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**Ivan Ostroumov**[1]
**Volodymyr Kharchenko**[2]
**Nataliia Kuzmenko**[3]

# OPTIMIZATION TASK OF NAVIGATIONAL AIDS GROUND NETWORK

National Aviation University
1, Kosmonavta Komarova Avenue, Kyiv, 03058, Ukraine
E-mails: [1]vany@nau.edu.ua; [2]kharch@nau.edu.ua;[3]nataliiakuzmenko@ukr.net

**Abstract**

***Purpose:*** *The represented research results are aimed to formulate an optimization task of ground based navigational aids network in order to improve performance of provided navigational service. Proposed approach is based on iterative process with estimation performance of positioning in each point of airspace and further selection of the most optimal location for new ground facilities.* ***Methods:*** *Represented approach is grounded on analytical and statistical methods of positioning estimation performance, binary integer linear programing theory, and computer-based simulation at verification stage of development.* ***Results:*** *Ground navigational aids network has been represented as a set of geometrical location of standard service volumes in tree-dimensional space. The possible locations for new ground stations were considered together with an existing navigational aids network. The optimal location of new ground stations of navigational aids are result of objective function maximization with specific constraints. Weighted coefficients of linear objective function indicate a volume of predefined performance level of positioning by navigational aids. Results of optimization task solution in terms of linear programming will provide the most optimal location for new ground station within a pool of possible coordinates.* ***Discussion:*** *Formulation of optimization task in terms of binary integer linear programing represents the problem of optimal location search for new navigational aids in one linear objective function and constraints that can be solved by various math methods. Represented results can be implemented during airspace design and in the development of navigational aids network.*

**Keywords:** aircraft; navigation; BILP; DME; ground station; navigational aids; RNAV

## 1. Introduction

Characteristics of accuracy and availability of positioning by navigational aids are fully dependent on the composition and characteristics of the ground infrastructure. Navigational aids equipment type, characteristics of antenna system, amount and geometrical location determine characteristics of the navigation signals field in a space for positioning [1, 2]. One of the possible ways to increase the characteristics of navigation field is the optimization of navigational aids ground network [3].

Optimization addresses the issues of optimal location of ground equipment in order to increase performance of the navigation field of radio navigation system signals, or the choice of optimal locations for new navigational aids. The process of navigation infrastructure optimization is one of the main tasks of the National Service Provider (NSP), which is being implemented to meet requirements of continuously increasing levels of traffic congestion and to increase air traffic safety [4].

National network of Ukrainian navigational aids has been formed over a long history. Its majority is formed in order to provide flights on the route and provide schemes of aircraft traffic in the area of the aerodrome. Such a configuration of ground infrastructure is not optimal from Performance-Based Navigation (PBN) point of view [5], which is implemented today in the airspace of Ukraine [4], because it should be focused on providing the required level of positioning characteristics.

## 2. Analysis of the research and publications

The well-known scientists such as P. Enge, S. Lo [6, 7], Euiho Kim [8] and others were engaged in the questions of aircraft positioning by pairs of Distance Measuring Equipment (DME). In particular, the effect of the geometry of mutual location of the navigational aids ground network on the accuracy of positioning has been investigated in [9, 10]. A present state of the network of DME ground stations for different regions has been analyzed too [10]. Possible ways of using DME network in future concepts of air traffic development have been explored [6].

According to PBN [5], the main constraints for navigational aids pair are defined as follows: an airplane should be in the standard service volume [11] of navigational aid and the inclusion angle between the directions on DMEs should vary between 30 and 150 degrees.

However, the question of formulating the task of optimizing the DME ground network and choosing places for new navigational aids in Ukraine using binary integer linear programming (BILP) has not been considered before.

## 3. Research tasks

The research tasks are:

- Selection of optimization criteria
- Formulation of optimization task in terms of BILP
- Standard service volume analysis and performance estimation of DME ground network.

## 4. Consideration of Ukrainian airspace requirements

An optimization of the navigation signals field is based on the required characteristics in accordance with approved specifications. However, the problem of optimization is complicated by the fact that airspace is different in use and there are different specifications requirements in its different parts.

According to an existing airspace classification, it is expedient to optimize the field of characteristics of navigational parameters in the route airspace (Class “C”, located between FL 195 and FL 660, Fig. 1.) and terminal control areas (TMA) simultaneously to provide RNAV 1 requirements defined for the airspace indicated in accordance with the national roadmap [4].

Multilevel airspace puts the optimization task on a plane of a particular flight level to spatial evaluation throughout the range of heights with restrictions on the geometric dimensions of TMA areas fixed by location of the airports. Implementation of the specifications for the lower airspace is also an important task for the development of air navigation service. However, today, the requirements for this airspace are not approved yet.

The main objective of the optimization problem is optimal location of ground navigational aids for the purpose of their optimal use to create the field of navigational signals providing established requirements for characteristics.

The deployment of Free Route Airspace of Ukraine (FRAU), defined between FL 275 and FL660, requires compliance with navigational specifications not only along the routes, but also throughout the specified airspace. Since the flight can be determined by a certain desired trajectory of an air carrier, there are particularly rigid requirements for the accuracy of navigational aids for determining an aircraft location in space provided by Global Navigation Satellite System and alternative positioning methods.

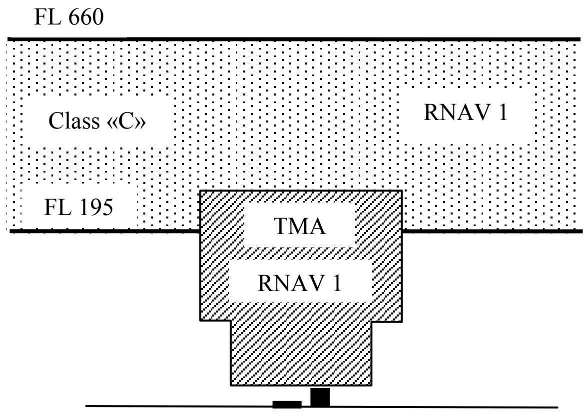


Fig. 1. Boundaries of specification requirements

Optimization of air navigation services is an indispensable component of the development of air navigation infrastructure, which should precede the introduction of new, more precise specifications. An optimization task should be considered according to two important points of view:

1. Optimization of the existing network of ground navigational aids for the purpose of facilities optimal usage. For example, an existing accumulation of navigational aids in a certain part of the space provides the redundancy of the resources in navigation field, while in some its parts there is a need for basic services.
2. Optimal location selection for the establishment of additional navigational aids for extending network scope and enhancing the specification requirements (e.g. RNAV 0.3 in certain TMAs). Results of previous studies indicate an incompatibility of the existing air navigation system in accordance with new concepts of air traffic management in the part of Alternative Positioning, Navigation, and Timing (APNT).

A military conflict in eastern Ukraine made adjustments to the country's air navigation service. A part of the aeronautical equipment was decommissioned [10], which led to a change in the navigational characteristics of the signal field at significant distances from the restricted flight areas. An existing situation requires the revision of air navigation system in order to make it optimal.

Another important element of optimization is that the national network of navigational aids is a part of the global system, and the field of navigation parameters is the result of usage of navigational aids located in neighboring countries. Therefore, optimization process should take place taking into account a stable field of navigation signals of the neighboring countries.

In modern conditions of the national air navigation system, navigational aids optimization should be carried out according to the criterion of compliance with the specification requirements [5] in the maximum space volume, taking into account the design features of the TMA areas and operational characteristics of navigational aids. It should be mentioned that air transport is developing rapidly and in the future the question about the transition to more accurate navigational specifications of the A-RNAV will arise. For example, RNAV 0.3 is used in TMA areas to increase airspace capacity.

## 5. Optimization task formulation

Unfortunately, the optimization task of ground part of navigational aids can not be solved by analytical approach, but it can be solved by iterative methods for searching of all possible combinations and finding an optimal solution for each of them. An algorithm for selecting an optimal location of navigational aids considers possible combinations with some performance level.

An optimization problem can be formulated in terms of integer linear programming and can be solved by one of the methods of linear programming theory. Let's consider the task of ensuring the coverage of airspace by the field of navigation signals in accordance with RNAV 1 requirements.

The solution of this task will be achieved within the existing ground network with the addition of new navigational aids. In general case, an optimization task consists in searching an optimal location for new navigational aids to meet RNAV 1 requirements. Also, airspace optimization can be done based on GDOP values [3, 12], which makes an optimization task more simpler. However, current on-board equipment works on a pair basis. Thus, it is more appropriate to use characteristics of the optimal navigational aids pair at a defined point in the airspace. Therefore, an optimization task can be formulated as a search of optimal solution at each iteration for a single navigational aid.

Points of possible location are selected within the surface area located at the nodes of the assessment grid. The geometric dimensions of the grid element determine the algorithm performance, which is limited to the computing ability of the equipment. To solve the problem, an iterative algorithm is proposed, which at each stage provides a search for a solution with a decrease in a searching area of the optimal location, in conjunction with an increase in the resolution of the search, that is, by reducing the distance between the nodes of the optimization grid (Fig. 2).

Usage of an iterative algorithm is proved because, after finding the optimal location with a rough error, the boundaries of a possible location are determined by computation performance. On the other hand, maximum range of navigational aids is limited by a standard service volume. Therefore, it is not necessary to recalculate the whole airspace performance in selection of a new ground station location, but use only involved part of service volume. Thus, the necessary accuracy of estimation is achieved by gradual iteration. Physically, the nodes of a grid will be set in the latitude, longitude and altitude coordinate system with height of the relief at a certain point, which corresponds to the location of equipment on the earth's surface.

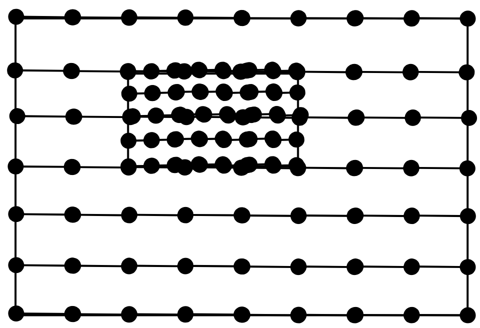

Fig. 2. Grid a possible location at various iteration steps

Let the vector $x=[x_1,x_2,x_3,..,x_n]$ corresponds to the indexes of the points of the navigational aids possible location, the elements of which can be $x_i=1$ in case of navigational aid location or $x_i=0$, which corresponds to the non-optimal navigational aid location. Vector $x$ contains $n$ nodes in a certain iteration step. Vector $x$ will be combined with a vector of indices of existing navigational aids in a general vector of navigational aids: $X=[GS, x]$.

In terms of linear programming theory, the objective function, or optimization function can be written as follows:

$$wx \Rightarrow max \qquad (1)$$

where $w$ is a vector of weight coefficients.

Vector $w$ contains weight coefficients of the vector $x$. The higher its value is, then the optimization value of the candidate's location of navigational aid is higher too. In case of optimization at the maximum of occupied volume, $w$ is the total airspace meeting RNAV 1 requirements, for specific location of a certain navigational aid. In case of area optimization for a certain altitude level, $w$ is the value of the area of the territory that meets RNAV 1 requirements. The value of weight coefficient is calculated on the basis of accuracy estimation of optimal navigational aids pair for a given volume of airspace with the subsequent contour analysis of the space for which appropriate RNAV characteristics are satisfied.

Another component of the linear programming problem is setting constraints to optimization. First, let's consider constraint that establishes navigational aid availability, because it is necessary to have a simultaneous interaction with at least two navigational aids ($N_{max}$). To do this, we establish a grid of possible aircraft location, just as in the case of positioning availability estimation, and estimate an availability matrix $A$. The lines of matrix A correspond to the grid of aircraft location, and the columns are navigational aids stations. Each element of the matrix $a_{i,j}$ corresponds to value 1 in case of navigational aid availability in a point of aircraft location, and $a_{i,j}=0$ in case of unavailability:

$$AX^T \geq N_{max.} \qquad (2)$$

The following constraints are set by the requirements for the optimal navigational aid pair. Here, for each point of space, an optimal combination of the navigational aids for Nmax> 2 is estimated. In case of presence of only one pair of navigational aids, its contribution to the estimation of characteristics is estimated. In accordance with the requirements [171], there are rigid requirements for the inclusion angle between the directions for two different navigational aids in the case of positioning by pairs. Therefore, if the inner angle satisfies PBN requirements, the corresponding of matrix B $b_{i,j}$=1:

$$b_{i,j}=1, \text{ if } 30^\circ \leq \alpha \leq 150^\circ$$
$$b_{i,j}=0, \text{ if } 30^\circ \geq \alpha \geq 150^\circ$$

Since at least two stations in one pair must satisfy the requirements of the angle of constraints, then $Bmax = 2$:

$$BX^T \geq B_{max.} \qquad (3)$$

Constraints on the number of allowable navigational aids that will be used additionally are the following:

$$TX^T=1, \qquad (4)$$

where $T$ is an indicator matrix indicating the possibility of choosing among the new variants: $t_i=0$ for the established navigational aids and $t_i=1$, for alternative means.

In general case, an optimization problem can be written as follows:

$$\begin{aligned} &wx \Rightarrow \max \qquad (5)\\ &AX^T \geq N_{max.}\\ &BX^T \geq B_{max.}\\ &TX^T=1 \end{aligned}$$

Solving (5) by one of the BILP methods we get a binary vector $x$ which indices correspondance to the optimal location of a new navigational aid.

## 6. Performance estimation of Ukrainian DME network

The national network of DME ground stations consists of 7 en-route and 13 terminal DMEs (BAH, BRP, DNP, IVF, IHA, IHR, IKI, IKV, KHR, KSN, KVH, CAR, LIV, ILO, ILV, ODS, SLV, STB, VIN, YHT) [13]. Figure 3 shows the configuration of DME ground network. The navigation signals field formed by DME ground stations network in Ukraine, taking into account signals from neighboring countries, allows to select areas with the same availability (Fig. 3).

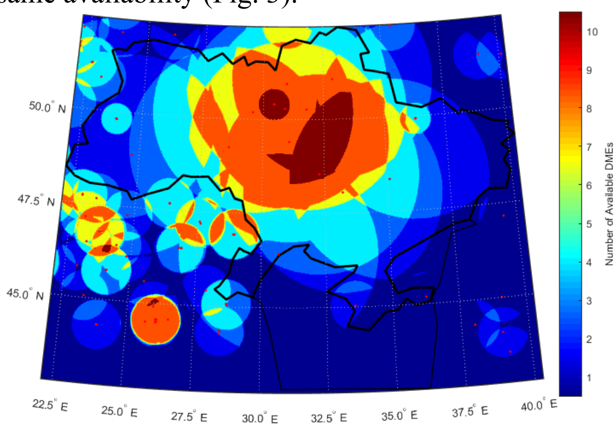


Fig. 3. Available amount of DMEs for FL 105

Therefore, availability constraints (2) in the form of matrix A are formed in a binary representation according to Fig. 3 for each pair of navigational aids separately.

Results of calculation of inclusion angle between the directions on navigational aids for optimal DME/DME pair in the form of contour graph are shown in Fig. 4, and results of the air space area with a 10 ° grid angle are shown in Fig. 5. Based on Fig. 4, a binary matrix *B* is constructed for the condition (3).

The simulation results showed that a satisfactory inclusion angle in DME/DME pair between 80 ° and 100 ° corresponds to:

- FL 105 for 21.3% of the airspace (181.43 thousand km$^2$);
- FL 195 for 35.3% of the airspace (301.17 thousand km$^2$);
- for FL 490, 30.8% of the airspace (262.68 thousand km$^2$).

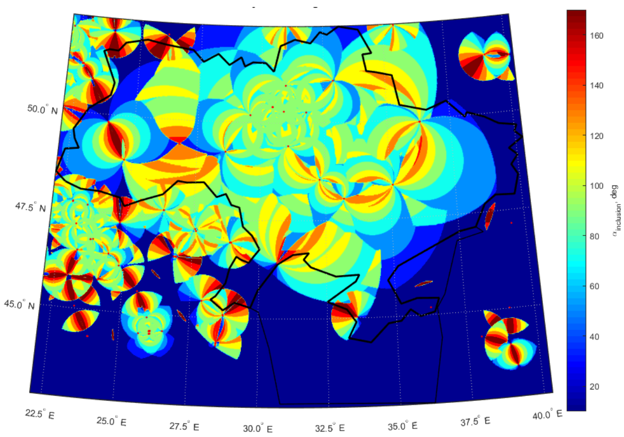


Fig. 4. Inclusion angle between directions in optimal DME/DME pair for FL 105

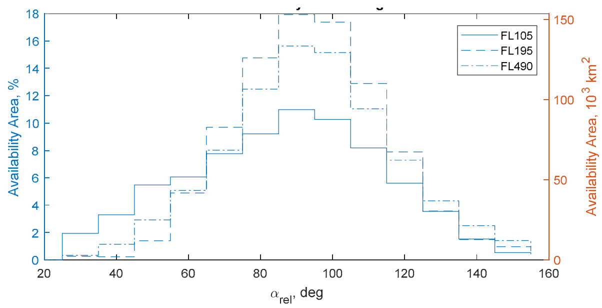


Fig. 5. Analysis of inclusion angle between the directions on DMEs in the airspace of Ukraine

From Fig. 5 it is evident that the behavior of the angle by area has the form of normal distribution with the best performance on FL 195. Results of calculation of inclusion angle are used for estimation of the radial error. The contour graphs of results of a positioning accuracy calculation for optimal DME/DME pair are shown in Fig. 6

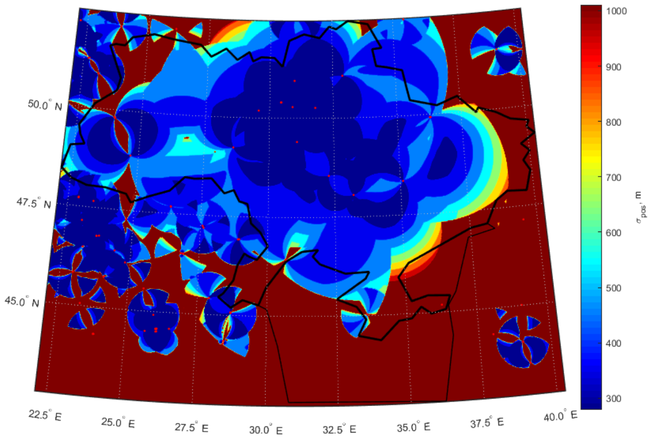


Fig. 6. Mean squared deviation of positioning error in horizontal plane

Positioning accuracy in horizontal plane acts as the values of weight coefficients vector in the objective function (1) and optimization is reduced to finding a minimum of this objective function.

## 7. Conclusions

Represented form of optimization task of choosing the optimal location of navigational aids by volume of airspace, in terms of integer linear programming, allows determining the location for a new ground station from a set of predetermined coordinates, maximizing the amount of space that meets requirements of a specific RNAV specification. In case of reaching a certain level of specification requirements throughout the study area, weights of the objective function are proposed to be used as the indicator of navigation system error, which corresponds to a double mean squared deviation of aircraft positioning error.

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**І.В. Остроумов[1], В.П. Харченко[2], Н.С. Кузьменко[3]**

**Формулювання задачі оптимізації мережі наземних радіо-навігаційних засобів**

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680
E-mail: [1]vany@nau.edu.ua; [2]kharch@nau.edu.ua; [3]nataliiakuzmenko@ukr.net

**Мета:** Представлені результати досліджень спрямовані на формулювання задачі оптимізації мережі наземних радіо-навігаційних засобів з метою підвищення ефективності наданих навігаційних послуг. Запропонований підхід базується на ітеративному підході на основі ефективності позиціонування в кожній точці повітряного простору та подальшому вибору найбільш оптимального місця для нового радіонавігаційного засобу. **Методи:** представлений підхід ґрунтується на аналітичних та статистичних методах оцінювання точності позиціонування, методах теорії цілочисленого лінійного програмування та комп'ютерного моделювання на етапі верифікації результатів. **Результати:** мережа наземних раді-навігаційних засобів розглядається у вигляді геометричної сукупності стандартних об'ємів простору у межах яких забезпечується належне їх функціонування у три-мірному просторі. Місця можливого розташування нової наземної станції розглядаються разом з існуючою мережею навігаційних засобів. Оптимальне розташування нової наземної станції навігаційних засобів є результатом мінімізації цільової функції з певними обмеженнями. Зважені коефіцієнти лінійної цільової функції відображають характеристики позиціонування за навігаційними засобами. Результати рішення задачі оптимізації в термінах лінійного програмування забезпечать найбільш оптимальне розташування нової наземної станції з ряду можливих координат. **Обговорення**: Формулювання задачі оптимізації в термінах двійкового цілочисленного лінійного програмування представляє собою проблему оптимального пошуку місця розташування нових радіо-навігаційних засобів за допомогою однієї лінійної функції та обмежень, для вирішення якої можуть застосовуватись різні математичні методи. Отримані результати можуть бути застосовані під час проектування повітряного простору та модернізації мережі наземних радіо-навігаційних засобів.

**Ключові слова:** літак; навігація; наземна станція; навігаційні засоби; BILP; DME; RNAV

**И.В. Остроумов[1], В.П. Харченко[2], Н.С. Кузьменко[3]**

**Формулировка задачи оптимизации сети наземных радио-навигационных средств**

Национальный авиационный университет, ул. Космонавта Комарова, 1, Киев, Украина, 03680
E-mail: [1]vany@nau.edu.ua; [2]kharch@nau.edu.ua; [3]nataliiakuzmenko@ukr.net

**Цель:** Представлены результаты исследований направлены на формулировку задачи оптимизации сети наземных радио-навигационных средств с целью повышения эффективности предоставляемых навигационных услуг. Предложенный подход базируется на итеративном подходе на основе эффективности позиционирования в каждой точке воздушного пространства и дальнейшем выбора наиболее оптимального места для нового радионавигационного средства. **Методы:** представлен подход основывается на аналитических и статистических методах оценки точности позиционирования, методах теории целочисленного линейного программирования и компьютерного моделирования на этапе верификации результатов. **Результаты** сеть наземных рады-навигационных средств рассматривается в виде геометрической совокупности стандартных объемов пространства в пределах которых обеспечивается надлежащее функционирование в три-мерном пространстве. Места возможного расположения новой наземной станции рассматриваются вместе с существующей сетью навигационных средств. Оптимальное расположение новой наземной станции навигационных средств является результатом минимизации целевой функции с определенными ограничениями. Взвешенные коэффициенты линейной целевой функции отражают характеристики позиционирования по навигационным средствами. Результаты решения задачи оптимизации в терминах линейного программирования обеспечат наиболее оптимальное расположение новой наземной станции из ряда возможных координат. **Обсуждение:** Формулировка задачи оптимизации в терминах двоичного отсечения линейного программирования представляет собой проблему оптимального поиска местоположения новых радио-навигационных средств с помощью одной линейной функции и ограничений, для решения которой могут применяться различные математические методы. Полученные результаты могут быть применены при проектировании воздушного пространства и модернизации сети наземных радио-навигационных средств.

**Ключевые слова:** летательный апарат; навигация; наземная станция; навигационные средства; BILP; DME; RNAV

**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: 118.
E-mail: vany@nau.edu.ua

**Kharchenko Volodymyr**. Doctor of Engineering. Professor.
Vice-Rector on Scientific Work, National Aviation University, Kyiv, Ukraine.
Winner of the State Prize of Ukraine in Science and Technology, Honored Worker of Science and Technology of Ukraine.
Education: Kyiv Institute of Civil Aviation Engineers, Kyiv, Ukraine.
Research area: management of complex socio-technical systems, air navigation systems and automatic decision-making systems aimed at avoidance conflict situations, space information technology design, air navigation services in Ukraine provided by CNS/ATM systems.
Publications: 540.
E-mail: knarch@nau.edu.ua

**Kuzmenko Nataliia** (1990). Candidate of Engineering. Junior researcher.
National Aviation University.
Education: National Aviation University, Kyiv, Ukraine (2013).
Research area: navigation and control of dynamic systems, artificial intelligence.
Publications: 38.
E-mail: nataliiakuzmenko@ukr.net