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AN ACCURACY OF LOCATION LINE MAINTAINING BY ANGLES AT LIMITED AIRSPACE VOLUME

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Abstract**—***The accuracy of maintaining navigational characteristics is the most important factor in the development of avionics of a civil aircraft. The on-board computing system of aircraft uses a variety of different algorithms for maintaining a given trajectory and determining the exact location in the airspace. Nowadays many aircraft are equipped with system that uses measurements of angles or distances to specific ground-based navigational aids for positioning as a backup or alternative to the global navigation satellite. Represented mathematical dependence makes possible to estimate the accuracy of maintaining the position line for angular-based approach during navigation by optimal pair of VOR / VOR through internal angles. As initial data, information from VOR on-board receivers are used, as well as information about the location of ground-based navigation aids. Statistical analysis is used as a main method of data study. The obtained mathematical dependencies can be used in the algorithms of on-board navigation systems to assess the availability and accuracy of VOR / VOR navigation in real-time. Based on the results of computer modeling, the maximum accuracy of navigation was estimated in the case of using the optimal pair of navigational aids for the airspace of Ukraine.*

Index Terms—Navigation; angle of arrival method; positioning; VOR / VOR; accuracy; Ukraine; airspace; internal angle.

I. INTRODUCTION

Maintaining the given aircraft location lines is one of the main tasks of navigation and automated piloting systems. Currently, the problem of aircraft movement in the airspace is solved by accurately determining the coordinates of the aircraft location or maintaining specified lines of constant distances or angles relative to ground radio navigation points.

In accordance with regulative documents [1], [2], the Global Satellite Navigation System (GNSS) is the main source of coordinate information on board an aircraft. During operation, the GNSS availability and accuracy can significantly vary due to a number of factors [3]. Currently, positioning accuracy has been significantly improved due to optimization of the geometry of the space segment, errors associated with the influence of the ionosphere [3] that are partially solved by using ground stations of differential corrections. But the problems of electromagnetic compatibility and intentional jamming of satellite signals do not have a simple solution [4]. The global use of GNSS has led to the widespread use of low-cost personal jamming systems. The low power of such systems does not allow them to be effectively detected and counteracted by existing methods [4], [5]. On the other hand, the operation of such systems is dangerous for aircraft located at a low altitude at the stages of takeoff and landing [5].

II. PROBLEM STATEMENT

In cases of deterioration in the accuracy of GNSS positioning, the flight management system (FMS) uses algorithms of alternative positioning methods. The main of them are: positioning using pairs of Distance Measuring Equipment (DME), positioning using a pair of VOR/DME, positioning using pairs of angular-based navigational aids (VOR), positioning by two non-directional beacons (NDB) according to the automatic radio compass (ARC) [6], [7].

The level of accuracy for aircraft positioning by alternative methods can not reach a GNSS level. An accuracy depends on geometry of ground infrastructure and positioning method is used. Therefore, there is a need to estimate an error of positioning by navigational aids and to study error behavior at specific volume of airspace.

Based on the above, the aim of the paper is to estimate the maximum acceptable value for the accuracy of determining the aircraft position line, which can be achieved in FMS algorithms using data from the optimal pair of VORs in their availability areas.

III. Review

Positioning by navigational aids is done by solving the navigation equation according to the known coordinates of the location of the radio navigation points and the range and angular information inherent in these systems. All these algorithms are alternative to GNSS positioning methods on board the aircraft [5], [7], [8], which is defined by the relevant regulatory documents [9]. In addition, in the absence of coordinate information for a short period of time, an inertial navigation system is activated. In accordance with the rules for performing instrument flights, methods of maintaining specified position lines can be used at certain stages of flight to determine the aircraft trajectory in the horizontal plane.

The issues of accuracy estimation using DME are considered in numerous publications both for the case of their pairwise use [6], [7] and for all available at a certain point of airspace [10], [11]. Also, the ground infrastructure of VOR beacons is considered in detail in the context of optimizing the location of beacons and assessing the geometric factor of accuracy deterioration for all available beacons at a certain point of airspace [12], [13]. In the case of using a multi-sensor system, the DOP (Dilution of precision) coefficient [14] – [16] can be used as the simplest approach for accuracy estimation. Moreover, the issues of choosing the optimal pair of VOR beacons in certain airspace and accuracy estimation remain to be open.

II. Accuracy of Positioning

Let us estimate the positioning accuracy according to information from two VORs. We consider the case when the aircraft is at point B and measures the azimuths of the RNP α_A and α_B (Fig. 1).

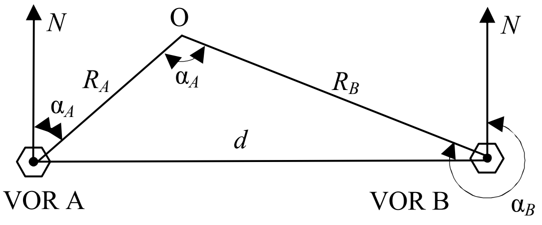

Fig. 1. Relative distances of VORs

In this case, the uncertainty area associated with the VOR error is shown in Fig. 2. The quadrangle obtained by crossing the error angles of the measuring equipment directly depends on the aircraft relative position and VOR ground beacons. Let us estimate the error of aircraft positioning by the known errors of the VOR system. Here, we assume that VOR equipment has a certain error in measuring the azimuth $\Delta\alpha$. In comparison with DME, the error $\Delta\alpha$ does not depend on the distance to the RNP and consists of the air and ground components. But, in the general case, the errors of the ground part can be common in accordance with the use of the same equipment.

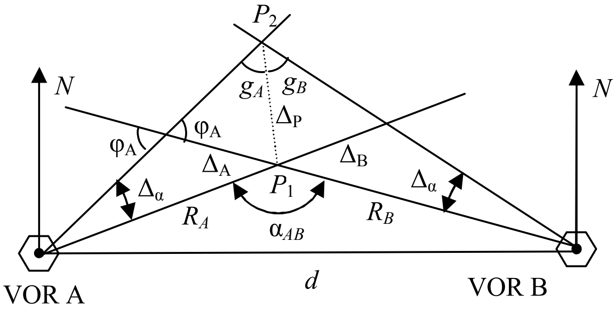

Fig. 2. An error of location line maintaining

We determine the value of the ΔP error from the triangle AP_1P_2. Using sine theorem, we have:

$$\frac{R_A}{\sin(g_A)} = \frac{\Delta_P}{\sin(\Delta\alpha)},$$

$$\Delta_P = \varphi(\Delta\alpha) = \frac{R_A \sin(\Delta\alpha)}{\sin(g_A)}. \tag{1}$$

Since,

$$g_A + g_B = 2\pi - 2(\Delta\alpha - \alpha_{AB} + \pi) - \alpha_{AB} = \alpha_{AB} - 2\Delta\alpha,$$

then,

$$g_B = \alpha_{AB} - 2\Delta\alpha - g_A.$$

On the other hand, from the triangles AP_1P_2 and BP_1P_2, by the sine theorem, we can write:

$$\frac{\Delta_P}{\sin(\Delta_\alpha)} = \frac{R_A}{\sin(g_A)} = \frac{R_B}{\sin(g_B)},$$

$$R_A \sin(g_B) = R_B \sin(g_A),$$

$$R_A \sin(\alpha_{AB} - 2\Delta\alpha - g_A) = R_B \sin(g_A),$$

$$R_A \sin(\alpha_{AB} - 2\Delta\alpha) = \frac{\sin(g_A)}{\cos(g_A)}\left(R_B + R_A \cos(\alpha_{AB} - 2\Delta\alpha)\right),$$

$$\operatorname{tg}(g_A) = \frac{R_A \sin(\alpha_{AB} - 2\Delta\alpha)}{R_B + R_A \cos(\alpha_{AB} - 2\Delta\alpha)},$$

$$g_A = \operatorname{arctg}\left(\frac{R_A \sin(\alpha_{AB} - 2\Delta\alpha)}{R_B + R_A \cos(\alpha_{AB} - 2\Delta\alpha)}\right). \quad (2)$$

In the formula (2), it is necessary to take into account the fact that α_{AB} can take values more than 90°. In accordance with this, the values of the cos function at the interval from 90° to 180° will have a negative sign. To exclude this influence, we take the absolute values of the cos function:

$$g_A = \operatorname{arctg}\left(\frac{R_A \sin(\alpha_{AB} - 2\Delta\alpha)}{R_B + R_A \left|\cos(\alpha_{AB} - 2\Delta\alpha)\right|}\right). \quad (3)$$

The lines of constant angles g_A relative to the RNP VOR A are shown in Fig. 3. The nature of the dependence for the g_B angles will have a symmetrical form with respect to the VOR B. Substituting expression (3) into the general error formula (1), we obtain the dependence for the random variable $\Delta\alpha$:

$$\varphi(\Delta\alpha) = \frac{R_A \sin(\Delta\alpha)}{\sin\left(\operatorname{arctg}\left(\frac{R_A \sin(\alpha_{AB} - 2\Delta\alpha)}{R_B + R_A \left|\cos(\alpha_{AB} - 2\Delta\alpha)\right|}\right)\right)}. \quad (4)$$

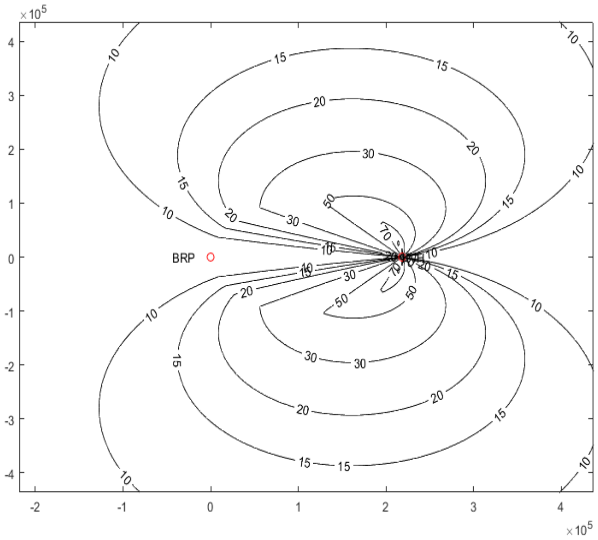

Fig. 3. Lines of constant g_A angles

Then, the variance of a continuous random variable can be written in this form [17]:

$$\sigma^2_{\text{VOR/VOR}} = D\left[\varphi(\Delta\alpha)\right] = \int_{-\infty}^{\infty} \left(\varphi(\Delta\alpha) - E\left[\varphi(\Delta\alpha)\right]\right)^2 f(\Delta\alpha) d\Delta\alpha,$$

where $f(\Delta\alpha)$ is the probability density of the normal law.

In the general case, the line of constant errors in maintaining the position line along the VOR will look like ellipses. For a pair of radio navigation points "BRP" (Boryspil) and "KVH" (Kirovohrad), the lines of constant errors are shown in Fig. 4.

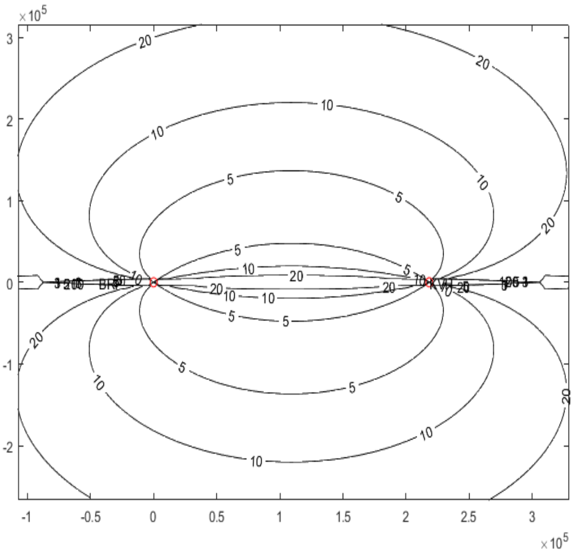

Fig. 4. Lines of constant errors for VOR/VOR navigation

III. ESTIMATION OF UNCERTAINTY AREA

Another important characteristic of geometry of mutual location of ground navigational aids and aircraft is the area of the quadrangle of uncertainty. In the common approach an area can be estimated as a half the product of the diagonals (Fig. 5) and the sin of angle between them:

$$S = \frac{\Delta_P \Delta_{P2} \sin(\nu)}{2} = \frac{\Delta_P \Delta_{P2} \sin(g_A + \theta_A)}{2}.$$

Let's estimate Δ_{P2} by counting Δ_A and Δ_B with the help of $\Delta\alpha$:

$$\Delta_A = \frac{R_A \sin(\Delta\alpha)}{\sin(\pi - \alpha_{AB} + \Delta\alpha)} = \frac{R_A \sin(\Delta\alpha)}{\sin(\alpha_{AB} - \Delta\alpha)},$$

analogically have

$$\Delta_B = \frac{R_B \sin(\Delta\alpha)}{\sin(\alpha_{AB} - \Delta\alpha)}.$$

Substituting the results in (1) we have:

$$\Delta_{D2}{}^2 = \frac{\left(R_B \sin(\Delta\alpha)\right)^2 + \left(R_A \sin(\Delta\alpha)\right)^2 - 2R_A \sin(\Delta\alpha) R_B \sin(\Delta\alpha) \cos(\alpha_{AB})}{\sin(\alpha_{AB} - \Delta\alpha)^2},$$

$$\Delta_{D2}^{\;2}=\frac{\sin(\Delta\alpha)^2\left(R_B^{\;2}+R_A^{\;2}-2R_AR_B\cos(\alpha_{AB})\right)}{\sin(\alpha_{AB}-\Delta\alpha)^2},$$

$$\Delta_{D2}=\frac{\sin(\Delta\alpha)\sqrt{R_B^{\;2}+R_A^{\;2}-2R_AR_B\cos(\alpha_{AB})}}{\sin(\alpha_{AB}-\Delta\alpha)}=\frac{\sin(\Delta\alpha)\sqrt{d^2}}{\sin(\alpha_{AB}-\Delta\alpha)}\qquad \Delta_{D2}=\frac{d\sin(\Delta\alpha)}{\sin(\alpha_{AB}-\Delta\alpha)}.$$

Thus we have:

$$\frac{\Delta_{D2}}{\sin(\alpha_{AB})}=\frac{\Delta_B}{\sin(\theta_A)},\qquad \theta_A=\arcsin\left(\frac{\Delta_B\sin(\alpha_{AB})}{\Delta_{D2}}\right),$$

$$\theta_A=\arcsin\left(\frac{\dfrac{R_B\sin(\Delta\alpha)}{\sin(\alpha_{AB}-\Delta\alpha)}\sin(\alpha_{AB})}{\dfrac{d\sin(\Delta\alpha)}{\sin(\alpha_{AB}-\Delta\alpha)}}\right)=\arcsin\left(\frac{R_B\sin(\alpha_{AB})}{d}\right).$$

$$\theta=(\Delta\alpha-\alpha_{AB}+\pi)-\theta_A.$$

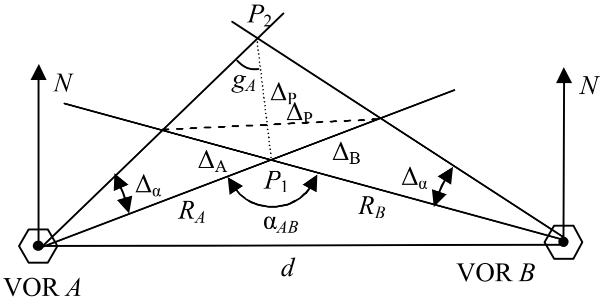

Fig. 5. Diagonals of the quadrangle of uncertainty

The angle between the diagonals of the quadrangle intersect is estimated as follows:

$$\nu=\pi-g_A-\theta=\alpha_{AB}-g_A-\Delta\alpha+\theta_A.$$

An angle α_{AB} can be represented from known angles α_A and α_{AB} as following:

$$\alpha_{AB}=\pi-(\varphi_A+\varphi_B),$$

where

case 1. If $y_O > 0$ and $x_O > X_B$, have

$$\varphi_A=\frac{\pi}{2}-\alpha_A \text{ and } \varphi_B=\alpha_B+\frac{\pi}{2},$$

case 2. If $y_O>0$ and $X_A < x_O < X_B$, have

$$\varphi_A=\frac{\pi}{2}-\alpha_A \text{ and } \varphi_B=\alpha_B-\frac{3\pi}{2},$$

case 3. If $y_O>0$ and $X_A > x_O$, have

$$\varphi_A=\frac{5\pi}{2}-\alpha_A \text{ and } \varphi_B=\alpha_B-\frac{3\pi}{2}.$$

During measurements on board of aircraft distances R_A and R_B are unknown. Thus we can count these distances by next formulas:

$$R_A=d\frac{\sin(\varphi_B)}{\sin(\varphi_A+\varphi_B)},\quad R_B=d\frac{\sin(\varphi_A)}{\sin(\varphi_A+\varphi_B)}.$$

According to formula (2), the lines of constant errors are elliptical. The determination of the line with the smallest error is performed by finding the derivative of (2) with respect to α_{AB} and equating its value to zero. The obtained dependence can be solved by one of the methods for solving nonlinear equations and estimate the α_{AB} value. The obtained value of α_{AB} will correspond to the line with the smallest error.

Obtained location line of aircraft can be used in tasks of positioning [5], [6] or in tasks of classification of air situation [18].

IV. NUMERICAL DEMONSTRATION

For numerical demonstration, we estimate the accuracy of keeping the position line by angular based approach at a certain point of investigated airspace volume. Also, we use simplified cylindrical coverage model of VOR in simulation of availability area. The data of navigational signals availability in space is used for choosing the optimal pair of VOR for navigation with the help of linear binary integer programming [19]. We use only one pair of VOR for navigation according to minimum equipment list of aircraft. Also, we use a pair that can guaranty the maximum level of positioning accuracy.

Let's estimate the accuracy of keeping the position line by angular based approach for whole Ukrainian airspace at specific flight level. In this case we divide an investigated airspace at elementary particles, within which we assume accuracy level constant. The results of estimating the number of available VORs for navigation within Ukrainian airspace are presented in Fig. 6 for FL 490. According to obtained list of available VOR at each elementary particle we create a list of possible combinations of VOR pairs.

The results of estimating the angle α_{AB} for optimal combination at each point in the airspace are presented in Fig. 7. In Figure 8 the accuracy of keeping the position lines is represented.

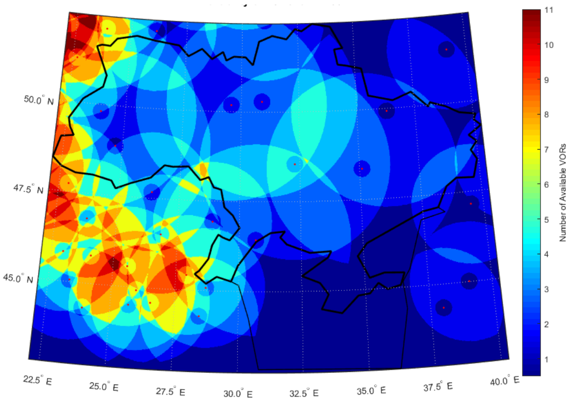

Fig. 6. Total number of available VOR for navigation at FL 490

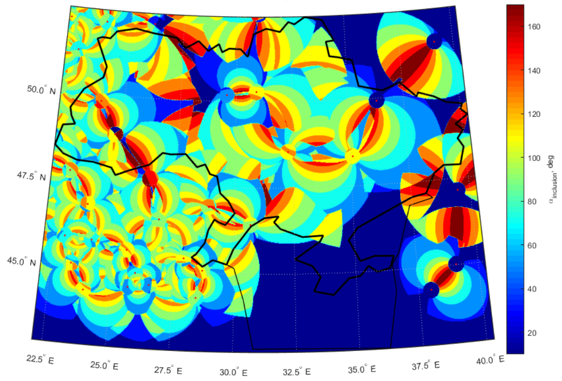

Fig. 7. An α_{AB} angle at FL 490

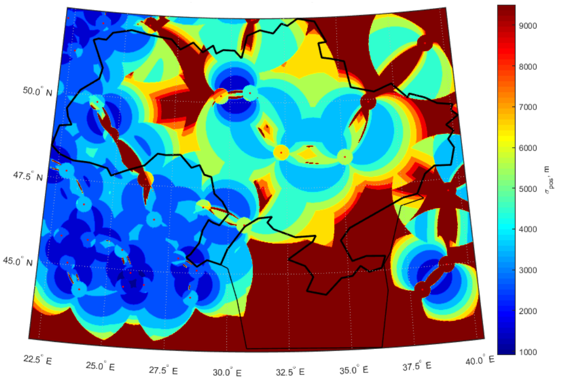

Fig. 8. Accuracy of positioning by optimal VOR pair in Ukrainian airspace

Obtained results of numerical demonstration indicate a low value of positioning accuracy by optimal pair of VOR, which does not support required minimal level according to requirements [2], [20], [21].

VI. CONCLUSIONS

The paper deals with accuracy estimation of airplane positioning by angular data. In this work, a formula for estimation accuracy of maintaining a location line uses angles in geometrical relation is proposed. Proposed approach may be useful for representation results of accuracy estimation in terms of lines of constant angles for one of VOR.

Obtained results of positioning accuracy for Ukrainian airspace depends on geometry of navigational aids location and does not meet current requirements for RNP/RNAV 1. However, in the central and western parts of airspace there are small areas with an accuracy of positioning under RNAV 2 and RNAV 5 [2] requirements. In total an accuracy less than 5 km was obtained for 341.9 thousand km^2 or 40.06% of the total airspace of Ukraine for FL 490.

Low accuracy in this region is caused by a limited number of VOR and low accuracy of the angular-based navigation method in comparison with DME-based approach. In addition, it should be noted that in the central part and the western regions of the country, this method of navigation can be used in the case of positioning lack.

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І. В. Остроумов, Н. С. Кузьменко. Точність витримування лінії положення за кутомірним обладнанням VOR у обмеженому повітряному просторі

Точність витримування навігаційних характеристик є найважливішим фактором розвитку авіоніки літального апарату цивільної авіації. Бортові обчислювальні системи літаководіння використовують різноманітні алгоритми витримування заданої траєкторії і визначення місця розташування літального апарату. В даний час багато літальних апаратів оснащені системою, яка використовує вимірювання кутів або відстаней до конкретних наземних навігаційних пристроїв для позиціонування в якості резервного або альтернативного до глобальних навігаційних супутникових систем навігації. У статті виведено математичну залежність для визначення точності витримування лінії положення за кутомірним обладнанням при VOR/VOR навігації через внутрішні кути. В якості вихідних даних використовується інформація від бортових приймачів сигналів VOR, а також інформація про місцезнаходження наземних навігаційних засобів. Отримані математичні залежності можуть бути використані в алгоритмах бортових навігаційних комплексів для оцінювання доступності і точності VOR/VOR навігації під час польоту. За результатами комп'ютерного моделювання виконано оцінювання максимальної точності навігації в разі використання оптимальної пари наземних радіомаяків для повітряного простору України.

Ключові слова: навігація; кутомірний метод; позиціонування; VOR / VOR; точність; Україна; повітряний простір; внутрішні кути.

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Напрямок наукової діяльності: навігація; альтернативні методи навігації, позиціонування та точного часу.
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И. В. Остроумов, Н. С. Кузьменко. Точность выдерживания лини положения по угломерному радиооборудованию VOR в ограниченном воздушном пространстве

Точность выдерживания навигационных характеристик является важнейшим фактором развития авионики летательного аппарата гражданской авиации. Бортовые вычислительные системы самолётовождения используют разнообразные алгоритмы выдерживания заданной траектории и определения местоположения летательного аппарата. В настоящее время многие летательных аппаратов оснащены системой, которая использует измерения углов или расстояний до конкретных наземных навигационных устройств для позиционирования в качестве резервного или альтернативного глобальных навигационных спутниковых систем навигации. В статье выведена математическую зависимость для определения точности выдерживания линии положения по угломерному оборудованию при VOR/VOR навигации через внутренние углы. В качестве исходных данных используется информация от бортовых приёмников сигналов VOR, а также информация о месторасположении наземных средств навигации. Полученные математические зависимости могут быть использованы в алгоритмах бортовых навигационных комплексов для оценивания доступности и точности VOR/VOR навигации в полете. По результатам компьютерного моделирования выполнено оценивание максимальной точности навигации в случае использования оптимальной пары наземных радиомаяков для воздушного пространства Украины.

Ключевые слова: навигация; угломерный метод, позиционирование; VOR / VOR; точность; Украина; воздушное пространство; внутренние углы.

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