Doris Novak
Tomislav Radišić
Izidor Alfirević

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DETERMINING THE INFLUENCE OF OUTSIDE AIR TEMPERATURE ON AIRCRAFT AIRSPEED

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Summary

Errors that occur in conventional measurement instruments connected to a pitot-static system affect the accuracy and reliability of indicating the basic navigation elements required for the safety of flight. This paper is to present the manner and methods of preparing and implementing experimental measurements in order to determine the stochastic and functional laws of deviation and change in the actual aircraft flying speed with the changes in altitude and airspeed, as well as to determine the influence of the change in air temperature on the measured values of airspeed up to the pressure altitude of 5,000 m. Using a comparative analysis of parameters measured during the flight by means of a sensor system on a twin-engine turboprop aircraft Antonov AN-32 and by means of a GPS instrument as well as theoretical calculations of pressure obtained in accordance with the measured values, this paper will present the problems of measuring the parameters by a pitot-static system.

Key words: *Pitot-static system, air temperature, aircraft speed*

1. Introduction

Aircraft instruments which use the values of air pressure (static, dynamic or total) to indicate the navigation flight elements (airspeed, altitude, rate-of-climb/descent) are calibrated to the conditions and relations that are valid according to the International Standard Atmosphere (ISA). In actual conditions, values of air pressure rarely coincide with ISA, thus generating a certain error in navigation flight elements. If instrument errors and installed errors are taken as a constant value based on the calibrated data, it is possible to determine the methodical error which occurs due to the method of measuring certain parameters, i.e. its relation to the change in speed and aircraft flight level and the stochastic value of deviation from the theoretically calculated values based on exact measurements during the flight. The influence of atmospheric elements expressed primarily through the external air temperature, which was the available and thus also a measurable parameter, had a greater effect on the deviations of the simulated rather than the actual results because of temperature inversions, passing through clouds, flying over the sea and/or land, etc. Therefore, in this paper, the influence of air temperature on the values of airspeed measured by means of a pitot-static system (where the primary parameter is air pressure) is analyzed in the first place, and also, an attempt to find stochastic laws of the influence on the measured values is made.

On the territory of the Republic of Croatia where the measurements of aircraft An-32 flights were carried out, the air pressure at flight level had little effect on the results because its change on the flight segment of 1,000 km amounted up to maximally 2 hPa (depending on the current position of the field of high or low air pressure).

2. Background

In order to create a theoretical simulation model which will show the interdependence of different types of speeds and the change in flight level (air pressure as primary value), basic equations for the calibrated and the equivalent airspeed have been developed. As the speed of sound in a perfect gas depends only on the temperature of gas, it can be expressed by equation (1):

$$a^2 = \gamma gRT, \text{ i.e. } a_t^2 = \gamma gRT_t \tag{1}$$

Thus, the relationship between the speed of sound and the total temperature is:

$$\frac{a_t^2}{a^2} = \frac{T_t}{T} \tag{2}$$

The speed of sound is connected with the Mach number (the ratio between the fluid velocity and the speed of sound at the same point), and can also be written as:

$$\mathrm{Ma}^2 = \frac{v^2}{a^2} \tag{3}$$

When expressions (2) and (3) are connected with the compressible form of the Bernoulli equation, a relation between temperature and velocity can be derived [1]:

$$\frac{1}{\gamma - 1}\frac{T_t}{T} = \frac{\mathrm{Ma}^2}{2} + \frac{1}{\gamma - 1}, \quad \text{i.e.} \quad \frac{T_t}{T} = 1 + \left(\frac{\gamma - 1}{2}\right)\mathrm{Ma}^2 \tag{4}$$

In equation (4), T represents the static temperature which differs from the stagnation temperature T_t. The stagnation temperature remains constant on the shock wave regardless of the fact that the total or the stagnation pressure can decrease. In this way, enthalpy, i.e. the product of specific heat and temperature ($C_P T$), is defined. It naturally remains constant on the shock wave. The total enthalpy is expressed as:

$$C_P T_t = c_P T + \frac{v^2}{2} \tag{5}$$

where $C_P T_t$ is the total enthalpy or amount of heat, and $c_P T$ is the content of heat along the streamline. If the airflow in the tunnel is ideally adiabatic, respective relations for air pressure and density can be derived by applying the state equation in the form: $p = \rho gRT$ and equation (4) [1]:

$$\frac{\rho_t}{\rho} = \left(1 + \frac{\gamma - 1}{2}\mathrm{Ma}^2\right)^{\frac{1}{\gamma - 1}} \tag{6}$$

$$\frac{p_t}{p} = \left(1 + \frac{\gamma - 1}{2}\mathrm{Ma}^2\right)^{\frac{1}{\gamma - 1}} \tag{7}$$

If 1 is removed from equation (7), both from the left and from the right side of the equation, it follows that

$$\frac{p_t - p}{p} = \left(1 - \frac{\gamma - 1}{2}\mathrm{Ma}^2\right)^{\frac{1}{\gamma-1}} \tag{8}$$

From this equation, Ma can be expressed as:

$$\mathrm{Ma}^2 = \frac{2}{\gamma - 1}\left[\left(\frac{p_t}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{9}$$

When the specific heat ratio (γ = 1.4) is inserted into equation (8), it follows that:

$$p_t - p = p\left[\left(1 + 0.2\mathrm{Ma}^2\right)^{3.5} - 1\right] \tag{10}$$

Expression $(1 + 0.2\,\mathrm{Ma}^2)$ represents the adiabatic heating due to the air compressibility. Under the conditions in ISA at the sea level, altimeters which indicate airspeed are calibrated so that the actual, equivalent and calibrated speeds are equivalent. From basic principles of pitot-static measurement it is known that speed measurement is a function of pressure p and the difference between pressures $p_t - p$ [1]. Considering the compressible flow relationship and the Mach number, equation (11) can be derived:

$$v\sqrt{\sigma} = \sqrt{\frac{2\gamma p}{(\gamma - 1)\rho_0}\left[\left(\frac{p_t - p}{p} + 1\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{11}$$

Parameter $v\sqrt{\sigma}$ presented by equation (11) is the measure of kinetic energy of the air and is defined as **equivalent airspeed (EAS)**. All airspeed indicators have been calibrated to indicate the true airspeed under the ISA conditions at the sea level (no installation errors), so that at flight levels that differ from the sea level it is necessary to calculate corrections of the adiabatic compressible stream at a certain altitude. Airspeed indicators cannot measure the airspeed precisely since for that they would always have to have a different scale distribution for different flight level pressures. Since this would be impractical in reality, a unique distribution on the scale that corresponds to the pressure at the sea level has been adopted. This scale is used to define the **calibrated airspeeds (CAS)**. If standard values for the sea level according to ISA are calculated in expression (11), *CAS* can be expressed as:

$$CAS = \sqrt{\frac{2a_0^2}{\gamma - 1}\left[\left(\frac{p_t - p}{p_0} + 1\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{12}$$

Similarly to calculating the calibrated airspeed (*CAS)*, in calculating the equivalent airspeed (EAS), corrections for air compressibility at the flight level have been made (adiabatic compressible reduction at the altitude, where a represents the speed of sound at the flight level, and p_1 the air pressure at the flight level). The expression for *EAS* in principle represents a method of measuring the kinetic airspeed during the flight:

$$EAS=\sqrt{\frac{2a^2}{\gamma-1}\left[\left(\frac{p_t-p}{p_1}+1\right)^{\frac{\gamma-1}{\gamma}}-1\right]} \tag{13}$$

Expressions for the calibrated and the equivalent speed have been taken as a basis for developing a simulation model. According to expression (13), the true airspeed can be expressed as:

$$TAS=\frac{EAS}{\sqrt{\sigma}} \tag{14}$$

where $\sigma = \rho/\rho_0$, which represents the relative air density. Therefore, the true airspeed (TAS) represents the airspeed with respect to the ground under the conditions free of wind influence. In measuring the airspeed with a pitot-static system it is important to note that the dynamic pressure q is a function of TAS: $q=\frac{1}{2}\rho TAS^2$. If the right side of the equation is multiplied by ρ_0/ρ_0, the following expression is obtained:

$$q=\frac{1}{2}\rho_0\sigma TAS^2,$$

where $\sigma TAS^2 = EAS$.

3. Motivation

The basic hypothesis in this research is based on the fact that the change in the air temperature with the change in the altitude is linear up to the altitude of 11,000 meters and the pressure and density decrease exponentially with the increase in altitude. However, from the sea level up to the altitude of 5,000 meters they may also be considered linear (in accordance with the conclusions of the simulation model about speed-altitude relation, cf. Fig.1). It is precisely these values that affect the operation and the indication of pitot-static instruments which measure the navigation flight parameters (altimeter and airspeed indicator). On the basis of these values, linear changes in instrument indication deviations are also expected with the increase in altitude and airspeed in real conditions during the performed in-flight measurements. The measurement, i.e. the speed indication, is affected by the fact that up to 360 km/h air is considered non-compressible [2], and above this speed it is considered compressible. This fact affects the differences between EAS and CAS, which eventually has implications on the true airspeed.

The assumption applied here, with the aim of performing the calculation for the true airspeed – TAS, is that the equivalent airspeed (EAS) and the calibrated airspeed (CAS) in the range of measurements – up to the altitude of 5,000m and speed of 400 km/h – are equal.

In accordance with the technical characteristics of the FDR (Flight Data Recorder) system on the An-32 aircraft, used in the experiment, the calibrated airspeed is to be measured and it will represent the true value which does not change with the change in altitude. Thus, the values of calibrated airspeed can be taken as the starting values.

In order to show as clearly as possible the interrelation of the calibrated, equivalent, and true airspeed at different flight levels, the program package MATLAB was used and the results are presented in *Figure 1* (each dot on the graph lines of airspeeds represents a 500 m altitude increase).

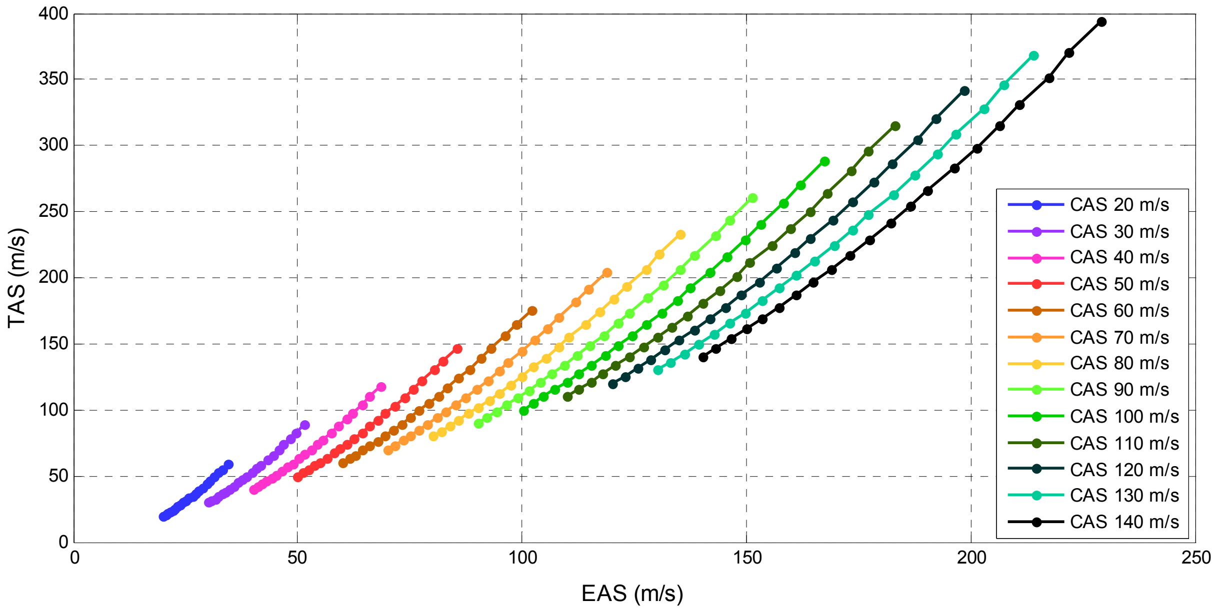

Fig. 1 EAS – TAS relation with constant values of CAS

A conclusion of the analysis of the theoretical model may be that, although the dependence of the calibrated, the equivalent and the true airspeed is defined exponentially (with changes in the calibrated airspeed and an increase in the flight level measured per pressure), for lower speeds up to 360 km/h and flight levels up to 5,000 meters, this dependence may be considered linear. In this sense, it may be expected that the measurements taken in real conditions on the An-32 aircraft will confirm these results, i.e. that the deviations in the mentioned range of speeds and in altitude from the calculated values in real conditions will also be linear.

4. Approach

The results of the performed experiment give the values of the measured flying parameters based on which the calculations will be made. Also, every single flight will be presented, processed and analyzed in order to determine single segments suitable for carrying out a comparative analysis. From these segments, and based on the total flight time on the route, the values of absolute speed parameters, planned (instrumental) airspeed on the route, ground distance between waypoints on the flight segment, and magnetic course of a single flight phase will be determined. For every single segment of a specific route, the measured true Mach number (only for the cruising regime) and the measured outside air temperature (OAT) will also be recorded. In order to determine the true airspeed, the data on wind direction and speed obtained by the interpolation of data from meteorological maps and the values of air pressure at the take-off, en-route and landing airports will be given. Based on these data, the air pressure at the flight level with respect to the take-off aerodrome will be calculated.

The parameter values are based on the values recorded during the flight (Mach number, OAT, airport air temperature, air pressure at take-off and landing aerodromes, flight level), on the calculated values based on real data (wind direction and speed, air pressure at the flight level) and on the flight plan data (magnetic course, distance, planned speed, and flight time on single route segments).

Based on thus presented and processed parameters, functional deviations of the processed parameters in characteristic flight regimes in real conditions in the atmosphere will be quantitatively analyzed and the characteristic deviations will be measured.

The route profiles where measurements have been done by two autonomous and mutually independent systems (FDR and GPS) will be presented and analyzed. The planned sections and segments of single routes where recordings are to be made by means of the FDR system and the GPS device are presented as follows:

- Route A: segments Zagreb – Pula – Zadar – Split – Zagreb,
- Route B: test (check) flight in the Zagreb airport area,
- Route C: segment Zagreb – Pula – Zadar - Zagreb,
- Route D: segment Zagreb – Zadar - Zagreb,
- Route E: segments Zagreb - Zadar – Dubrovnik - Zagreb

These routes are round routes (with take-offs and landings always at the same airport), and a single route does not exceed the distance of 1000km in one direction. The planned change in the flight level pressure caused by atmospheric fronts (cyclones and anticyclones) should not significantly affect the measurement and calculations of the atmosphere condition since it amounts to maximally 2 hPa. Therefore, the influence of the high and low pressure fields and their shifting during the experiment are neglected.

5. Data collection and evaluation

Based on the data from the analysis of meteorological elements, the presentation of the processed and measured data per segments on single routes, and on the measured values of the outside air temperature during the flight, the project includes the data processing in order to perform a comparative analysis of the influence of a change in speed and flight level on the measured and calculated parameters of the calibrated and true airspeed.

It is planned to carry out the analysis on the basis of collected data by means of the following methodology:

- **Flight level air pressure value** (static pressure - p) will be calculated in relation to the air pressure at departure airports (respective data are found in METAR reports), by taking the pressure fall gradient 1hPa for 8m (30ft) of flight level increase [3]. If the aircraft is flying at FL 170 (17,000ft), this altitude is called the standard pressure altitude in relation to the standard air pressure of 1013.25 hPa. Since precisely this pressure is never present at the airport, the difference in relation to the pressure at the departure airport was added to or subtracted from this value (with the gradient of 30 ft for 1 hPa of change in pressure, the true altitude in relation to the departure airport was also obtained). For instance, if pressure of 1,000 hPa is present at the Zagreb Airport, and the aircraft is flying at FL 170, it is necessary to subtract 390 ft from the aircraft's altitude of 17,000 ft because the difference from the standard pressure is 13 hPa (this difference is subtracted because the standard pressure isobar is below the aerodrome pressure isobar). For thus obtained flight level value (16,610ft), the pressure value (554 hPa) is calculated according to the vertical pressure gradient, and it is then subtracted from the value of the pressure at the aerodrome level in order to obtain the isobar at the flight level in real conditions (1,000 – 554 = 446 hPa). The obtained flight level pressure value at which the measurement was done represents, naturally, the best possible approximation in relation to real conditions in the atmosphere. On the other hand, it does not represent the directly measured value since it was not possible to use instruments for measuring this value during the flight. This was due to the lack of equipment and of extremely complex modifications to the aircraft which result in time-consuming and expensive procedures of homologation and attestation. The same is true of the data on the flight level air density [3].

- The **total air pressure** (p_t) measured by the pitot-tube will be calculated on the basis of data on the flight level air pressure (p) and real values of the Mach number.
- **Dynamic air pressure** represents the difference between the total pressure measured by the pitot-tube and the flight level static air pressure, calculated for the real flight conditions.
- The data on **wind at the flight level** have been obtained by interpolation of data on wind direction and speed at targeted flight levels from meteorological maps (upper wind maps and air temperature for Europe and maps of winds and temperatures for Croatia issued by the Zagreb Airport meteorological office).
- **OAT** and the **Mach number** are obtained by the visual reading and the recording of the data from the measurement instruments in the cockpit during the flight.
- Airspeed as compared to the ground *(Ground Speed)* has been measured by means of a GPS device (Garmin 296 - which is not the standard aircraft equipment), and an antenna which was located on the navigator's observatory shaft on the port side during the flight. The processing of readings and the data analysis were carried out by means of the *Ozi Explorer* navigation software. According to the data on wind direction and speed (in relation to the true north) and based on the aircraft magnetic course (in relation to the magnetic north) for segments of cruising regimes where airspeed and altitude are constant, the drift and correction angles have been calculated. With the known ground speed and value of track component (head or tail wind component) the values of true airspeed (TAS) have been determined on the measurement flight segments in the cruising regimes (that is the opposite procedure that pilots use during the flight when they want to know the ground speed in order to make adequate navigation calculations).
- The true airspeed (TAS) will be calculated based on the data on the measured Mach number and the calculated value of the speed of sound at the flight level (where the key parameter is the measured flight level outside air temperature). The difference between the obtained true airspeed and the true airspeed, calculated by including in the calculation the components of the head-tail wind on the measured value of the ground speed, should not exceed **5%**.
- The values of the calibrated airspeed (CAS) recorded by the FDR system onboard the AN-32 aircraft represent the basic data which are used for the comparison and for the final conclusion [4].

- The values of the calibrated airspeed have been calculated for real flight conditions through equation (11) into which the values of the calculated dynamic pressure, of the speed of sound, and of the air pressure at the sea level, that are based on the data from ISA, are inserted.
- Based on Fig. 1, the influence of the air temperature deviation from standard values according to ISA, due to the warmer or colder air caused by the fronts and other influences that are present in the standard atmosphere, **on the value of air pressure at flight levels is neglected**.

Since the air temperature measured during the flight is an important factor for the calculation of real conditions in the atmosphere during the flight, the graphs of the temperatures measured during the flight on certain routes and the deviations of the measured data from the ISA values that are valid in ideal conditions will be presented in *Figure 2*. Based on these data, the flight level speeds of sound will be calculated.

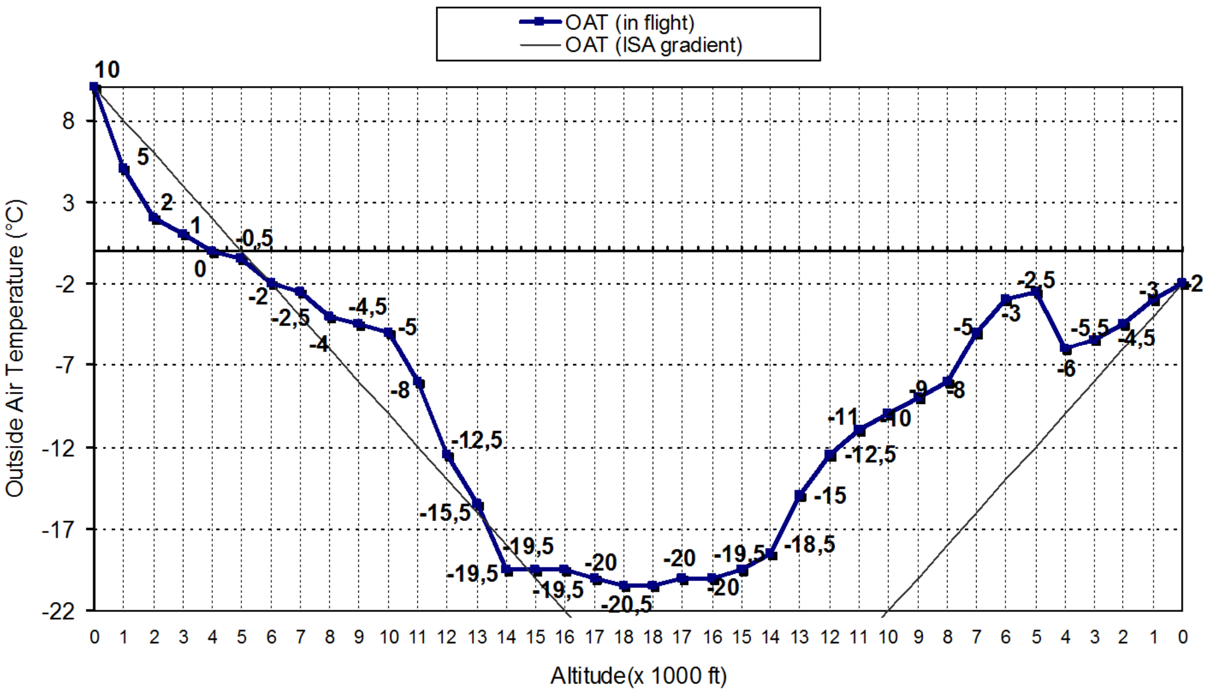

Fig. 2 Measured OAT deviations from ideal conditions (ISA temperature gradient) during the climb and the descent phase of flight

6. Conclusions and further work

Based on the measured (real in-flight conditions) and parameters calculated from real data about pressure and air temperature in flying conditions (for horizontal flying regimes at different speeds and altitudes), a comparative analysis will be done. It will show the relations between the measured and calculated calibrated airspeed (CAS) as well as the resulting relations between the changes in true airspeed (TAS) and the measured calibrated airspeed (CAS).

In accordance with the basic hypothesis, the difference between the measured and calculated values of the CAS will depend on the difference between the true air temperature at the flight level and the theoretical values according to ISA [5], especially if the temperature at the flight level is higher than the temperature according to ISA at the same altitude. Determination of CAS values includes the calculated true airspeed obtained by the interpolation of data on the ground speeds for the wind component and the calculated values of true airspeeds based on real parameters measured during the flight.

The objective of the experiment is to confirm or disprove the influence of the changes in air temperature, in comparison to the standard values according to ISA up to the altitude of 5,000 m and the flying speed of up to 360 km/h, as a significant factor related to precise determining of the flight speed. The changes in the values of the air pressure on flight levels during the cruising flight actually have a secondary influence on the occurrence of errors, i.e. deviation, since the air pressure variation above the measurement area covering 1,000 km amounts to negligible 2 hPa (variation in altitude of approximately ± 60ft). The effect of pressure at a certain altitude on the speed (instrumental – calibrated) is felt only at altitudes and flight speeds exceeding the considered ones in the measurements carried out in this study.

In other words, at the ambient temperature different from the standard one, the calibrated airspeed, and thus also the true speed (which is the basis for the ground speed calculation) will be changed. Such a conclusion can be applied in practice to the flight of up to 5,000 m altitude and the speed of up to 360 km/h, and the afore mentioned interdependencies are expected to be determined as direct research results.

Using this analogy and monitoring the condition of atmosphere regarding the air temperature on the planned flight levels, savings in the overall flight duration from one point to another can be made in practice for the flights exceeding 1,000 km, which also results in lower fuel consumption and a possibility of increasing the maximum take-off mass. It is precisely the increase in the overall take-off mass, as the basic factor in calculating the performance of the aircraft during the flight, which allows great savings in terms of transporting a greater volume of cargo or a larger number of passengers. With the same mass of payload, the overall aircraft flying range increases due to the possibility of using greater volumes (quantities) of fuel. These implications refer primarily to the turbo-prop aircraft that fly up to the altitude of 5,000 meters. Also, by calculating the influence of outside air temperature on airspeed, it is possible to make corrections of the expected times of arrival to certain navigation waypoints or radio-navigation facilities. Such corrections would not demand changes in the expected times, which has a negative influence on planning and performing flights in relatively saturated airspace (time slots due to the congested sector in the ATC sectors, diverting to other routes or alternations, etc.), but would rather make the navigation along routes much more precise [6]. This precision would be reflected in a greater throughput capacity of air traffic and in the reduction of delays of aircraft in arrivals and departures.

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Doris Novak
Tomislav Radišić
Izidor Alfirević
Department of Aeronautics
Faculty of Traffic and Transport Sciences
Vukelićeva 4
10 000 Zagreb, Croatia