UDC 629.735.05(045)
DOI 10.18372/2306-1472.75.13113

Ivan Ostroumov

PASSIVE POSITIONING METHOD USING DISTANCE MEASURING EQUIPMENT AND AUTOMATIC DEPENDENT SURVEILLANCE-BROADCAST DATA

National Aviation University
Kosmonavta Komarova avenue 1, Kyiv, 03680, Ukraine
E-mail: ostroumovv@ukr.net

Abstract

Purpose: *The represented research results are aimed to develop a new positioning method that uses DME signals in space and ADS-B messages from airspace users. Proposed approach of positioning is based on passive signal collection and analysis. One aircraft interacting with two different DMEs is a source of three hyperbolic lines of location, crossed point of which can indicate passive user location.* ***Methods:*** *Presented approach is grounded at time difference of arrival methods, statistical methods of error estimation and computer-based simulation at verification stage of development.* ***Results:*** *Proposed method of aircraft coordinates detection can reduce the load on DME ground network, since it focuses on the passive observation of DME signals that are present in airspace.* ***Discussion:*** *The approach can be implemented in algorithms of flight management system as an alternative positioning method to existing ones.*

Keywords: ADS-B; aircraft; coordinates; DME; passive; positioning; TDOA

1. Introduction

Positioning methods for aircraft navigation play one of the key roles in guaranteeing safety of air transport. This introduces strong requirements for accuracy characteristics of determining the aircraft location in the airspace. A task of aircraft positioning is especially topical in conditions of constant increase of airspace loading and strengthening of precision requirements to performance based navigation. The modern air navigation system introduces rigid requirements regarding an availability, accuracy, continuity and integrity of aircraft positioning systems [1]. The services of each of today's positioning systems are limited to certain values of these parameters [2]. Integrity is considered to be the most important factor in terms of aviation safety. It is not possible to know if the received information is accurate without guaranteeing an integrity of the system. Today, the global navigation satellite system (GNSS), the Inertial Navigation System and area navigation methods, used in the flight management system, use information from navigational aids (VOR, DME, NDB, TACAN) for positioning purposes, act as coordinate information sensors on board of civil aircraft.

Modern air navigation system operates using a large number of radio equipment, each of which uses electromagnetic waves of a certain radio frequency. Different on-board equipment of aircraft uses electromagnetic waves in different ways. Communication equipment provides the transmission of information messages, equipment of navigation and surveillance provides determination of angular and time information. During the flight, each of these systems is engaged and, together with other systems, transform an aircraft into a source of electromagnetic waves propagation. In particular Distance Measurement Equipment (DME) uses radio waves for distance measuring. After receiving the request signal, the ground DME is blocked by the delay time for other requests, which limits the total number of aircraft with which DME can interact. On the other hand, the volume of air traffic is constantly increasing, and each 15 years it doubles. This leads to a constant increase in airspace loading and to increase in sources of electromagnetic radiation. Passive signal tracking allows to determine the location of radiation sources and to use the aeronautical signal field for positioning in airspace.

2. Analysis of the research and publications

The use of signals from DME for passive positioning purposes was considered by Lo S. and Enge P. [3, 4]. They proposed that special DME ground interrogators, located in a known location, should be used. Using known time of transmission, an aircraft can receive the DME periodic responses and detect distance to DME. Also, many studies have been conducted on the integration of various navigation systems. In particular, Euiho Kim explored the combination of Time-of-Arrival positioning method with multilateration [5, 6]. Positioning questions with the use of diverse ranging were considered by Wu R. and S. Davidson in [7]. However, the issues of passive positioning using DME signals within the existing aeronautical system were not investigated.

Results represented in the article are the continuation of author's research on the development and study of alternatives to GNSS positioning techniques using the existing network of navigational aids [8, 9].

3. Aim of the paper

Therefore, the main purpose of the paper is to develop and study an alternative positioning method for the passive use of DME signals from interrogators of other airspace users and a use of combination of coordinate information received by Automatic Dependent Surveillance Broadcast (ADS-B) concept.

4. Navigation equation

The DME signals field is sufficiently informatively defined to determine aircraft location using its parameters. In addition, the DME system is considered to be perspective in accordance with modern concepts. We will use the field of DME signals generated by a single aircraft that interacts with one DME/DME pair simultaneously for purposes of passive positioning (fig. 1). Both on-board DMEs work synchronously and use the same encoded distance between paired pulses in the request signals.

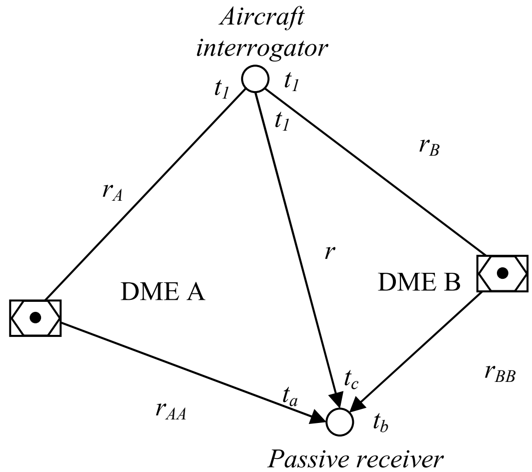

Fig. 1. The principle of passive method to determine aircraft coordinates

Also, both of them are tuned to the frequency of two different DMEs. The use of one coded distance in the request signals enables an aircraft, containing the passive DME signal receiver, to capture the signal propagation time and recognize the response from the DME ground stations.As can be seen from fig. 1, an aircraft with active interrogation sends request signals simultaneously to DME A and DME B at time t_1. After t_A time, the request signal is received in DME A and after a certain delay t_A, a response signal is generated at the response frequency, which can be received by the passive receiver after t_{AA} time (Fig. 2). Time of signal arrival via DME A is:

$$t_a=t_1+t_A+\tau_A+t_{AA}.$$

Similarly, the arrival time of a navigation signal to a passive observer via DME B is:

$$t_b=t_1+t_B+\tau_B+t_{BB}.$$

Request signal from an active aircraft to passive receiver is the following:

$$t_c= t_1+rc^{-1}.$$

If we use the hyperbolic navigation principle, we can find the line of position - hyperbole. Let's write the difference in time of fixing signals by a passive receiver:

$$(R_A-R_B)c^{-1}=t_a-t_b= t_1+t_A+\tau_A+t_{AA}- t_1-t_B-\tau_B-t_{BB},$$
$$t_a-t_b= t_A+\tau_A+t_{AA}-t_B-\tau_B-t_{BB},$$
$$(R_A-r)c^{-1}=t_a-t_c= t_1+t_A+\tau_A+t_{AA}- t_1-rc^{-1},$$
$$t_a-t_c= t_A+\tau_A+t_{AA}- rc^{-1},$$
$$(R_B-r)c^{-1}=t_b-t_c= t_1+ t_B+\tau_B+t_{BB} - t_1-rc^{-1},$$
$$t_b-t_c=t_B+\tau_B+t_{BB} - rc^{-1}.$$

Also, let's assume that an active aircraft uses the same DME channel, then:

$$\tau=\tau_A=\tau_B.$$

Thus:

$$c(t_a-t_b)= ct_A+ ct_{AA} - ct_B - ct_{BB},$$
$$c(t_a-t_c)= ct_A+c\tau_A+ct_{AA} - r,$$
$$c(t_b-t_c) = ct_B+c\tau_B+ct_{BB} - r.$$

Navigation equation using distances can be represented as follow:

$$\begin{aligned} c(t_a-t_b)&= r_A+ r_{AA}-r_B-r_{BB},\\ c(t_a-t_c)&= r_A+c\tau+r_{AA} - r,\\ c(t_b-t_c) &= r_B+c\tau+r_{BB} - r. \end{aligned} \quad (1)$$

If we add distance formulas in (1) we can obtain the general system of equations in the next form:

$$\begin{aligned} c(t_a-t_b)&= r_A-r_B +r_{AA}-r_{BB},\\ c(t_a-t_c)&= r_A- r+r_{AA} +c\tau,\\ c(t_b-t_c) &= r_B-r+r_{BB} +c\tau,\\ r^2_A&=(x_C-x_A)^2+(y_C-y_A)^2+(z_C-z_A)^2,\\ r^2_B&=(x_C-x_B)^2+(y_C-y_B)^2+(z_C-z_B)^2,\\ r^2_C&=(x-x_C)^2+(y-y_C)^2+(z-z_C)^2,\\ r^2_{AA}&=(x-x_A)^2+(y-y_A)^2+(z-z_A)^2,\\ r^2_{BB}&=(x-x_B)^2+(y-y_B)^2+(z-z_B)^2. \end{aligned} \quad (2)$$

As can be seen from the system of equations (2), for its solution it is necessary to have coordinates of DMEs position and the location of the active aircraft that can be obtained from ADS-B message.

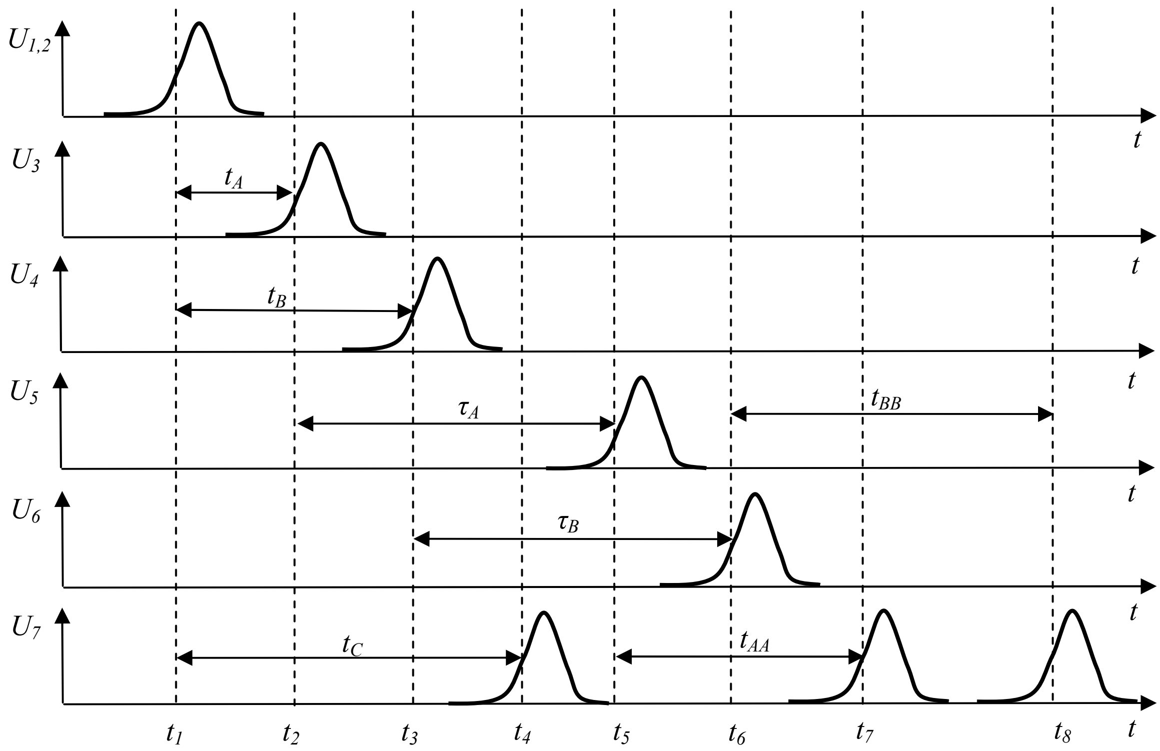

Fig. 2. Time signal diagram of passive positioning

For the solution of the system of equations (2) we apply an iterative approach with linearization in a Taylor series expansion. The matrix of partial derivatives according to Taylor series expansion of (2) for unknown coordinates is:

$$H=\begin{bmatrix} \frac{x_{ACFTi}-x_A}{r_{AA}}-\frac{x_{ACFTi}-x_B}{r_{BB}} & \frac{y_{ACFTi}-y_A}{r_{AA}}-\frac{y_{ACFTi}-y_B}{r_{BB}} & \frac{z_{ACFTi}-z_A}{r_{AA}}-\frac{z_{ACFTi}-z_B}{r_{BB}} \\ \frac{x_{ACFTi}-x_A}{r_{AA}}-\frac{x_{ACFTi}-x_C}{r_C} & \frac{y_{ACFTi}-y_A}{r_{AA}}-\frac{y_{ACFTi}-y_C}{r_C} & \frac{z_{ACFTi}-z_A}{r_{AA}}-\frac{z_{ACFTi}-z_C}{r_C} \\ \frac{x_{ACFTi}-x_B}{r_{BB}}-\frac{x_{ACFTi}-x_C}{r_C} & \frac{y_{ACFTi}-y_B}{r_{BB}}-\frac{y_{ACFTi}-y_C}{r_C} & \frac{z_{ACFTi}-z_B}{r_{BB}}-\frac{z_{ACFTi}-z_C}{r_C} \end{bmatrix}. \quad (3)$$

The deviation of each iteration i from the true value is determined in the following way:

$$\Delta u= (H^{T}H^{-1})^{T} H^{T}\Delta R,$$

where

$$\Delta u=\begin{bmatrix}\Delta x\\ \Delta y\\ \Delta z\end{bmatrix},\ \Delta R=\begin{bmatrix}\Delta R_{i,1}-(R_A-R_B)\\ \Delta R_{i,2}-(R_A-R_C)\\ \Delta R_{i,3}-(R_B-R_C)\end{bmatrix}.$$

An iterative approach requires setting the starting point for finding a solution. The result of the solution of equation provides a deviation of the coordinates from the true value relatively to the previous one. The algorithm will consistently aproximate the solution until the solution satisfies the required precision by setting a certain value of accuracy.

5. Method of passive positioning

A method of passive positioning using combined information of DME and ADS-B is shown on fig. 3 in the form of a structural scheme. As an input, the method requires inaccurate coordinates of location that are necessary to estimate the availability of DMEs and to use as a reference point of the coordinate search. The estimation of availability is carried out according to the method specified in [10] using DME technical characteristics from aeronavigation database. The identifiers of the available navigational aids are used to configure the receiver to search available DMEs. Using received and decoded signals, the exact timestamp of their receiving and the unique aicraft identifier that sent them is captured.

Moreover, the receiver equipment monitors the frequencies of DMEs and response frequencies. At the next step, the presence of the minimum required information for positioning is checked. Comparing aircraft identifier, the DME request signals and two response signals are determined. On the basis of obtained t_a, t_b, t_c, their differences are determined and the distance differences ΔR_{AB}, ΔR_{AC}, ΔR_{BC} are calculated. At the last step, created H by (3) and ΔR matrices are used by an iterative linearization algorithm of Taylor series expansion to determine the coordinates of aircraft location. Estimated aircraft location in North-East-Down (NED) coordinate system are transformed to Latitude-Longitude-Altitude (LLA) for further usage by on-board systems.

Proposed method requires the use of a multi-channel receiver of DME signals and equipment for receiving ADS-B information about air traffic.

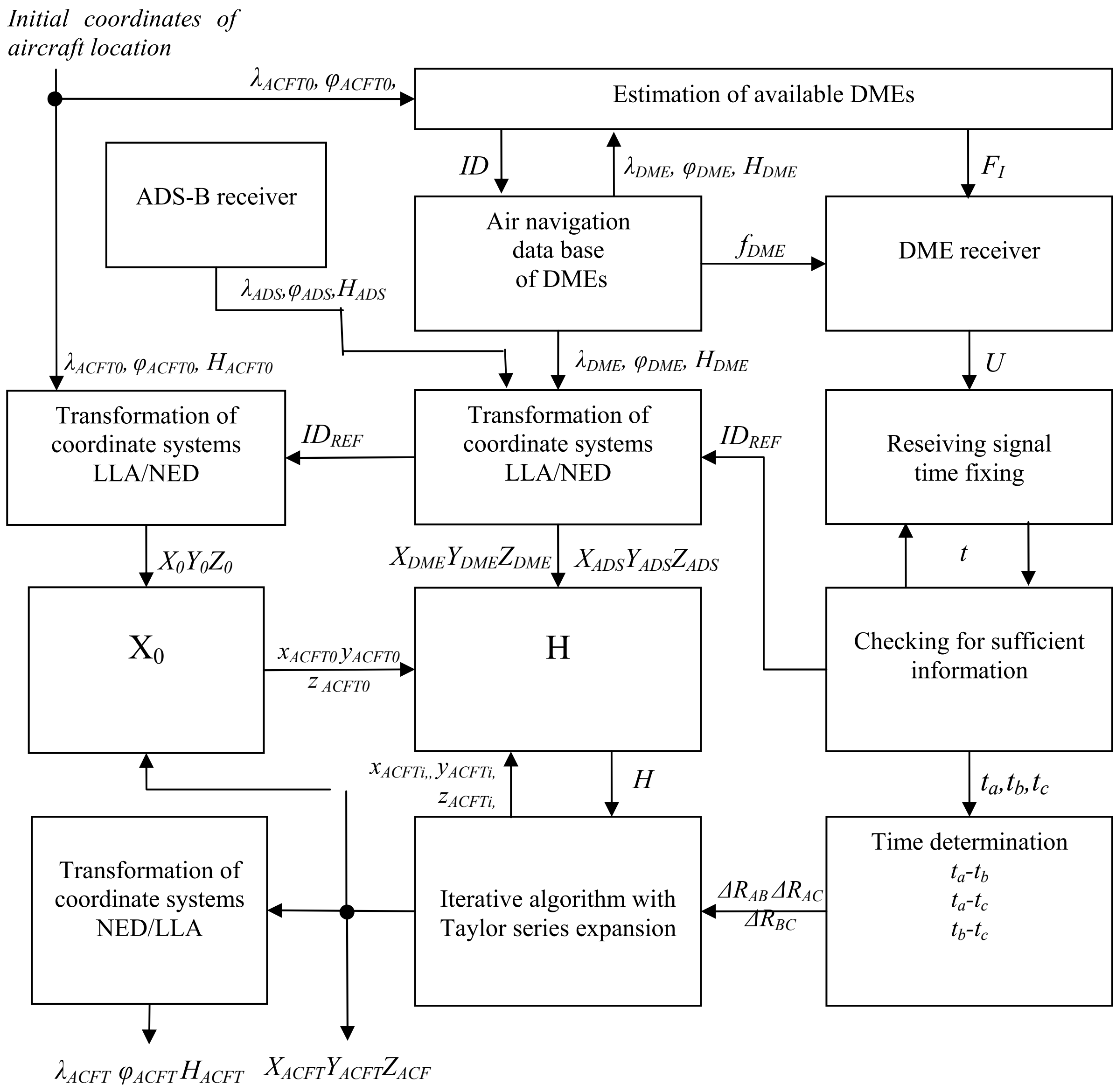

Fig. 3. Structural scheme of passive positioning method using combined DME and ADS-B data

6. Verification

Verification of proposed method was performed by computer simulation using information of air traffic. Air traffic data was recorded by the ground station receiving signals in ADS-B format. Trajectory information used in simulation contained aircraft location in latitude, longitude and barometric altitude format. In addition, each aircraft track was recognized by a unique ICAO aircraft identifier. Since ADS-B data contains non-synchronized aircraft coordinate measurements in time, the splinefunction interpolation method is applied to bring data to a common-time scale. Results of ADS-B observations were set to a common measurement time and air traffic data is represented on fig. 4. Aircraft are marked by diamonds with unique identification codes.

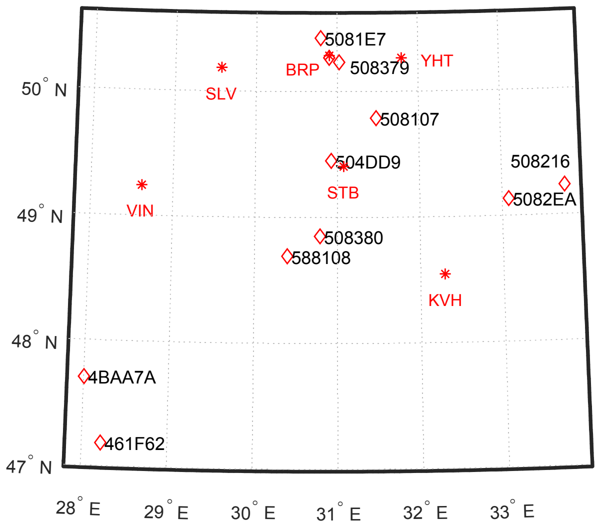

Fig. 4. Air traffic data from ADS-B messages set to a common measurement time

At the next step a computer simulation of DME ground network and its availability estimation for airspace users was performed. In the simulation, a model of DME equipment radio signals and propagation of radio waves in space were used. To simplify a simulation, the impact of terrain on distance determination in DME was not taken into account. In addition, the investigation assumed the multi-signaling of on-board equipment, that means that each aircraft interacted with all DMEs available within its operational range. Estimation of availability is carried out according to the method represented in [10]. As an example, results of distance measurements for aircraft with codes "5081E7" and "508107" together with DMEs "BRP" and "YHT" are shown on Fig. 5.

Simulation of the passive positioning method was done for the case of a stationary observer located at the coordinates (λ=50°N,φ=31° E) at a certain height of airspace (FL195). Results of determining the time difference between DME messages are shown on Fig. 6 without error influence. An accuracy of the proposed method is investigated using statistical observations. Results of coordinates estimation by passive approach (2) considering measuring errors are shown on Fig. 7.

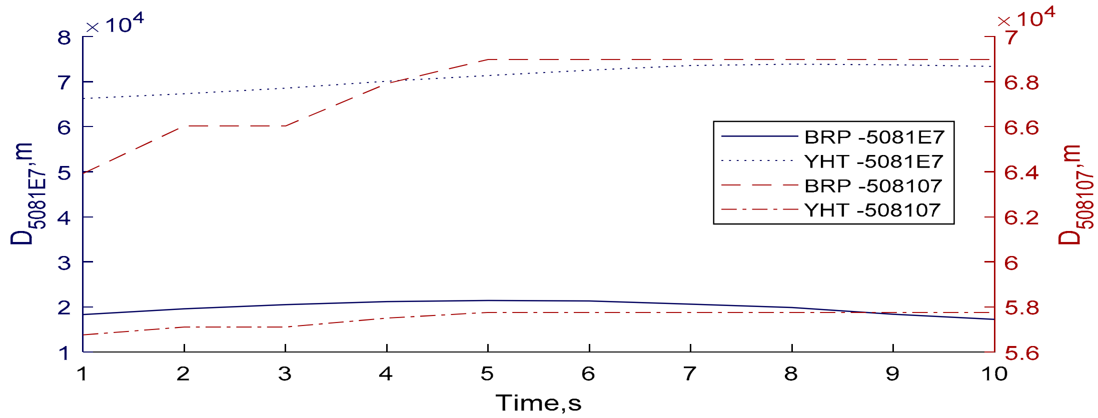

Fig. 5 Distances to DME

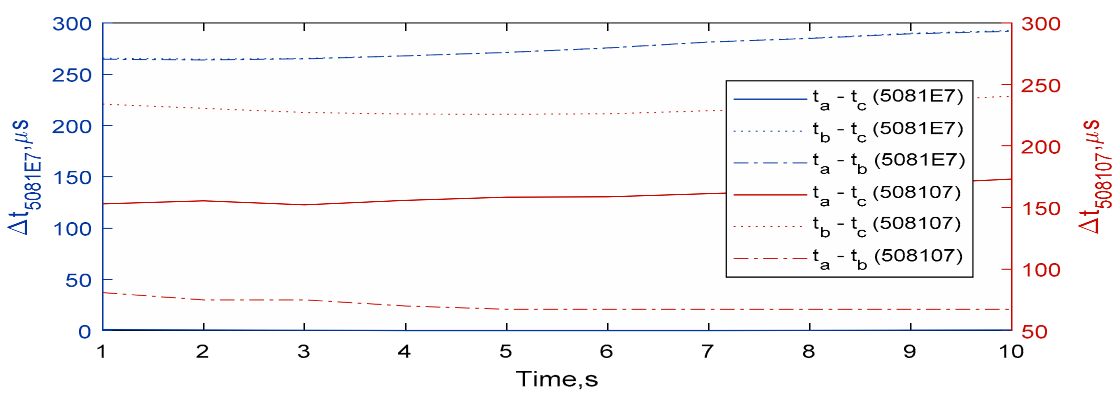

Fig.6. Differences in timing of DME messages

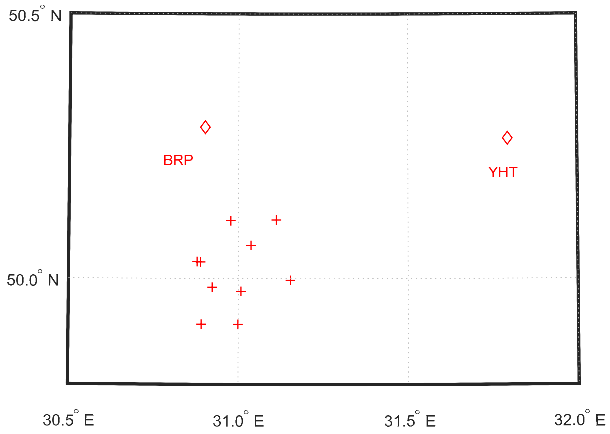

Fig.7. Results of coordinates estimation

7. Conclusions

Proposed method of passive positioning based on observations of DME signals and airspace users coordinate information allows to determine the coordinates of the observer's location within DME operational range. Proposed method can reduce the load on DME ground network, since it focuses on the passive observation of DME signals already present in airspace. One of the advantages of the method is usage currently available signals in airspace for positioning by TDOA principle. However, the introduction of method requires the development of new equipment for passive surveillance, that uses scanning receiver.

References

[1] ICAO, Doc 9613. (2008) Performance-Based Navigation (PBN) Manual. The Internaltional Civil Aviation Organization, Third edition, Montreal, Canada, 264 p.

[2] Narins, M., Eldredge, L., Enge, P., Harrison, M., Kenagy, R., & Lo, S. (2012, April). Alternative Position, Navigation, and Timing--The Need for Robust Radionavigation. In Global Navigation Satellite Systems: Report of a Joint Workshop of the National Academy of Engineering and the Chinese Academy of Engineering, 19-36 p.

[3] Lo S., Enge P. (2012, January). Signal structure study for passive ranging system using existing distance measuring equipment (DME). In Proceedings of the Institute of Navigation International Technical Meeting, Newport Beach, CA, 1–11 p.

[4] Lo S. (2012). Pseudolite alternatives for alternate positioning, navigation, and timing (APNT). FAA White Paper, August, 1 – 15p.

[5] Kim E. (2012, October). Hybrid APNT architecture using DME/DME and multilateration. In Digital Avionics Systems Conference (DASC), 2012 IEEE/AIAA 31st, 5A5-1 p.

[6] Kim E. (2011). A coverage analysis methodology for APNT pseudolite ground network. Proceedings of the 2011 ION GNSS, 1 –13 p.

[7] Wu R. H., Davidson S. A. (2014, May). An Alternative Positioning Navigation and Timing concept based on Diverse Ranging. In Position, Location and Navigation Symposium-PLANS 2014, 2014 IEEE/ION, 886-914 p.

[8] Ostroumov I.V. (2016) Analysis of DME/DME positioning facility for Ukrainian airspace. In the Seventh World Congress “Aviation in the XXI-st century – Safety in Aviation and Space Technologies”. Volume 2. NAU, 3.6.1-3.6.4 p.

[9] Ostroumov I. V., Kuzmenko, N. S. (2016, October). Accuracy estimation of alternative positioning in navigation. In Methods and Systems of Navigation and Motion Control (MSNMC), 2016 4th International Conference, IEEE, 291-294 p.

[10] Ostroumov I. V. (2017) Availability estimation of navigation aids. Visn. NTUU KPI, Ser. Radioteh. radioaparatobuduv., no. 69, 35-40 p. (in Ukrainian)

І.В. Остроумов

Пасивний метод позиціонування за інформацією далекоміра та цифрових повідомлень у форматі автоматичного залежного спостереження

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, 03680, Україна
E-mail: ostroumovv@ukr.net

Мета: представлені результати досліджень спрямовані на розробку нового методу позиціонування, що використовує сигнали DME в просторі та повідомлення ADS-B від користувачів повітряного простору. Запропонований підхід позиціонування базується на зборі та аналізі сигналів. Один літак, що взаємодіє з двома різними DME, є джерелом трьох гіперболічних ліній розташування, перетин яких може вказувати на розташування користувача. **Методи дослідження:** представлений підхід ґрунтується на використанні різницево-далекомірному методу, статистичних методах оцінки похибок та комп'ютерному моделюванні. **Результати**: запропонований метод виявлення координат літальних апаратів може зменшити навантаження на наземну мережу DME, оскільки він базується на пасивному спостереженні сигналів DME, присутніх у повітряному просторі. **Обговорення:** Підхід може бути застосований в алгоритмах обчислювальної системи літаководіння у якості альтернативного методу позиціонування до існуючих.

Ключові слова: літак; координати; пасивний; позиціонування; ADS-B; DME; TDOA

И.В. Остроумов

Пассивный метод позиционирования по информации дальномера и цифровых сообщений в формате автоматического зависимого наблюдения

Национальный авиационный университет, ул. Космонавта Комарова, 1, Киев, 03680, Украина
E-mail: ostroumovv@ukr.net

Цель: представленные результаты исследований направлены на разработку нового метода позиционирования, который использует сигналы DME в пространстве и сообщения ADS-B пользователей воздушного пространства. Предложенный подход позиционирования базируется на сборе и анализе сигналов. Один самолёт, взаимодействуя с двумя различными DME, является источником трёх гиперболических линий положения, пересечение которых может указывать на местоположение пользователя. **Методы исследования:** представленный подход основывается на использовании разностно-дальномерного метода, статистических методах оценки погрешностей и компьютерном моделировании. **Результаты:** предложенный метод определения координат летательных аппаратов может уменьшить нагрузку на наземную сеть DME, поскольку базируется на пассивном наблюдении сигналов DME, присутствующих в воздушном пространстве. **Обсуждение:** подход может быть применён в алгоритмах вычислительной системы самолётовождения как альтернативный метод позиционирования к существующим.

Ключевые слова: координаты; летательный аппарат; пассивный; позиционирование; ADS-B; DME; TDOA

Ostroumov Ivan(1983). Candidate of Engineering. Associate Professor.
National Aviation University.
Education: National Aviation University, Kyiv, Ukraine (2005).
Research area: navigation, alternative Position, navigation and timing.
Publications: 113.
E-mail: ostroumovv@ukr.net