude signals of an air data system while the HMU stations receive only the signals transmitted by the transponder.

Future work will focus on the further extension of the ATRA database w.r.t. to flights in RVSM airspace and the determination of the ASE for the respective flights. Procedures must be established in collaboration with an aircraft operator how to obtain flight data from an airline in-service aircraft without having flight test instrumentation.

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The authors are looking forward to future interesting discussions and collaborations.

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