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Long-term monitoring of barometric altitude measurement performance using the example of a research aircraft

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Abstract
The barometric flight altitude is the decisive variable for the vertical separation of aircraft in the airspace. At present, no aircraft operator is able to independently monitor the proper function of barometric altimetry in flight. In this paper, a method is presented for long-term monitoring of barometric altimetry system performance only by means of flight data and model output data from a numerical weather prediction model. This method enables aircraft operators to independently monitor barometric altimetry system performance of their aircraft fleet. Aberrant aircraft can be identified earlier and can be taken out of service for inspection measures more predictable, or inspected as part of already planned maintenance measures. Already existing flight data from DLR's research aircraft Airbus A320-232 ATRA from 2014 to 2020 were used to determine the long-term behavior of the barometric altitude measurement performance using this method. During two of the flights under consideration, the aircraft was equipped with a trailing cone system, which is currently considered the most accurate way for measuring ambient pressure airborne. Hence, these flights were used as a reference. The summary of the implementation, evaluation, and main results is presented in this paper, starting with a brief introduction to numerical weather prediction models and their model output data. Details on the air data system and position measurement of the research aircraft are addressed as well as prerequisites regarding selection of parameters. Both reference and distance flights are described during which the analyzed flight data were gathered. Data pre-processing and evaluation are explained comprehensively. Finally, obtained results and findings are assessed and discussed with regard to the applicability of the method and future research work. In summary, application of the presented method to a research aircraft has shown good agreement compared to an established method such as the trailing cone system.

Keywords Barometric altimetry system performance · Monitoring · Reduced vertical separation minimum · Numerical weather prediction model

Abbreviations

ADIRU	Air data inertial reference unit
ADM	Air data module
ADR	Air data reference
ADS-B	Automatic dependent surveillance broadcast
AGHME	Aircraft geometric height measurement element
ATRA	Advanced Technology Research Aircraft
DLR	German Aerospace Center
DWD	Deutscher Wetterdienst
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA	ECMWF reanalysis
EUR RMA	European Regional Monitoring Agency
FAA	Federal Aviation Administration
FAC	Flight augmentation computer
FCS	Flight control system
FDM	Flight data monitoring
GNSS	Global Navigation Satellite System
GPS	NAVSTAR Global Positioning System
HMU	Height monitoring unit
IFS	Integrated forecasting system
IR	Inertial reference
LTH	Aeronautical engineering handbook
MMR	Multi-mode receiver
NAARMO	North American Approvals Registry and Monitoring Organization
NAVSTAR	Navigational satellite timing and ranging

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NWP	Numerical weather prediction
PFD	Primary flight display
RVSM	Reduced vertical separation minimum
SA	Selective availability
SBAS	Satellite-based augmentation system
TC	Trailing cone
US	United States of America

List of symbols

H_{ADRx}	Barometric altitude H from ADRx
$H_{NWP-GPSIRx}$	Barometric altitude H derived from NWP based on GPS from IRx
Ma	Mach number
p_{ADRx}	Static pressure p from ADRx
S	Standard deviation

1 Introduction

At present, no aircraft operator is able to independently monitor altimetry system performance of its aircraft by simple means, i.e., without modification to the aircraft or additional assets like a calibrated aircraft. The higher and faster the aircraft can fly, the more difficult this becomes. In particular for the participation in general air traffic, altitude-keeping in the airspace of reduced vertical separation is a fundamental requirement that must be met und maintained. This requires regular proof of this capability in the form of a check of the barometric altimetry.

Nowadays, for monitoring the barometric altimetry system performance of aircraft in the reduced vertical separation minimum (RVSM) airspace [1], analysis data from numerical weather prediction (NWP) models are used to provide the geometric altitude of the different flight levels. For the determination of the position and the geometric height of the aircraft, stationary ground-based receiving stations are used in Europe, which determine the required information from the transponder signal of the aircraft. These so-called Height Monitoring Units (HMU) [2] are positioned at three strategic locations on the European mainland with high traffic density in order to detect as many relevant aircraft as possible. Any aircraft transmitting an ICAO 24-bit aircraft identifier, flying between FL 290 and FL 410 within the operational coverage area of the HMUs (a radius of 45 NM) will be detected by the HMU systems. The Federal Aviation Administration (FAA) has developed its own ground-based monitoring system called Aircraft Geometric Height Measurement Element (AGHME) [3] for the North American Airspace that works on similar principles to the HMU but in different design. But the FAA offers an additional monitoring procedure named ADS-B Out RVSM monitoring [4]. Aircraft equipped with qualified ADS-B Out systems is height-monitored each day during normal operations in US ADS-B rule airspace at RVSM altitudes.

The evaluation of the measured data is automated at designated organizations [5] such as European Regional Monitoring Agency (EUR RMA) or North American Approvals Registry and Monitoring Organization (NAARMO), which only inform the respective aircraft operator about the measurement deviation after a threshold value has been exceeded. Detailed altitude monitoring results are not normally provided directly to the aircraft operators.

As part of the so-called flight data monitoring (FDM) process, which aircraft operators with aircraft over 27 tons maximum take-off weight obliged to perform in accordance with ICAO Annex 6 or EASA EU-OPS 1.037, flight data are collected and analyzed to improve aircrew efficiency, operational procedures, flight training, air navigation services support, aircraft maintenance and aircraft design. Monitoring barometric altitude measurement performance could thus become a further analysis case within this process. Only the model output data from the numerical weather prediction models would have to be provided by an external data provider.

An independent check of the barometric altimetry in flight without the involvement of external organizations would allow any deviations to be identified earlier, analyzed in more detail and, if necessary, targeted countermeasures can be initiated already at an early stage since detailed altitude monitoring results are available to the aircraft operator in-house. This would allow checks of the barometric altimetry system performance with very little effort which could be carried out continuously as part of the operator's flight data monitoring program.

Even though commercial aircraft in particular should by now be equipped with suitable ADS-B Out systems or at least fly regularly over ground-based receiving stations, there are also aircraft to which neither applies. Here, for example, military aircraft should be mentioned, which either do not have the required aircraft systems or rarely fly over ground-based receiving stations due to their typical missions. However, these reasons may also apply to general aviation aircraft, making independent operator monitoring of barometric altitude measurement a beneficial predictive maintenance measure. Last but not least, aircraft with special ambient pressure sensors (e.g., research aircraft) should be mentioned, whose measuring signals are not recorded by the automated monitoring systems.

Such an independent monitoring of the barometric altitude measurement was carried out for flights over a six-year period exemplarily on a DLR research aircraft. The objective of the long-term monitoring of the barometric altimetry was not to determine the exact measurement deviation and its reason; instead, the aim was to demonstrate that the altimetry system error can be calculated by simply comparing the barometric altitude determined by the aircraft systems with the flight altitude based on the output data of a numerical weather forecast model. The determination of the altimetry system error has to be sufficiently accurate and precise to be able to recognize an increasing deterioration in the measurement of the aircraft systems. Patenting procedures related with the method have been successfully completed national and abroad [6–9].

This paper presents a summary of the implementation, evaluation, and main results. A brief introduction to numerical weather prediction models and their model output data is given in Sect. 2. A description of the air data system as well as the position measurement on board the research aircraft is also included in this section. The reference flights are described in Sect. 3. The main part in Sect. 4 deals with the flight data gathering during the distance flights and their evaluation. Findings are discussed and recommendations for future research work are presented. Finally, a conclusion is drawn.

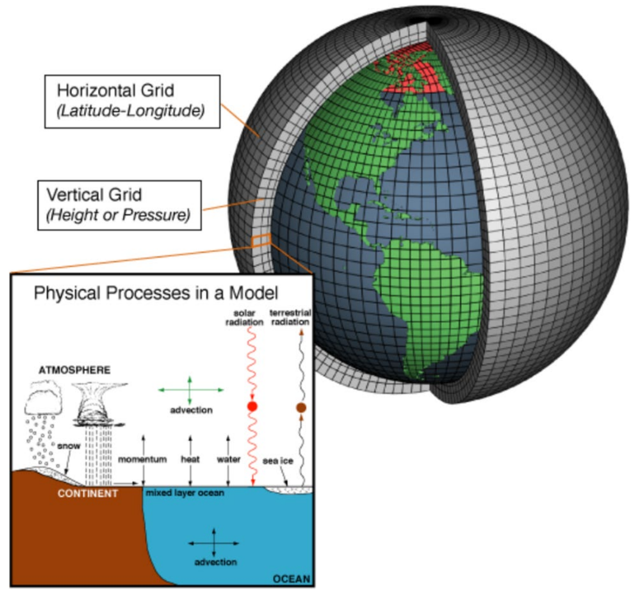

Fig. 1 Physical processes in a NWP model [12]

2 Data provision

2.1 Numerical weather prediction models and their output data

The term numerical weather prediction describes the advance calculation of main meteorological variables, such as ambient air pressure, temperature, density, wind velocity components of the three spatial axes and the humidity, based on the present state of the atmosphere (initial conditions) and the global long-term climate information (boundary conditions). The basis for the prediction is the diagnosis of the three-dimensional atmospheric state at the starting point, which is referred to as *analysis*. This provides the initial conditions for the numerical integration of the equations.

As shown in Fig. 1, NWP models use systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. They use a coordinate system which divides the planet into a 3-dimensional grid to calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points.

The website of the German weather service Deutscher Wetterdienst (DWD) provides a comprehensive description of numerical modeling including NWP models, data assimilation, etc. The information is available both in German [10] and English [11] language.

Not only forecasts are produced, instead, some meteorological service provider periodically use their NWP models and data assimilation systems to re-analyze archived observations in order to create global data sets that describe the recent history of the atmosphere, land surface, and oceans. Like an analysis, a climate reanalysis gives a numerical description of the recent climate, produced by combining models with observations. It contains estimates of atmospheric parameters, such as air temperature, pressure and wind, at different altitudes as well as surface parameters, such as rainfall and soil moisture content.

During the creation of a *reanalysis*, analyses are recalculated from several years to several decades in the past, including all current observations using a modern weather forecast model with a frozen version. That is, while archived analyses may have been produced using different model versions (always the latest version at the time of production), reanalyses of historical observational data are typically produced using the same model version. Reanalysis data may also be limited to a selected number of parameters.

In order to compare the output data of the numerical weather prediction model with atmospheric measurements from real flights, the consideration in this paper is limited to the use of *reanalysis* data only.

A few years ago, research was carried out into the accuracy of such model output data of NWP models. Giez et al. [13] compared and assessed the accuracy of aircraft measurements and NWP analysis of static pressure and altitude at various flight conditions of two research aircraft. Both aircraft were equipped with a trailing cone system, which is currently considered the most accurate way for measuring ambient pressure airborne. They concluded that the agreement between the measurements and the NWP analysis is noteworthy for both aviation and meteorology. The altitude differences between NWP and trailing cone system measurement stay below 9 m / 30 ft for a total of 159 data points performed on six days with two different aircraft. Due to the limited set of analyzed flights, the authors recommend to further investigate the suitability of selected time periods and regions for such comparisons, but they come finally to the conclusion that the method has potential for the control of the altitude-keeping performance of aircraft during operation. Another study [14] came also to the conclusion that the comparison of output data from NWP models with in-flight measurement shows high congruence. Hence, both studies showed with the direct comparison of NWP output data and trailing cone measurements (highly accurate static pressure measurement) the resulting expectable accuracy of a NWP model output.

The European Centre for Medium-Range Weather Forecasts (ECMWF) is an intergovernmental organization that provides data for the national weather services of its member states. The latest reanalysis data set produced by ECMWF's Integrated Forecasting System (IFS) is called ERA5 [15], where ERA stands for ECMWF ReAnalysis. It provides hourly data of many atmospheric data on 37 pressure surfaces and in a regular latitude/longitude grid at a $0.25° \times 0.25°$ resolution. The ERA5 dataset is used as a meteorological reference for the analysis of the flight data described later.

2.2 Research aircraft and its flight data

As already mentioned above, flight test data have been gathered with DLR's research aircraft Airbus A320-232 ATRA, which was deployed by DLR in late 2008 and serves as a modern and flexible flight test platform [16] (Fig. 2).

2.2.1 Air data system

The air data system of the DLR research aircraft Airbus A320-232 ATRA is a non-modified series air data system for the A320 family. The so-called air data reference (ADR) component measures air temperature, static and total pressure as well as angle of attack. From this, the system calculates usable data such as airspeed or altitude and makes it available to other aircraft systems.

Fig. 2 DLR research aircraft Airbus A320-232 ATRA (credit: DLR (CC BY-NC-ND 3.0))

Sensors convert the measurements into electronic signals, which are then sent to the three air data inertial reference units (ADIRUs), where conversion into usable system data ultimately takes place.

In the ADIRUs, an average static pressure of the respective left and right air data module (ADM) is formed, i.e., the pressure readings of the left and right ADM are added and divided by two. Based on the average static pressure, the corrected static pressure is calculated considering a correction factor. The correction factor depends mainly on the Mach number, the angle of attack and the slat and flap position and is stored in the form of a table in the software of the air data system. The corrected static pressure is used in the final step to determine the barometric flight altitude based on the standard atmosphere. The air data system complies with an ARINC standard [17], from which more detailed information can be taken.

A review of the aircraft maintenance history revealed that the static pressure sensors installed on the aircraft have not changed since late November 2012, and therefore all considered flights were conducted with the same static pressure sensors.

2.2.2 Position measurement

In addition to the meteorological model data, the position data of the aircraft are essential for monitoring the barometric altitude measurement, in particular the vertical position measurement in form of the ellipsoidal or geometric flight altitude. Nowadays, the position is determined using global navigation satellite systems (GNSS), such as the Navigational Satellite Timing and Ranging (NAVSTAR) Global Positioning System (GPS).

Modern GNSS receivers can process corrections transmitted from reference stations on the ground in a differential mode. However, these corrections to time, as well as information about ephemerides and the ionosphere, can also be transmitted to the GNSS receiver via geostationary satellites. The satellite-based correction is performed by means of a satellite-based augmentation system (SBAS), of which there are several operational systems worldwide, each with a regional distribution.

The so-called selective availability (SA) was a deliberate degradation of public GPS signals implemented by the United States government for national security reasons. This error had a negative impact on GPS accuracy and was deactivated in May 2000. There are several multi-mode receiver (MMR) types certified for use in Airbus aircraft that handle selective availability differently in calculations [18].

For devices of the "SA on" type, the error possibly caused by the selective availability is included in the calculation of the accuracy, regardless of whether the selective availability is switched on or not. Since the selective availability is switched off in the meantime, the calculated error(s) will be higher than they actually are.

To determine the exact position, the Airbus A320 has two independent GPS receivers as part of the basic equipment (only GPS position data is currently used in Airbus aircraft [19]), which are integrated in the so-called MMR. In the research aircraft in question, MMRs of type Collins Aerospace GLU-920 are used, which have a somewhat older standard. Therefore, this MMR type belongs to the "SA on" type devices, so that errors estimated by the device will be larger.

Since mid-2015, the DLR research aircraft ATRA has also been equipped with an additional JAVAD Delta-3 GNSS receiver that can receive and process satellite-based correction data in addition to satellite signals from other satellite navigation systems such as Galileo. This position data source is thus expected to provide higher accuracy position data. In addition, this will give an impression of the accuracy of the uncorrected standard GPS on which series-production aircraft with avionics of this generation must rely.

2.2.3 Parameter selection

With regard to the possibility of applying long-term monitoring of barometric altitude measurement to series-production aircraft without additional flight test instrumentation, only parameters that are provided by the respective systems in each Airbus A320 series production aircraft were considered in the parameter selection. However, this does not necessarily mean that the selected parameters are actually recorded in the respective series aircraft for external use and must therefore be checked individually in each flight operation.

In addition, attention was also paid to data minimization. On the one hand, this was done to keep the required data volumes as low as possible, and on the other hand, to make the required flight data less sensitive. For example, the control inputs of the aircraft pilots were omitted in order to avoid any possibility of inference here. The engine parameters necessary for determining the mostly confidential flight performance are also not included in the parameters considered. The following parameter groups, based on the example of an Airbus A320, provide the parameters required for effective monitoring:

- date and time
- ADR1, ADR2, ADR3 Bus line (static pressure, total pressure, airspeed, Mach number, temperature, …)
- IR1, IR2, IR3 Bus line (latitude, longitude, GPS-height, wind, angle, angular rates, accelerations, …)

The flight augmentation computer (FAC) provides parameters for a possible deeper analysis if the influence of the mentioned parameters on the barometric altitude measurement is to be considered

- FAC1 General Bus (weight, center of gravity, slats, flaps, angle of sideslip)

3 Reference flights

For a DLR flight test campaign in summer 2015, the research aircraft was equipped with a trailing cone system. It consists of the main components cone and hose. Here, a pressure tapping point in front of the trailing cone takes the calmed static pressure of the surrounding atmosphere and provides it as reference pressure. This is done by pulling the trailing cone behind the aircraft during the calibration flight. The distance to the aircraft must be sufficiently large so that the surrounding air can be described as almost undisturbed by the actual aircraft. The cone is used mainly for stabilization and as an aerodynamic drag to pull the hose out of the aircraft. This type of in-flight reference pressure measurement is currently considered the most accurate way to measure ambient static pressure. Therefore, most prototypes of new transport aircraft also have such a trailing cone system installed to calibrate the air data system.

Functional check flights were performed prior to the reference measurement flights to verify proper operation of the trailing cone system. The flight test method and results are described in Ref. [14].

The measurement data obtained with the established flight test technique were used to verify the barometric altitude measurement of the ATRA. The measurement deviations determined in the process are also the reference values for the planned long-term monitoring using reference data from numerical weather forecast models.

In the course of two flights within the flight test campaign, so-called racetrack patterns were flown, which resemble holding patterns and are shown in Fig. 3. These were flown on different flight levels, whereby only flight levels 300, 350 and 390 were considered for the determination of the reference values, since they are located in the altitude range of reduced vertical separation. In the measurement sections, a specified airspeed was flown in horizontal and unaccelerated flight. The measured static pressures and the derived flight altitudes as well as the resulting deviations were averaged over the measurement section.

While the pressure sensor of the trailing cone system is located in the rear part of the aircraft, the basic pressure

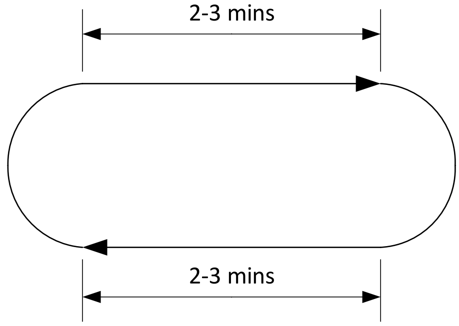

Fig. 3 Racetrack pattern

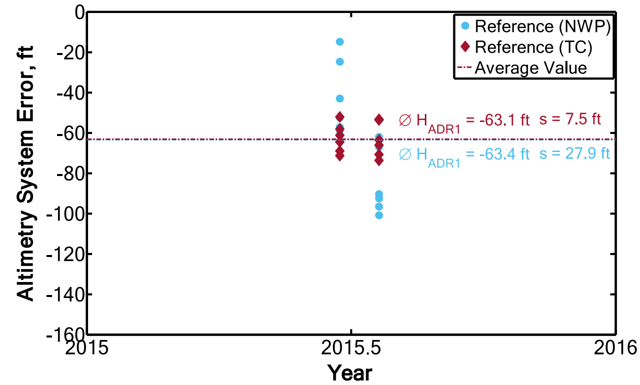

Fig. 4 Altimetry system error during reference flights for ADR1

sensors for the ambient pressure are mounted in the front part of the aircraft. Due to the horizontal distance of about 20 m, there is a vertical distance that depends on the pitch angle of the aircraft. For the flight segments considered, a vertical height difference of about 3–4 ft was determined, which is considered negligible for these purposes and consequently not included in the evaluation.

With three flight altitudes and two measuring sections each, there are six measuring points, whereby for the second flight a uniform duration of 160 s could be defined for each measuring section. For the first flight, on the other hand, it was only possible to define a uniform measurement length for each flight altitude, which were also significantly shorter in each case (between 20 and 70 s). The average pressure measured with the trailing cone system and the corresponding barometric flight altitude were determined over the duration of each measuring section. The following basic aircraft parameters were considered:

- STANDARD ALTITUDE
- CORRECTED AVERAGE STATIC PRESSURE
- MACH NUMBER
- CORRECTED ANGLE OF ATTACK

for ADR1 and ADR2, respectively. Since the correction of the measured (uncorrected) static pressure depends on the Mach number and the corrected angle of attack, these two parameters are included for completeness.

The altimetry system error shown below is the difference between the barometric altitude calculated by the basic air data system and reference barometric altitude values assumed to be true. On the one hand, the trailing cone system was used to determine the altimetry system error, which are shown in a diamond shape in the following Fig. 4. Due to the direct comparison of the two measured values, no position data are required for this. In another evaluation, model output data from numerical weather prediction models as described in Sect. 2.1 were used as a reference for determining the altimetry system error. The position data from the additional GNSS receiver were used for this purpose. The cyan-colored points correspond to the test points based on the numerical weather prediction model output data as true assumed reference.

According to international standards [20], an aircraft configured to comply with the requirements of an RVSM minimum aircraft system performance specification is non-compliant if it is found through height monitoring to have an altimetry system error of 245 ft or more. However, the threshold at which follow-up action is initiated should take account of the inherent accuracy of the monitoring procedure.

The respective mean values are shown both as a dash-dot line in the diagram (the cyan mean line is covered by the red line) and as numerical value. Even though the mean values of the measurements with the trailing cone system and the reference data based on the data from the numerical weather forecast model are almost the same (they differ by less than 0.5 ft), the already visually recognizable scatter in the model-based results is also evident in the determined standard deviations of the averaged data from the segments flown. This is almost four times as large as for the trailing cone system-based results.

The deviations of the calculated barometric altitude are negative. This means that the aircraft systems are calculating a lower flight altitude than it is actually flying. In principle, this is the "safer" deviation since the safety margin between an obstacle and the aircraft is therefore greater. At a cruising altitude, obstacle clearance is obviously less relevant.

The output data from the numerical weather prediction model are dependent on the vertical position measurement (cf. Sect. 2.2.2), i.e., the geometric flight altitude. Unfortunately, it is not possible to answer whether the vertical position measurement or numerical weather prediction model itself is responsible for the observed scatter. Viewed as a whole, however, the reference based on the numerical weather prediction model output data agrees well with the measurements of the trailing cone system and remains clearly below the threshold of 245 ft for a non-compliant aircraft. At the same time, the order of magnitude and the sign of the measurement deviations of the basic air data system are confirmed.

The differences of the flight altitude computed by ADR1 and ADR2, respectively, are less than 20 ft and therefore not shown or discussed separately here.

4 Distance flights

4.1 Overview

Typically, a commercial airliner flies from one airport to another airport, with a cruise segment at cruise altitude, in which the aircraft flies at constant barometric altitude and airspeed. The cruise flight segment is particularly suitable for monitoring the barometric altitude measurement performance since the measurement of the static pressure is preferably performed in horizontal and unaccelerated straight flight in a calm atmosphere, in order to minimize the influences from the motion of the aircraft.

Among the available flight data, flights were identified in which the research aircraft had a flight profile similar to that of a normal commercial aircraft, i.e., flights from A to B with a longer en route flight component. In addition, the research aircraft must not be modified externally to ensure no disturbing influence on the ambient pressure measurement. A total of 25 flights between end of 2014 and end of 2020 were selected having this flight profile. The following Fig. 5 shows the flight paths of the distance flights on a map.

The focus of the considered flights has been on mainland Europe with one-off flights to French Guyana, Norway and Cyprus. Due to known disturbances of the satellite navigation in the Cypriot airspace with corresponding influence on the determination of the geometric flight altitude, route sections in this area were sorted out on a large scale.

The following histogram Fig. 6 shows the cumulative flights per month in which they took place.

It can be clearly seen that the majority of distance flights took place during the meteorological autumn and winter months (9 and 14 flights, respectively). Only two distance flights were performed in a summer month, and no distance flights were conducted at all in the springtime. Unfortunately, this uneven distribution means that any seasonal influence on the output data of numerical weather prediction models cannot be investigated. This is not a drawback, as the atmospheric conditions were not considered when selecting the flight segments.

4.2 Data pre-processing

The preparation of the different data sets was done according to the following block diagram in Fig. 7. The complete calculation process for determining the static pressure along the flight path, including the theoretical background, is described in detail in Ref. [21].

Air data includes the ADR1, ADR2, and ADR3 parameter groups with a focus on the first two parameter groups since they are used in both the primary flight display (PFD) and the flight control system (FCS). Here the CORRECTED AVERAGE STATIC PRESSURE represents the main monitoring parameter since this is the basis for the calculation of the barometric altitude. The so-called stand-by system ADR3 is not considered for the time being.

The position data are derived primarily from the GPS from the inertial reference (IR) units, which are part of the basic equipment of an Airbus A320. Starting from the fourth flight, a special GNSS receiver was also available, which receives correction data via satellite to increase accuracy. In anticipation of higher accuracy, the GNSS position data will

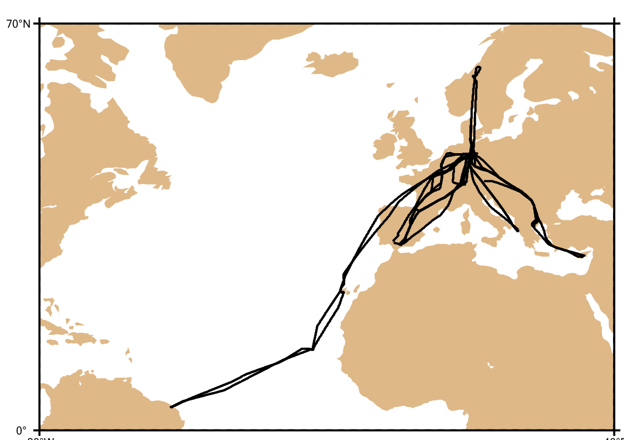

Fig. 5 Flight paths of the distance flights considered for monitoring

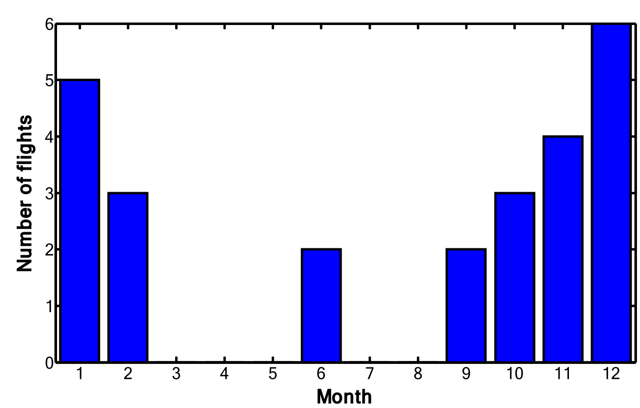

Fig. 6 Distribution of flights over the calendar months

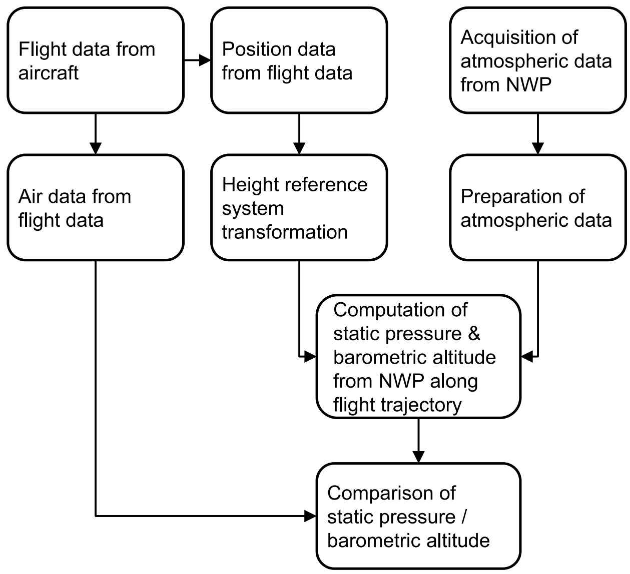

Fig. 7 Flowchart of the calculation process

be used primarily to verify the uncorrected GPS position data from inertial reference units.

For the respective flight days, the reanalysis data of the ERA5 dataset [15] were downloaded to the necessary temporal and geographic extent. Subsequently, the reanalysis data were processed accordingly so that they can be used to determine the static pressure along the flight trajectory. This was done in the penultimate process step for the GPS_IR1 and GPS_IR2 position data and, if available, for the GNSS position data. Thus, there are a maximum of three references for the static pressure, based on the respective measured geometric flight altitude. In addition, the reference pressures were converted to the barometric flight altitude as the reference flight altitude corresponding to the standard atmosphere, so that a direct comparison could be made with the barometric flight altitudes from the air data systems.

4.3 Data reduction

In a first step, the usable flight segments were identified for each available flight, i.e., cruise phases with constant flight altitude and constant Mach number. Climb and descent segments as well as altitudes below flight level 290 were not considered. Turning flight segments during the cruise phase have not been sorted out at first in order to be able to estimate a possible influence on the results (Fig. 8).

A total of 46 time segments were identified across all flights that meet the previously mentioned criteria. Across all flights, the time segments are between 86 s and 5 h 40 min long with a mean value of about one hour. The time periods thus differ significantly in length. Without a finer subdivision of the time segments, it was initially only determined

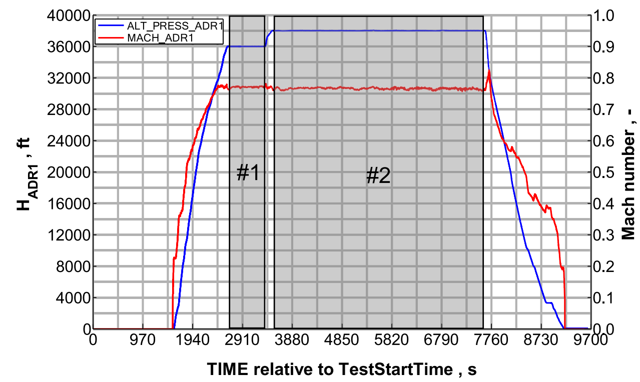

Fig. 8 Preselection flight segments

that the minimum length for a time segment should be at least 300 s. This minimum length of the time segment is identical to the required minimum time in the coverage area of the EUR RMA HMU receiving stations which are currently monitoring altitude-keeping performance in the area of the reduced vertical separation [22]. With the minimum time length established, 39 flight segments remained with a total flight time of approximately 47 ½ hours. The distribution of the time segments over the flight altitude is shown in the following Fig. 9.

It can be clearly seen that the distribution is quite uneven. The flight altitudes from 35,000 ft to 39,000 ft account for nearly 90 percent of the time segments, with about 30 percent being at a flight altitude of 38,000 ft. Looking at the distribution of the lengths of the time segments in Fig. 10, a similar picture emerges.

Over 40 percent of the total flight time took place at an altitude of 38,000 ft, while only about five percent of the total flight time is assigned to flight altitudes from 30,000 ft to 34,000 ft.

For each time period, the two barometric flight altitudes from the air data system (ADR1 and ADR2) and

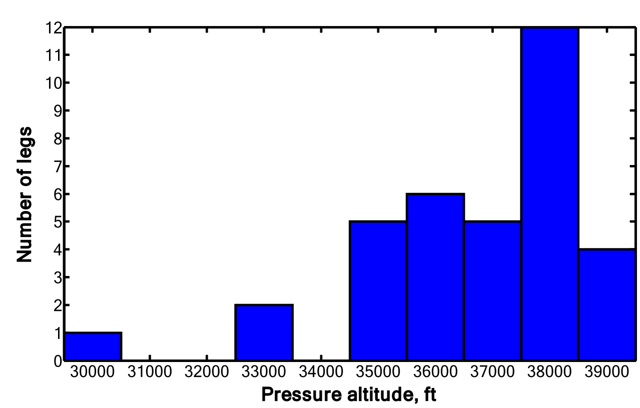

Fig. 9 Number of flight segments per flight altitude

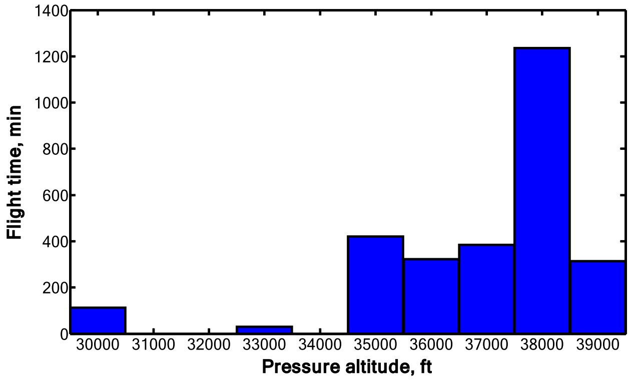

Fig. 10 Cumulative flight segment lengths per flight altitude

the available reference flight altitudes (based on GPSIR1 and GPSIR2) were plotted over the time, as exemplified in Fig. 11. The lower diagram of Fig. 11 shows the difference between the two barometric flight altitudes from the air data system and the reference flight altitudes. The reference altitude $H_{NWP-GPSIR1}$ (i.e., barometric altitude derived from NWP based on GPS from IR1) was used for the difference formation for both H_{ADR1} and H_{ADR2} in order not to superimpose possible effects. For each computed difference, the average value was calculated, as well as the standard deviation as an indicator of dispersion. In the example shown, the average values of the differences are negative, i.e., the aircraft is actually flying higher than indicated.

In addition to the flight altitude, the Mach number, the angle of bank, and the horizontal or vertical accelerations are important evaluation parameters for an unaccelerated, horizontal straight and level flight. These were evaluated in a further step together with the corrected angle of attack since the calculation of the barometric altitude depends on the corrected angle of attack. In case parameters indicating not a straight and level flight, the time interval was adjusted as appropriate by means of engineering judgment.

Using the previously described method, time segments were preselected (cf. Figure 8) and then relevant parameters were plotted graphically. Where appropriate, the preselected time segments were slightly adjusted manually. For all final time segments, the average value of the difference between the two barometric flight altitudes from the air data system and the reference flight altitudes was determined.

4.4 Data evaluation results

During the data evaluation, it was found that the satellite-based correction function was unfortunately not switched on at the GNSS receiver from flight 17 onwards, so that only uncorrected position data were output. In addition, the vertical GNSS position data for some other flights were disturbed or erroneous, so that these could not be considered either. Overall, additional GNSS position data were available for only about half of the flight segments, which would allow a direct comparison between the A320 baseline system and

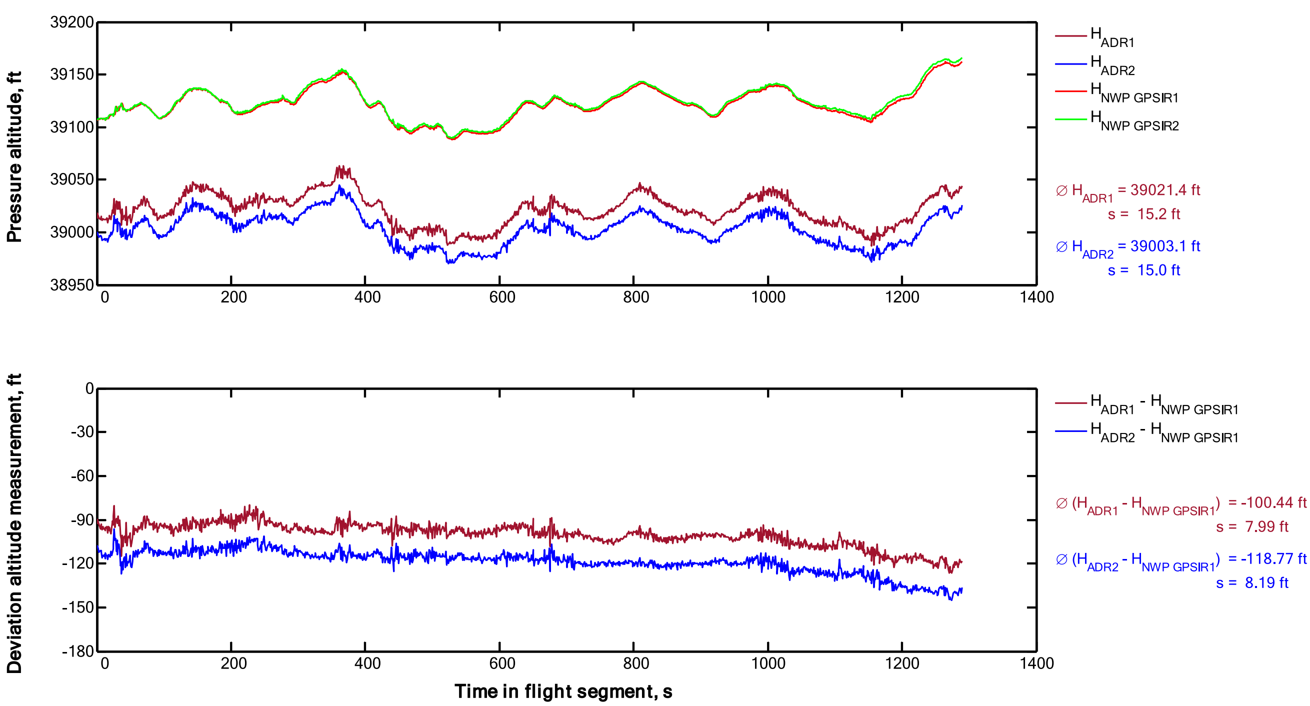

Fig. 11 Barometric flight altitudes from aircraft systems and their measurement deviations

corrected GNSS position data. Therefore, it was decided not to include the additional GNSS-based results in the diagrams since the different data basis could lead to distortions in the interpretation of the results.

As explained in the introduction section, the objective of the long-term monitoring of the barometric altimetry system performance was not to determine the exact measurement deviation and its cause. For this reason, only the development of the altimetry system error over the analyzed period is presented below.

The measurement deviation of the barometric altitude measurement based on the GPS position data from the A320 basic system is shown for H_{ADR1} in the following Fig. 12 by means of black dots. As already explained in Sect. 3, in contrast to trailing cone system measurement, the deviations based on NWP output data include not only the altimetry system error but also possible errors from the NWP model and the vertical position measurement. It is not possible to separate the two possible error contributions.

Figure 12 is an addition and extension of Fig. 4 by the deviations of the barometric altitude measurement, which were determined during the evaluation of the distance flights. The mean value of the black data points is 21 ft larger than that of the reference flights (based on NWP), with the standard deviation being slightly smaller.

It can also be seen that, for example, the deviations at the end of 2014 are all above the mean, with the largest deviation in terms of amount of about -140 ft also in this period. Furthermore, this data point is the only data point at 30,000 ft, so there is no way to include other deviations at this flight altitude in the evaluation. A reason for the above-average measurement deviations for this flight segment could not be found. Furthermore, if one looks at the scatter before and after the turn of the year 2016/2017, it appears that the scatter is lower thereafter. For the time being, there is no rationale for this on the aircraft system side either. One more shortcoming is the long data gap between flights in early 2017 and flights in late 2018, during which no usable flight is available.

Another parameter influencing the correction of the measured (uncorrected) static pressure is the Mach number. For the black data points shown in Fig. 12, this is on average approx. $Ma = 0.784$, which represents the typical cruise Mach number for an Airbus A320. The Mach numbers of the data points range from $Ma = 0.766$ to $Ma = 0.801$, i.e., about ± 0.017 around the average value. This range is considered to be small, so a more accurate correlation between barometric altitude measurement error and Mach number was not established and thus not investigated further. However, it should be noted that the reference measurements at 35,000 ft were flown at a lower Mach number ($Ma = 0.713$), so that an influence of the different Mach numbers cannot be excluded. In addition, the correlation between the observed deviations and other flight parameters, such as flight altitude and angle of attack, was analyzed, but no correlation could be derived that could explain the deviations.

The barometric altitude considered so far is not a directly measured quantity, but a parameter derived from the static pressure as the measured quantity. It should be noted that the gradient dH/dp_s is not the same over altitude, but increases with altitude, i.e., a static pressure change of 1 hPa represents a different altitude change at different altitudes. Therefore, the deviation of the static pressure measurement is presented below.

Except for the change in sign, Fig. 13 is similar to Fig. 12 although the position of the points relative to each other has changed slightly in some cases due to the altitude-dependent pressure gradient. While the data points at the beginning of 2017 are closer together, some of the data points of the reference measurements have drifted apart. And the outlier at the end of 2014 widened its gap to the rest of the points. The mean values are still close together with a difference of less than 0.2 hPa.

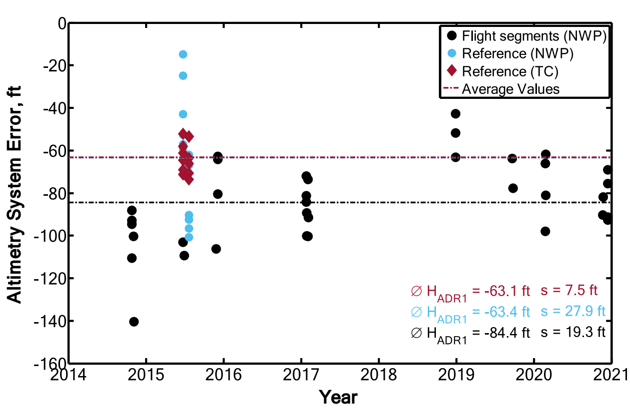

Fig. 12 Altimetry system error over the years 2014–2020

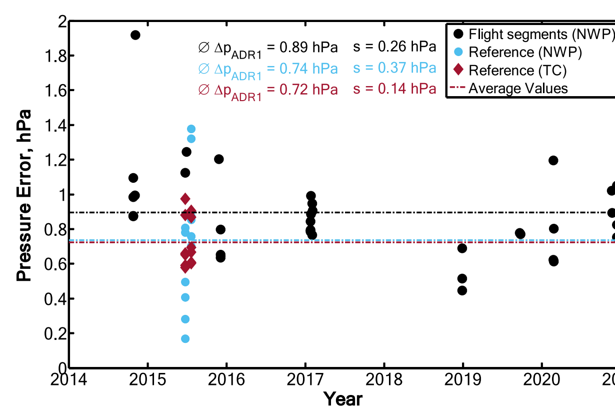

Fig. 13 Deviation of static pressure measurement over the years 2014–2020

Within the monitoring period of more than six years, there are larger intervals between the flights of up to two years. Furthermore, the majority of distance flights have taken place during the meteorological autumn and winter months, i.e., between September and February. The analyzed distance flights are thus unevenly distributed both over the year and over the years under consideration. The distribution over flight altitudes is also not uniform, here the flights are concentrated in the upper part of the airspace with reduced vertical separation minimum. In terms of flight time per flight altitude, one altitude clearly stands out. It is therefore desirable to have access to a larger database with more evenly distributed flights so that the results are more statistically meaningful. It should also be possible to derive from this the frequency with which an aircraft must be monitored so that any intolerable measurement deviations are detected in good time. However, these aspects are not expected to have a major influence on the overall result and therefore on the final conclusion of this study.

As described earlier, the maximum length of a stabilized flight segment of a flight altitude was selected for analysis. This leads to very different flight segment lengths, although the effects on the result were not investigated in detail. Two examples are shown below in Fig. 14.

In the upper diagram, the course of the measurement deviations over the rather long flight segment of more than one hour is almost constant, only toward the end the amount of the measurement deviation increases slightly. In this example, the length and/or location of the flight segment under consideration has only a minimal influence on the result, the average value of the measurement deviation. In contrast to this, the measurement deviation of the barometric flight altitude shown in the lower diagram of Fig. 14 is continuously and slightly increasing over a long flight segment. For ADR1, the measurement deviation starts at just below − 120 ft and ends at about− 70 ft after about 1.5 h. In this example, the length and/or the location of the considered flight segment would have a greater influence on the average value of the measurement deviation, especially if it would be located at the beginning or at the end of the flight segment. Driving factors for this progression can be considered to be, on the one hand, model data from numerical weather prediction models and, on the other hand, satellite-based position determination. Unfortunately, it is not possible to determine which effect predominates here.

5 Conclusion

The present study has been tackled with the motivation to develop a method with which almost every aircraft operator can independently monitor the barometric altimetry system performance of its aircraft. The flight data being necessary are generated on board the aircraft anyway and are usually recorded as well. The aim of this work was to demonstrate that the altimetry system error can be calculated by simply comparing the barometric altitude determined by the aircraft systems with the barometric altitude based on the output data of the numerical weather forecast model. It was not the aim of the work to investigate the

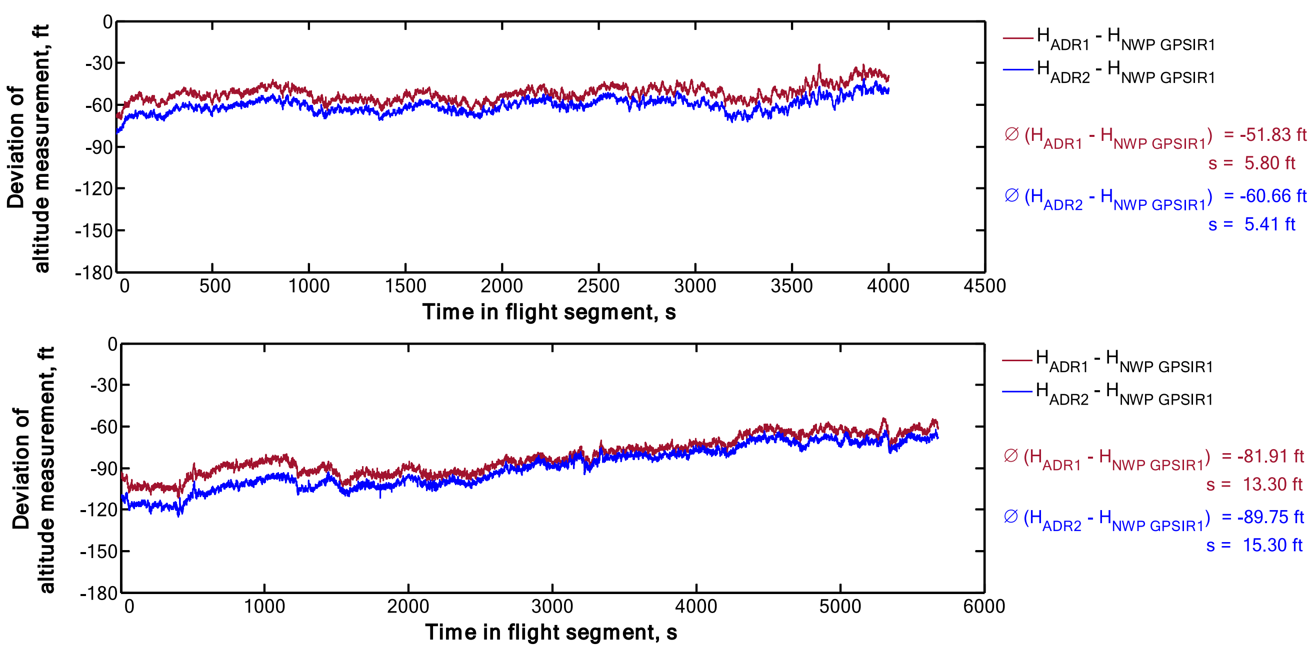

Fig. 14 Deviation of barometric altitude measurement for two flight segments of two different flights

exact cause of any identified altimetry system error. A total of 25 flights from existing flight data from a period of six years were identified that were suitable for demonstrating this method. The respective altimetry system error was determined for selected flight segments and plotted over the time period. Results from two flights with installed trailing cone system were added as a reference for comparison purposes.

Overall, the conducted long-term monitoring of barometric altimetry system performance based on output data from numerical weather prediction models has shown good agreement compared to established methods such as a trailing cone system. The difference of the mean values based on a trailing cone system and NWP model output data is below 25 ft which is approximately ten percent of the maximum allowed altimetry system error. This accuracy is sufficient to recognize any erroneous measurements before the threshold of 245 ft is reached. More considered flights reduce uncertainty in the altimetry system error average as uncertainty in the altimetry system error estimates due to errors in the current model output data of the numerical weather prediction models are averaged over time.

The presented method is verified with the given data available for this paper and needs to be validated with more flight data and/or aircraft in future work. Nevertheless, it is therefore a promising method to independently monitor the barometric altitude measurement performance of one's own fleet or, if necessary, to have additional data available for diagnosis in the event of error messages. However, some open questions and research work also offer the potential to optimize the evaluation and thus the results.

Even though the results are already very meaningful, the method was only demonstrated on one aircraft. Additional aircraft would not only increase confidence in the method, but also help answer the question how to deal with different length of flight segments and their optimum length.

A further development of the application would be the direct real-time monitoring of the barometric altitude measurement during the flight on board of the aircraft. For this purpose, the most current output data possible from the weather forecast models would have to be transmitted on board the aircraft and compared there with the current flight data. In addition to the significant increase in the degree of automation, one would also have an additional reference of the barometric flight altitude in the event of an acute system malfunction of the barometric altitude measurement.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interests The authors declare no competing interests.

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