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INFLUENCE OF AIRSPEED MEASUREMENT ERROR – IMPLICATIONS FOR DEAD RECKONING NAVIGATION

Summary

Errors in navigational instruments can significantly affect flight safety. Airspeed is a key piece of navigational data that depends on accurately measured air pressure, which in turn depends on accurately measured air temperature. Instead of measuring the outside air temperature in real time, cockpit instruments are preprogramed with standard air temperature values for different flight altitudes, but atmospheric conditions can cause the actual temperature to deviate substantially from these standard values. In the present study, test flights were conducted under various atmospheric conditions to examine how the actual temperature affects the deviation of the actual airspeed from the measured airspeed. Results indicate that the differences between the actual and the standard temperature, and not those between the actual and the standard pressure, are the primary cause of deviations of the measured from the actual airspeed. The results of this study may help establish aircraft flight models based on more accurate estimates of navigational parameters.

Key words: *Airspeed, outside air temperature, dead reckoning navigation*

1. Introduction

Air pressure forms a basis for measuring the navigational parameters of aircraft flights. Aircraft instruments that make measurements based on air pressure are calibrated according to the International Standard Atmosphere (ISA) model. These standards stipulate the expected values of air temperature and pressure at different altitudes. While these standard values often approximate the actual values reasonably well, they may fail to do so when various atmospheric parameters, such as density, humidity and temperature, cause the actual air pressure to differ significantly from the standard value. Such deviations can lead to serious errors during dead reckoning navigation during which the aircraft position is calculated based on the last known position and data on the airspeed, aircraft heading, course, and flight time.

While flight navigation systems could avoid most of these problems by relying on satellite-based global positioning systems (GPS) to determine the airspeed and altitude, this option is not normally available to civil aviation because of technical limitations. As a possible alternative, aircraft instruments could measure air pressure using a more accurate standard than the ISA standard. To understand better the limitations of the ISA standard, the present study explored the degree of deviation of the actual from the measured navigational parameters, particularly airspeed, under different atmospheric conditions. The goal was to identify atmospheric factors that can lead to deviations from the predicted airspeed. Airspeeds obtained in three ways, by direct measurement, ISA standard and GPS, were compared and used to determine the deviation of the actual speed from the speed displayed in the cockpit.

The obtained results show that the ISA standard does not model well the way how the air temperature changes with the flight altitude under various atmospheric conditions. The resulting difference between the actual air temperature, and therefore the air pressure, and the theoretical value programmed into the cockpit navigation system leads to differences in the airspeed. Thus, an accurate measurement of air temperature is a key to a precise determination of airspeed. The present study provides basic insights into developing more realistic and precise flight navigation systems, allowing safer and more efficient use of airspace.

Despite going through an extensive literature on aerodynamics, aircraft performance and navigation, both in English and in Croatian, we have not identified any published studies on how pitot-static navigational instrument readings relate to, or deviate from, real conditions. Similarly, we have been unable to find studies examining the interdependence of airspeed and altitude. Flight manuals typically contain graphs displaying the interdependence of true airspeed and the Mach number, but no detailed explanation is provided for this relationship. In addition, most aeronautics monographs and textbooks look at general relationships between airspeed and flight parameters based only on theoretical considerations (Anderson, [2]) or in relation to specific concepts [1], [7]. Knoedler [6] examined pitot-static airspeed errors based on GPS measurements, and Gray [4] used GPS to track the aircraft movement and speed relative to the ground position and speed in order to determine the true air speed (TAS) precisely. In Gray's approach, airspeed and position along a three-segment flight path, together with wind speed and direction, are used to calculate TAS. One limitation of this approach is that it requires wind speed and direction to be constant, which is often not the case under real atmospheric conditions. Lewis [8] further developed this approach for implementation in flight planning and in pilot training as a flight test technique. Numerous authors, such as Hearing [9] and Huston [10], have examined the precision of the pitot-static system, but they focus on system calibration and on quantifying errors within the system itself.

The calibrated and the real airspeed are usually calculated based on standard pressure values from the ISA model [5], which stipulates physical parameters of air at different altitudes. While this model may be appropriate for a theoretical calculation of flight performance, its predictions for the airspeed at a flight altitude may deviate significantly from the actual values under certain atmospheric conditions of density, pressure and temperature. In particular, such deviations can occur during temperature inversions, cyclone-anticyclone conditions, or flights through airspace of unusually low or high pressure. These deviations can lead to erroneous cockpit readings on the airspeed and altitude indicators, which are calibrated according to the ISA model. The present study describes how variations in air temperature and pressure lead to deviations of the actual flight speed from ISA predictions.

2. Methods

Air pressure is a key factor in calculating navigational parameters of aircraft flight, the most important of which are airspeed and altitude. The pitot-static system measures air pressure by determining the difference between the static and the total air pressure (measured by the airspeed indicator), while taking into account the reduction in the static pressure with an increasing altitude (measured by the altimeter). The present study is aimed at elucidating the way how the actual and expected airspeeds change with altitude, as well as at identifying the factors that cause the actual airspeed to deviate from the ISA standard values currently used in most civilian aircraft navigation systems.

Test flights were conducted with an Antonov AN-32 aircraft equipped with two independent and autonomous systems for air speed measurement: sensors forming part of a BUR-4-1-05 system for recording flight parameters, and a GPS-linked Garmin 296 receiver. The BUR-4-1-05 system is normally used to record data on pilot actions, technical state of the aircraft, weather, and identification (flight number, aircraft registration information, flight date). These data are often analysed in the event of an accident. A total of five test flights were conducted under diverse atmospheric conditions and at various altitudes and speeds in order to explore a broad range of flight situations. Each test flight involved one or more segments, where segments began with the take-off from the departure airport and ended with the landing at the next airport. For all test flights, the initial departure airport and the final destination airport was Zagreb, with intermediate segments involving the airports in Pula, Zadar, Split, and Dubrovnik. One test flight comprised four segments, with the initial departure from Zagreb, stops in Pula, Zadar, and Split, and the final landing in Zagreb. Each segment of all test flights was conducted according to a predefined flight plan and navigational parameters. The exception was one test flight around the area of the Zagreb airport; this flight, conceived to involve a single segment, was conducted without a predefined navigational route. The five test flights involved 13 segments altogether, each with its own set of measurements.

Meterological data during the test flights were used to calculate the influence of wind on airspeed as well as to determine the air pressure at the departure and destination airports for each segment. TAF reports and METAR reports, including TREND prognosis, were obtained from the departure and destination airports immediately before each flight and were used to generate a complete picture of atmospheric conditions at the airports. The wind direction and speed for each segment were calculated using the values for drift angle and wind speed read directly from the aircraft instruments. Wind direction and speed significantly affect airspeed and can be highly variable under real atmospheric conditions. The mean wind direction and speed for each segment, calculated by the interpolation from data in this study and from altitude wind charts, were used to analyse the airspeed data for that segment. Atmospheric parameters on flight routes were obtained from Significant Weather Charts (SWC) covering the Croatian airspace issued by the Meteorological Office at the Zagreb Airport. Additional meteorological data were obtained from the ALADIN prognostic model generated by the State Hydrometeorological Office (DHMZ) of Croatia.

Measurements made during the test flights included the pressure, altitude, ground speed, magnetic heading, calibrated airspeed, Mach number, and outside air temperature (OAT). Altitude (H) was read from the barometric altimeter set to the mid-sea level pressure according to the ISA standard ($10.132 \cdot 10^4$ N/m^2). Ground speed was measured using the Garmin 296 GPS receiver. Magnetic heading was used to calculate the drift angle and thereby to obtain data on the headwind and tailwind components. Calculations were carried out for the enrooted cruise part of each test flight segment, when the airspeed and altitude were constant. Data on the ground speed and the headwind and tailwind components were used to calculate the true airspeed (TAS). The corresponding values for the calibrated airspeed (CAS) were measured using the BUR-4-1-05 sensors installed on the aircraft, which operated independently of cockpit instruments. It was necessary to use a sensor system because CAS is not usually displayed on the airspeed indicator. The use of the BUR-4-1-05 sensors also allowed us to take into account measurement errors due to imprecision of aircraft instruments, which we did using the results of Hearing [9] and Huston [10]. CAS was calculated according to air pressure and outside air temperature measurements made during the flight. CAS was then compared with TAS.

The Mach number and OAT were read directly from the cockpit instruments during the test flights. TAS was calculated from the Mach number (M) and from the speed of sound at the flight altitude according to the ISA standard (a_0). This TAS value was compared with the corresponding TAS value calculated from the ground speed and the headwind and tailwind components. The largest difference between the two TAS values was 4.4%. During the analysis of test flight data, OAT was assumed to remain constant even though it can vary during horizontal flight when the aircraft crosses through areas of temperature inversion, turbulence and clouds. For each test segment, the mean OAT was calculated for the horizontal segment of the flight, which never lasted longer than 13 minutes. Static air pressure at a flight altitude (p) was calculated relative to the air pressure at the departure airport, assuming a 1-hPa reduction in the air pressure for each 8-m increase in the flight altitude. The resulting air pressure value provides the best available estimate of the actual atmospheric value. Due to technical difficulties, neither the air pressure nor the air density at flight altitude was measured directly. The total air pressure (p_t) was calculated from the static pressure and the Mach number (eq. 1). The specific heat ratio of air in normal conditions (γ) was taken to be 1.4. Dynamic air pressure is the difference between the *total* and the *static* air pressure at flight altitude.

$$\frac{p_t}{p} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}} \tag{1}$$

CAS was calculated according to actual flight conditions (eq. 2). Air pressure at flight altitude (p_0) was taken from the ISA standard.

$$CAS = \sqrt{\frac{2a_0^2}{\gamma - 1}\left[\left(\frac{p_t - p}{p_0} + 1\right)^{\frac{\gamma - 1}{\gamma}} - 1\right]} \tag{2}$$

Air pressure values at flight altitudes did not take into account deviations of the actual air temperature from the standard ISA temperature which can arise from atmospheric fronts and other factors. Several methods exist to determine the effect of wind on the flight path during dead reckoning navigation [3]. Given the high variability in wind speed and direction at higher altitudes, the trigonometric navigation triangle method was used.

3. Results

Five test flights were carried out at altitudes up to 5000 m and instrument speeds of 300-400 km/h. One set of measurements was taken at 8000 m to examine how the nonlinear fall in air temperature at higher altitudes might affect the results. Flight altitude and ground speed were measured using GPS. For example, Figure 1 shows the vertical profile for test flight 3, which consisted of three segments. Each test flight segment followed a predetermined flight plan, allowing flight parameters and atmospheric conditions to be analysed precisely.

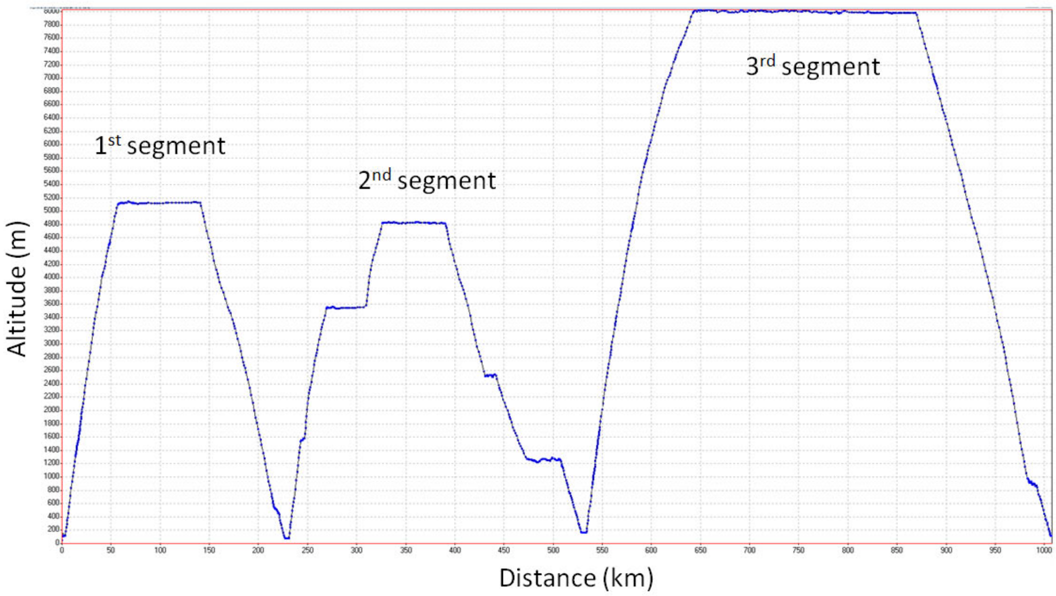

Fig. 1 Example of a vertical profile of a three-segment navigation route (test flight 3) based on GPS measurements of the flight altitude and ground speed.

Measurements based on air pressure, i.e. flight altitude and CAS, were obtained from BUR-4-1-05 sensors on the aircraft. Magnetic heading was also obtained from these sensors in order to analyse the effect of wind on the ground speed (Figure 2).

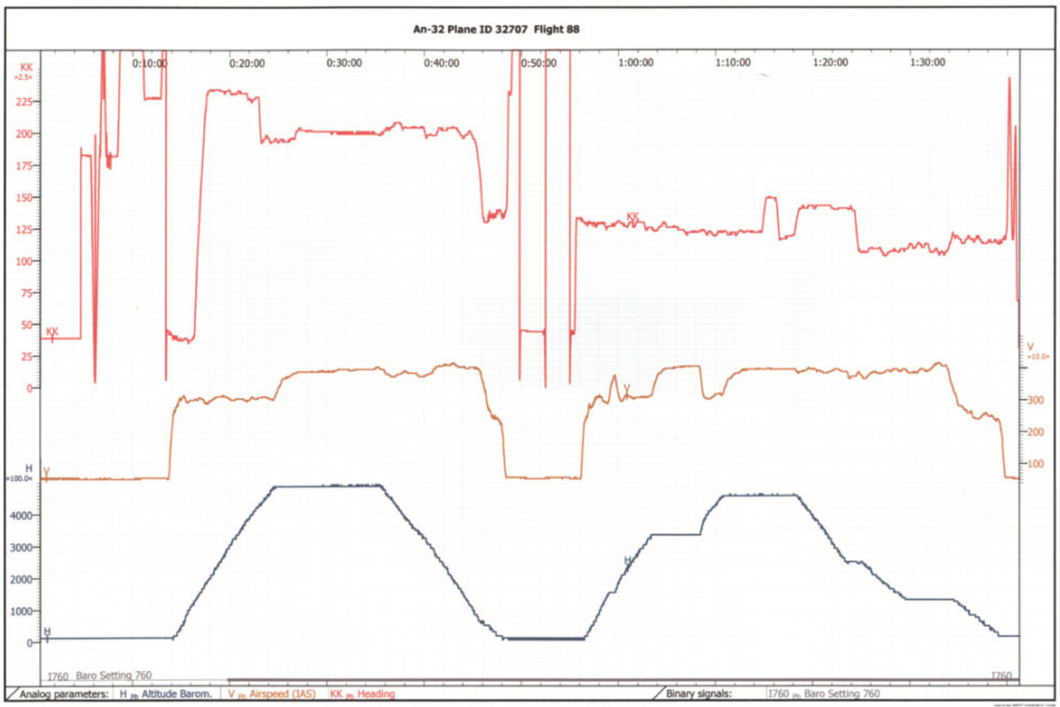

Fig. 2 Data log of CAS and flight altitude recorded by on-board BUR-4-1-05 sensors

Table 1 shows TAS, CAS and other flight parameters measured during the five test flights. Values for the speed of sound (a_0) and air pressure (p_0) were taken from the ISA standard for the flight altitude at which the parameters were measured. All data were collected during the horizontal part of each segment (enrooted cruise), at altitudes up to 8000 m.

Table 1 Calculated and measured air pressure and CAS by test flight and segment.

Test flight	Segment	***H*** m	a_0 m/s	**M**	**TAS** = M a_0 m/s	$p_t \cdot 10^4$ N/m^2	$p \cdot 10^4$ N/m^2	$p_0 \cdot 10^4$ N/m^2	**CAS** calculated m/s	**CAS** measured m/s
1	A	4900	320.9	0.39	125	4.95	4.46	5.47	113	112
	B	1500	334.5	0.34	114	9.00	8.31	8.46	112	110
	C	450	338.6	0.32	108	10.20	9.50	9.66	108	105
	D	5200	319.7	0.40	128	4.61	4.13	5.26	114	111
2	A	3000	328.6	0.32	105	7.30	6.80	7.01	104	99
	B	5800	317.3	0.42	133	4.29	3.80	4.85	119	93
3	A	4600	322.2	0.40	129	5.36	4.80	5.70	119	110
	B	1500	334.5	0.36	120	9.36	8.56	8.46	121	116
	C	4600	322.2	0.41	132	5.76	5.13	5.70	126	111
4	A	4900	320.9	0.40	128	5.36	4.80	5.47	121	111
	B	4900	320.9	0.44	141	5.48	4.80	5.47	132	113
5	A	5100	320.1	0.42	134	5.42	4.80	5.33	128	109
	B	3500	326.6	0.40	131	7.03	6.30	6.58	128	113
	C	4800	321.3	0.42	135	5.79	5.13	5.55	130	110
	D	8000	308.1	0.42	129	2.03	1.80	3.57	92	90

Table 2 shows the effects of wind on TAS during each segment of the test flights. The table also shows the actual OAT for each segment of flight and the deviation from the ISA standard OAT for the given flight altitude (ΔT). A negative sign for ΔT indicates that the air at the time of measurement was colder than predicted by the ISA standard.

Table 2 Measured and calculated TAS by test flight and segment

Test flight	Segment	***H*** m	Wind direction deg	Wind speed m/s	Magnetic heading deg	Ground speed m/s	**TAS** calculated m/s	T K	T_0 K	ΔT K
1	A	4900	290	19	242	109	124	252	256	-2
	B	1500	210	13	127	111	111	268	278	-6
	C	450	225	11	128	106	106	276	286	-10
	D	5200	200	48	337	163	129	253	254	-1
2	A	3000	n/a	n/a	n/a	103	103	266	269	-3
	B	5800	n/a	n/a	n/a	137	137	254	250	7
3	A	4600	055	13	242	142	129	260	258	8
	B	1500	045	6	127	119	119	275	278	-3
	C	4600	045	8	020	126	132	261	258	11
4	A	4900	025	13	240	145	132	269	256	10
	B	4900	025	13	020	133	143	260	256	12
5	A	5100	250	8	240	131	138	268	255	13
	B	3500	315	6	125	140	135	279	265	14
	C	4800	315	6	125	143	138	270	257	13
	D	8000	270	8	340	135	135	252	236	3

Changes in CAS, TAS and OAT with flight altitude are shown in Figure 3. These data allow the analysis of the deviation of CAS from TAS as a function of altitude. The results in Figure 3 were generated from the data in Tables 1-2. The results show that the difference between the calculated CAS and the measured CAS was greater when the difference between the measured OAT and the standard OAT was greater. This suggests that the deviation of CAS from TAS results directly from the difference between the measured and the standard OAT. Our data suggest that the deviation of CAS from TAS varies linearly with altitude up to 5000 m, and that the deviation increases linearly with increasing difference between the measured and the standard OAT. Future studies should validate these findings in a broader range of altitudes involving more test flights.

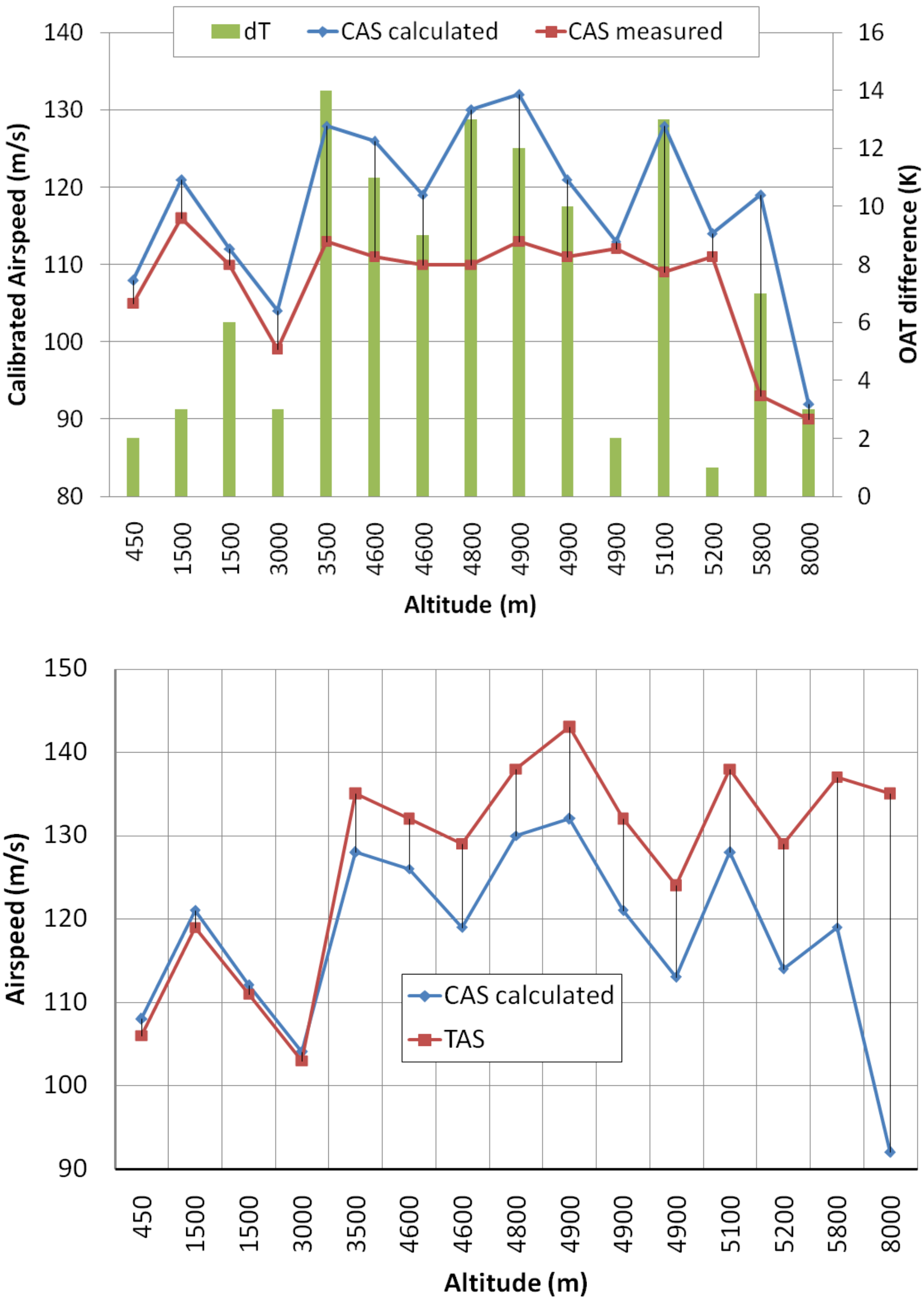

Fig. 3 Variation in CAS, TAS, and OAT with flight altitude. Plots were generated from the data in Tables 1-2

4. Discussion

This study is aimed at examining whether the deviations of the actual values of air pressure from the standard ones are a function of OAT, and whether the accuracy of OAT determination affects the precision of airspeed measurement. Data from the five test flights conducted under various atmospheric conditions at altitudes up to 5000 m support both hypotheses. The comparison between the standard values and the actual OAT, CAS and barometric altitude based on on-board sensors showed that different atmospheric conditions can give rise to deviations between the measured and the standard OAT. These deviations, which are altitude-dependent, in turn give rise to deviations of the measured from the standard air pressure, ultimately causing inaccuracies in airspeed. These findings, which should be validated in a larger test flight data set, may help improve the accuracy of aircraft navigation systems [11]. Deviations of the measured CAS from the calculated CAS were linear at altitudes up to 5000 m. This likely reflects the linear reduction in OAT with increasing altitude, in contrast to the exponential drop in air pressure with increasing altitude. This result suggests that the OAT deviations affect the airspeed accuracy more than the air pressure deviations. In addition, on the assumption that CAS is constant during the enrooted cruising at a constant altitude, we observed linear changes in CAS and TAS at lower altitudes. These linear changes presumably reflect the linear dependence of OAT on altitude and are not significantly affected by changes in air pressure, which is the basis for determining airspeed. These observed relationships may not hold at higher altitudes, so further studies are needed to establish the generalizability of our findings.

This study highlights the limitations of the ISA standard for providing an accurate determination of airspeed under real conditions. The ISA standard is based on mean values of atmospheric parameters measured over many years at northern latitude of 45°. However, the atmosphere changes dynamically in a ways that are difficult to model. As a result, cockpit instruments calibrated according to the ISA standard can show systematic errors depending on meteorological conditions and altitude, as demonstrated here. Our results lead to at least two important conclusions:

- deviation of the calculated CAS from the measured CAS changes linearly with the deviation of the ISA standard OAT from the measured OAT at flight altitude;
- deviation of the measured CAS from TAS changes linearly with altitude up to at least 5000 m.

Our relatively small data set suggests that, at altitudes up to 5000 m and instrument airspeeds up to 400 km/h, the differences between the actual air temperatures at flight altitude and the standard temperatures used to calibrate the aircraft navigation system cause instrument airspeed to deviate from the actual values. Thus, an accurate measurement of OAT is essential for a precise airspeed determination. In fact, deviations of the standard OAT from the actual OAT further reduce the accuracy of airspeed determination by causing standard air pressure values to deviate from the actual ones.

5. Conclusion

The deviation of the calculated CAS from the measured CAS depends on the difference between the actual OAT and the ISA standard OAT at a given flight altitude. This deviation is particularly large when the actual OAT is higher than the standard value. The same observations are true of CAS and TAS. All these findings are shown here to be valid on flights at altitudes up to 5000 m and speeds up to 400 km/h. Whether they are also valid under other conditions requires further research.

Airspeed and altitude are, together with heading and weather, the basic elements needed to determine the current and the expected position of an aircraft during flight. Both the airspeed and the altitude are measured on the basis of air pressure, which is affected by meteorological conditions that the ISA standard does not take into account. Our results suggest that on long-distance flights, if the aircraft enters an area where the actual OAT is warmer than the standard OAT predicted by ISA, the deviation of the indicated airspeed from the true airspeed will occur, and the discrepancy will increase with an increasing difference between the actual and the calculated OAT. In other words, the instrument speed (that the pilot sees in the cockpit) will underestimate TAS, assuming that the aircraft is moving at a constant instrument speed. In contrast, the ground speed depends on wind components and can be altered only by changing the flight heading or altitude. It may be possible to reduce the overall flight time on flights longer than 1000 km by monitoring atmospheric conditions (mainly air temperature) at the planned flight altitude. Such measures will also lead to lower fuel consumption and will allow greater maximal take-off mass. The latter implies the transport of a greater amount of cargo or a number of passengers. It also means that a larger volume of fuel can be loaded, thus increasing the maximum flight range.

Taking into account the influence of air temperature on airspeed may allow the correction of the time of arrival at waypoints or the correction of radio aid likely to be needed. While this may not be applied to adjustments of the estimated time of arrival at the final destination, it may make the dead reckoning navigation more precise, increase the air traffic flow in congested airspace and reduce the departure and arrival delays.

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