Radio Navigation Aids Network Optimization Using a Hexagonal Geospatial Indexing System

Ivan Ostroumov(✉) and Sergii Ivanets

Kyiv School of Economics, Mykoly Shpaka Street, 3, Kyiv 03113, Ukraine
iostroumov@kse.org.ua

Abstract. Ground-based radio navigation aid networks remain a critical component of civil aviation, ensuring the safety and reliability of air transportation. Distance Measuring Equipment (DME) is recognized as a robust backup positioning system capable of supporting the requirements of basic area navigation (RNAV) specifications. The global expansion of Free Route Airspace necessitates the optimization of DME ground networks to maintain the required levels of positioning accuracy and service continuity across all regions of the airspace. This paper proposes an algorithm for DME network enhancement based on airspace representation using a hexagonal geospatial indexing system. The algorithm identifies optimal candidate locations for ground beacon placement by maximizing the spatial distribution of positioning accuracy throughout the considered airspace. The airspace is partitioned into a set of regular hexagonal cells, enabling efficient spatial analysis. Logical operations on cell indices significantly reduce computational complexity compared to classical brute-force methods commonly used in ground network optimization. Spatial characteristic distribution of navigation system error is used to optimize network configuration. A case study of network optimization is presented using the developed software, demonstrating the effectiveness and advantages of the proposed approach.

Keywords: Air Navigation · Smart Infrastructure · Distance Measuring Equipment · Network · Intelligent Transportation System

1 Introduction

Over the past century, ground-based radio navigation aids have played a fundamental role in ensuring the safety and development of civil air transportation [1, 2]. These systems constitute a critical component of intelligent transportation system to supporting aviation operations [3, 4]. Airborne navigation equipment relies on signals transmitted by ground-based beacons to measure key parameters, such as slant range and azimuth angle. These measurements enable aircraft to follow predefined flight trajectories and to accurately determine its position in airspace.

Rapid development of Global Navigation Satellite Systems (GNSS) has led to a significant improvement in positioning performance [5, 6]. Today, GNSS serves as primary onboard positioning sensor in civil aviation due to its high levels of accuracy, availability,

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and continuity. In comparison, traditional ground-based radio navigation aids generally provide lower positioning performance [7]. However, vulnerability of GNSS to interference presents a critical challenge for its continued reliance in civil aviation. The number of interference events has increased dramatically over the past decade, driven by both intentional and unintentional jamming [8, 9]. Recent military conflicts, including the war in Ukraine and operations in countries of the Middle East and other regions of planet, have further underscored the importance of resilient navigation solutions and highlighted the risks associated with GNSS disruption [10]. Within the framework of Performance-Based Navigation (PBN), GNSS is considered the primary positioning source [11]. Nevertheless, in case of GNSS degradation or outage, positioning based on ground radio navigation aids or aircraft guidance using conventional systems can be employed to maintain safe flight operations. These considerations reinforce the necessity of maintaining and optimizing ground-based navigation infrastructures as a reliable backup to GNSS.

Modern roadmaps of aviation development [12] emphasize the need to maintain ground-based navigation infrastructure while promoting initiatives for its further development to enhance network configuration and positioning performance. At the same time, the air transportation system is undergoing a significant transformation toward the widespread implementation of Free Route Airspace (FRA) [13]. FRA enables aircraft to plan and operate direct trajectories between entry and exit points, particularly for en-route traffic, rather than following fixed airways. Compared to conventional airspace structures based on predefined routes, FRA offers multiple advantages, including increased operational and resource efficiency, reduced fuel consumption, and improved airspace capacity. However, its large-scale implementation requires a reconfiguration of navigational aid networks to ensure compliance with Area Navigation (RNAV) performance requirements throughout the entire airspace, rather than being limited to established flight routes [14]. Therefore, contemporary concepts of civil aviation development necessitate the modernization of navigational aid networks, including the reconfiguration of existing smart infrastructure and deployment of new nodes, to support evolving operational requirements.

Performance of navigational aid networks is typically characterized by two primary parameters: positioning accuracy and number of available station pairs [15, 16]. The number of available pairs is determined based on standard service volume model of each navigational aid. Positioning accuracy, in turn, is evaluated using standardized methodologies defined by ICAO, ensuring a globally consistent assessment framework applicable to aircraft operating in any region. These performance indicators are then compared against the minimum requirements specified by RNAV requirements. However, no analytical method exists for directly estimating spatial distribution of these parameters across a continuous airspace. As a result, existing approaches rely on discretizing airspace into a set of cells, followed by evaluation of performance metrics for each individual cell. Most current methods adopt brute-force strategies for parameter estimation within each cell [17, 18]. The primary distinction between these methods lies in the strategy used to traverse or prioritize the cells during analysis phase. Techniques such as sequential evaluation, gradient-based methods, and other variations of exhaustive search are commonly applied in airspace performance analysis.

The problem of optimal navigational aid network configuration is typically addressed through brute-force selection of candidate locations, followed by the maximization of an objective function aimed at achieving required positioning accuracy across the largest possible portion of airspace. However, such approaches require repeated evaluation of network performance metrics for every discretized cell within the considered airspace, resulting in high computational demands and the need for substantial processing resources.

Over the past decades, global indexing systems have undergone significant development, evolving from simple visualization libraries to sophisticated frameworks that provide advanced tools for navigation and geospatial data aggregation. The hierarchical structure of addressing systems facilitates efficient data aggregation, enabling adaptation to required level of spatial precision and available computational resources. Approaches such as Open Location Codes and Hierarchical Hexagonal Indexing [19, 20] demonstrate substantial potential for geospatial analysis. These global indexing systems are widely applied in data analysis tasks where parameters are spatially distributed across geographic areas [21, 22].

In this paper, we consider an approach for effective network configuration estimation based on available areas of potential nodes placement and local impact study in network configuration manipulation. Proposed approach incorporates both positioning accuracy and its spatial distribution as key parameters within the optimization objective function. The airspace is discretized using a hexagonal spatial indexing system, which significantly reduces computational complexity at each iteration step. This representation also enables efficient local adjustments of the network configuration, facilitating the identification of optimal locations for ground beacon deployment.

2 Network of Radio Navigation Aids

There are two basic types of navigational aids used in civil aviation: distance measuring equipment (DME, also known as Tactical Air Navigation or TACAN) and VHF omnidirectional ranging (VOR) [23]. DME measures range between the airplane and each node of DME ground network. VOR is measuring an azimuthal angle to ground station from airplane position. There are also non-directional beacons (NDB) ground networks, but their configuration is reduced significantly due to low precision of angle measuring equipment on board of airplane.

DME is an active measuring device. DME interrogator is an avionics part which generates interrogation signals and receives replies from ground stations. The interrogator measures time traveling in space and calculates range between airplane and ground beacon. Each ground beacon operates at a specific radio channel (there are 256 DME channels specified in normative documents). All channels are frequency distributed. Each DME ground station receives integration signals and, after a fixed time of delay, generates a reply at another co-located radio frequency. Ground DME network forms a graph with exactly known location of each node.

VOR has another operation principle. VOR ground station is continuously transmitting a navigation signal that includes two main components. One component has information about reference direction (North), and another component includes information about direction. Therefore, avionics part of VOR has only a receiver, which

includes amplitude and frequency demodulators. Both demodulated signals are compared to identify the shift of phases between them, which is proportional to measured angle.

Provider of air navigation services in each country is responsible in navigational aids network deployment and maintaining specified network parameters. Both DME and VOR networks are usually considered separately, however VOR/DME navigation could also be provided based on co-allocated VOR/DME beacons. An example of navigational aids networks is given in Fig. 1.

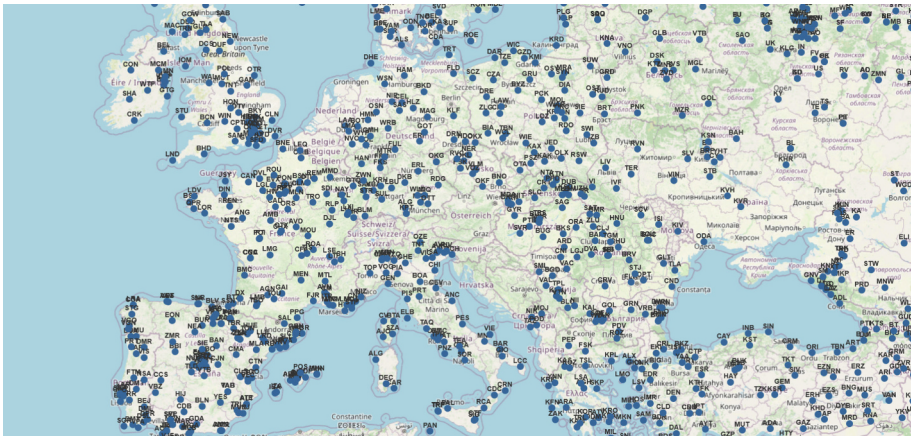

Fig. 1. Nodes of DME and VOR networks in Europe.

Low performance of azimuthal angle measuring in VOR significantly limits performance of VOR/VOR positioning method. Results of the previous study show that VOR/VOR ground facility could not support navigation by level of RNAV 1, which is required for continental flights [24, 25]. In contrast, DME/DME navigation fully supports RNAV 1 precision level and could guarantee safe air navigation [26, 27]. It makes DME/DME navigation useful for further consideration instead of VOR/VOR and makes DME network perspective, and VOR marked as a back-up capability which should be minimized to guarantee only the basic coverage in case of emergency.

In the common case, the network of navigational aids is represented as a graph with beacons placed in nodes. Beacons for which service areas are crossing an edge makes a connection between nodes.

3 Algorithm of Network Efficiency Improvement

This study considers the scenario in which an existing navigational aids network is already deployed, and objective is to identify optimal locations for installation of additional ground beacons. This problem is particularly relevant for air navigation service providers seeking to enhance network performance in accordance with modern development roadmaps. As input, the proposed approach assumes a predefined set of feasible

regions for ground station placement, reflecting practical constraints such as terrain, smart infrastructure availability, and regulatory limitations.

The airspace considered for network optimization is typically defined by administrative boundaries of a country or by limits of a Flight Information Region (FIR). The configuration of FIRs is established in regulatory documents and maintained through international agreements between states. In practical implementations, it is often more efficient to utilize standardized ICAO FIR identifiers to retrieve the corresponding airspace boundaries required for analysis.

Within the administrative boundaries of a FIR, the airspace is partitioned into hexagonal cells. The global hierarchical hexagonal indexing system (H3) provides an efficient and flexible framework for such spatial representation. H3 supports 17 hierarchical levels of precision, each defined by hexagonal cells of a specific size. The highest precision level corresponds to cells with an area of approximately 0.9 m^2[28]. Each H3 cell is assigned a unique address, which also encodes addresses of all its child sub-cells. The regular hexagonal geometry of H3 cells facilitates efficient computation of spatial properties, including area calculation, distance measurements, and the identification of all cells within a given radius, making it particularly suitable for airspace analysis and network optimization tasks.

H3 library provides flexible geo-coding by input polygon of coordinates. For network analysis, each hexagonal cell is assumed to have uniform network parameters, and the coordinates of the cell center are used as representative points for evaluating performance metrics. This approach simplifies computation while maintaining sufficient accuracy for network optimization.

Each network node is associated with a specific H3 cell index. There are two primary approaches for evaluating service volume of a navigational aids. The first approach is based on radio wave propagation equations and the maximum achievable range of communication link. The second approach employs standardized service volumes, typically approximated using cylindrical models. Often, multiple cylinders are combined to represent the service volume over varying terrain. Simplified cylindrical models are widely used in air navigation due to its computational efficiency, particularly for onboard equipment. Accordingly, adopting cylindrical models is a practical and effective choice for identifying candidate locations for new beacon placement.

Normative documents describe only four DME beacon types which could serve en-route phase of flight, low altitude (with 40NM radius), high altitude (130 NM), DME Low (130 NM) and DME High (130 NM) [29]. Each of these types has a different combination of cylinders with exponential approximation at low altitude.

In a computer simulation, a fixed altitude could be used for identification of radius of involved area around beacon. Functionality of H3 library includes a k-ring algorithm, which identifies indexes of all cells placed in the disk with a specified center and radius. It requests that all network nodes should be associated with cell indexes and radius of service area at considered altitude layer, transformed to the metric of parameter k.

The number of available beacons for each cell is estimated as intersection of sets as follows:

$N_i = \bigcap_{j=1}^{n} DME_j^i$ (1).

where n is number of cells; DME^i is a binary set of availability for i-th beacon.

A set of possible combinations of two is estimated for each available number of beacons at a particular cell. Each pair of beacons in combination is considered separately to estimate Total System Error (TSE). A pair with the lowest TSE is used as the most productive.

In case of DME/DME navigation TSE is estimated as follows:

$TSE^2 = FTE^2 + 4\frac{2\sigma_s^2+\sigma_{int1}^2+\sigma_{int2}^2}{sin(\alpha)^2}$ (2).

where FTE is flight technical error; α is inclusion angle at point of airplane location; σ_s is standard deviation error caused during communication line and uncertainty of beacons delays; σ_{int} is the standard deviation error of avionics interrogator of DME.

FTE is caused by an error of piloting mode used for airplane guidance. For the case of autopilot mode, which is most common for en-route phase of flight FTE = 0.25 NM.

Maximum value of standard deviation error caused by communication line and uncertainty of beacon delays is specified in normative documents at a level of 0.05 NM [11].

Standard deviation error of DME interrogator is distance-related and usually used as follows [11]:

$\sigma_{int} = max(0.125D, 0.085NM)$ (3).

where D is measured range between airplane and DME beacon.

Estimated TSE value at each cell is compared to peril value of 1 NM. If accuracy limit is reached, then binary flag is issued to a particular cell. Trigger function is as simple as following:

If $TSE_i < 1$, then $RNAV_i = 1$, else $RNAV_i = 0$. (4).

Algorithm uses each cell from available pull of possible new beacon locations as a candidate for network node placement with a particular DME type. Algorithm required recalculation of Eqs. (1–3) only for cells placed in disc cells centered at the candidate location. It does not require recalculation of whole network but only cells within the availability disc. Results of TSE triggering function (4) identify the number of additional cells that could be obtained from application candidate location. Thus, number of additional RNAV 1 valid cells is a good metric to identify the best candidate for node placement.

The search process considers each potential cell and estimates its impact in the overall network, based on number of additional RNAV 1 complement cells. Finally, the decision is given to place, which provides the maximum number of valid cells.

The structural scheme of proposed algorithm is given in Fig. 2. Initiation of search requires a connection to FIR boundaries database and navigational aids database. Also, setting up a precision level and specification of areas of possible beacon locations should be given in the beginning. Based on software realization scheme, areas of possible beacon locations could be specified by an interactive user interface and a map projection library.

The task of existing network reconfiguration could also be solved by proposed method by sequentially deleting one of the nodes and considering the network of low functionality with a search for the best place for additional beacons. Thus, proposed approach could be used not only for adding a new node, but also for updating the existing network configuration.

For multiple beacons, there are two strategies that could be applied: the first one is based on sequentially adding each new node to the network. The second one considers

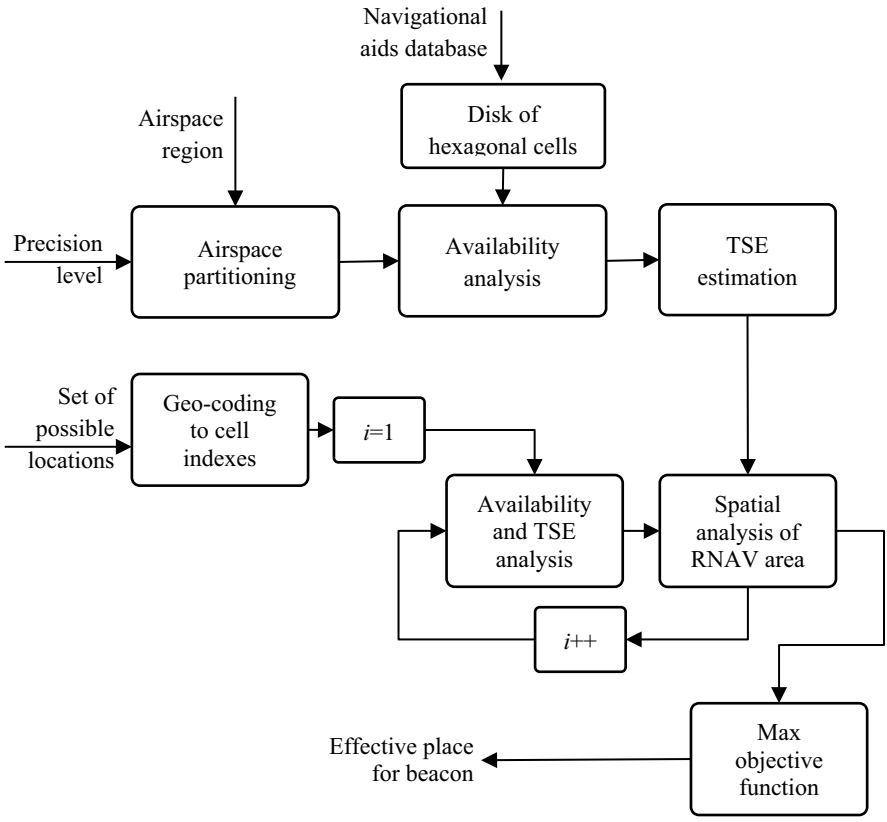

Fig. 2. Structural scheme of proposed algorithm for effective network improvement.

scenes with all possible combinations of beacon injection into the network. The last one is the most precise, but is the most computationally heavy. Both approaches are based on applying the same proposed algorithm, but work with a different set of cell indexes placed on the disks.

It makes sense to run the algorithm several times at a low level of precision first and then with improved precision for results identified in the rough first scanning phase. It works best if potential places for beacons are not specified and the whole area of airspace is considered as possible places for node placement.

4 Navigation Aids Network Improvement

In the numerical case study, the proposed method is applied to optimization of the navigational aids network of Ukraine with the objective of improving overall service coverage. War in Ukraine caused significant impact into configuration of navigational aids network [30, 31]. Due to reduced network functionality in the eastern and southern regions of considered airspace, the analysis focuses on identifying optimal locations for additional beacons in the central part of the airspace, where network enhancements

can provide the greatest overall performance benefit. Ukrainian airspace consists of five FIRs: UKLV, UKBV, UKOV, UKDV, and UKFV. Also, in this task, we consider only DME network with 16 ground beacons placed at different FIRs [32]:

- UKLV: UZH (Uzhhorod), IVF (Ivano-Frankivsk), LIV (Lviv), TER (Ternopil), RVN (Rivne);
- UKBV: VIN (Vinnytsia), SLV (Soloviivka), STB (Stebliv), BRP (Boryspil), KSN (Koshany), YHT (Yahotyn), BAH (Bakhmach), KVH (Kropy);
- UKOV: ODA (Odesa);
- UKDV: KHR (Kharkiv), KVR (Kryvyi Rih).

But this network is a part of neighboring airspace networks: Poland (42 DMEs), Slovak Republic (12 DMEs), Hungary (9 VOR/DMEs), Romania (24 DMEs), Moldova (1 VOR/DMEs), Bulgaria (12 DMEs), and Turkish (60 DMEs).

For practical realization, a software has been developed in JavaScript to validate the proposed algorithm [33]. Software for a browser is a good example of a cross-platform application. In addition, a variety of mapping libraries are available to support easy visualization of geographic data in different map projections. Also, H3 library has a friendly interface for integration in JavaScript solutions. A simple interface has been created to make access to set up network configuration and interact with geographic data. Basic features of software have been developed in PHP with MySQL to host navigational aids database and validate the security reasons for data protection from unauthorized access. All navigation calculations and algorithms are realized in user interface. Modern hardware has made possible to run big data analysis on common equipment. In case of low productivity, the lowest precision level should be used to make time of computation visible.

Results of network availability estimation are given in Fig. 3 for the initial network configuration. Total area of considered region is 790×10^3 km^2. For simulation, we use 7th level of H3 precision with an effective area of cell in 36 km^2. Services of 73 beacons are available in considered airspace. Area of DME service is 740.6×10^3 km^2 (which is above 93% of whole considered airspace).

Results of navigation system error estimation are given in Fig. 4 for initial network performance. In simulation, an area of possible candidates for ground facility installation is given as polygon shape. Restrictions on places for installation are important, because it does not make any sense to run optimization and get places where a ground station cannot possibly be deployed due to physical (terrain or water surface) or legal (restrictions due to private property) reasons. Therefore, specifying a polygonal area (or many areas) is important to get designed results. In our simulation, we consider a scenario of best candidate search for a node in UKDV FIR. And possible locations have been proposed in the vicinity of Dnipro city. Also, considering new places for beacons deployment is important to consider interference environment and the given logistical and technical infrastructure (for example, available power supply and availability of wired communication lines for stable remote connection).

Results of analysis show that in current network configuration, a significant improvement of performance from adding only one additional node could be obtained in the vicinity of Dnipro airport. Identified cell address is “862d64da7ffffff” (with a center point at 48.3605203N, 35.1102016E), which is highlighted by a red circle in Fig. 5.

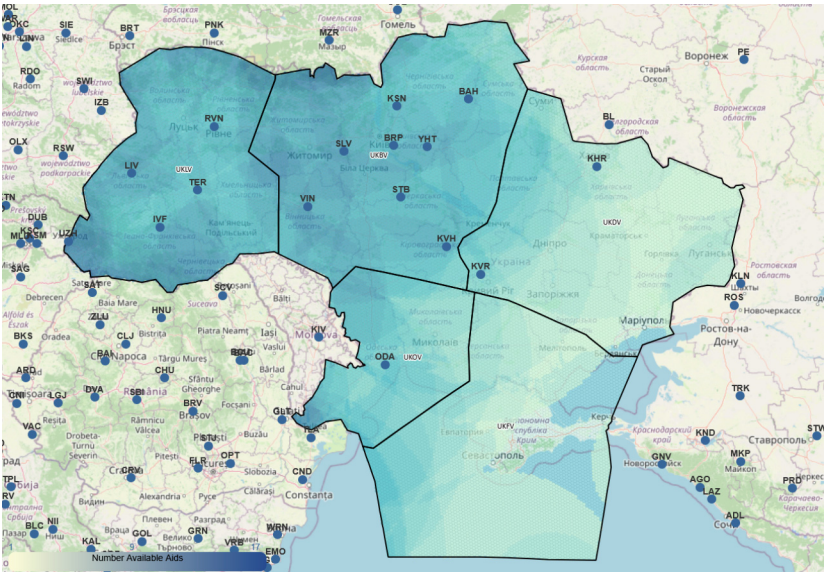

Fig. 3. Results of availability estimation for initial DME network configuration.

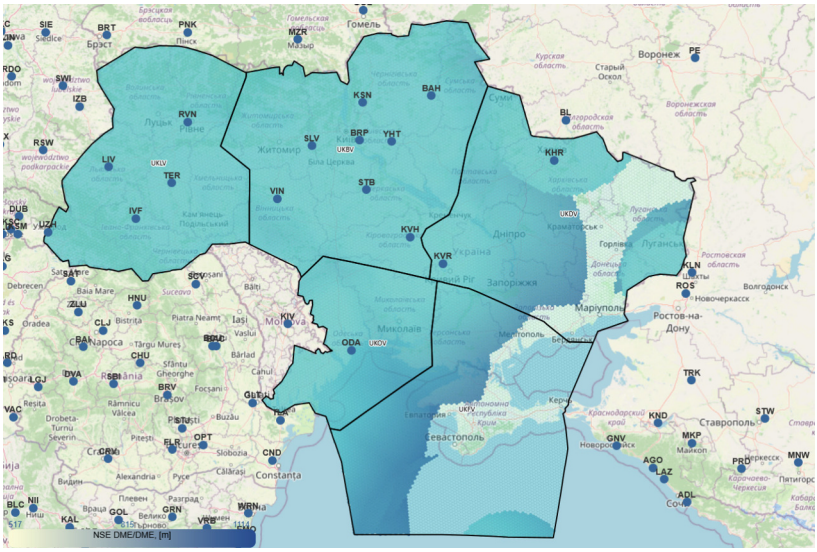

Fig. 4. Initial DME network performance.

Results of estimation of spatial characteristics for current and improved network performance are given in Fig. 6 for availability, and Fig. 7 presents results in navigation system error (NSE).

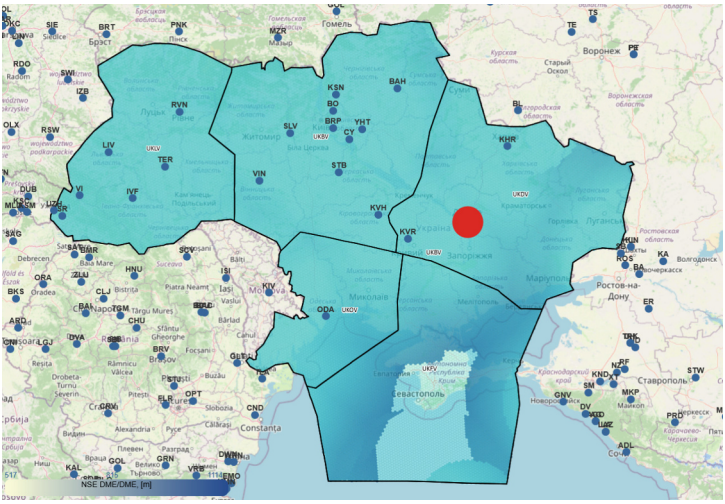

Fig. 5. Identified location of DME.

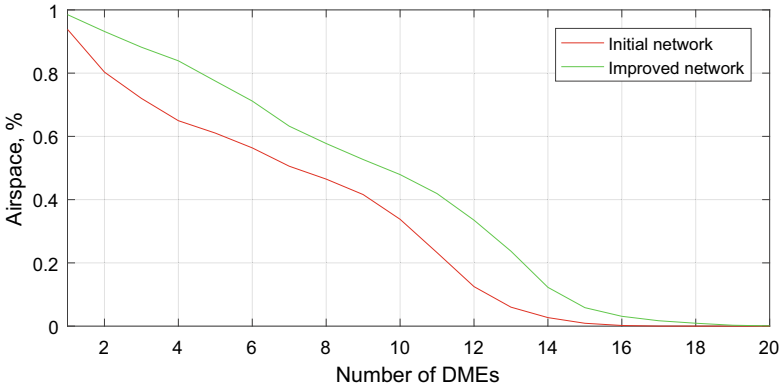

Fig. 6. Results of improved network availability.

Obtained results indicate that placement of only one additional node to the network configuration could result in significant network improvement. The best results could be reached in the peril zones of network when additional DME could be fruitful in the pair formation process. Obtained results show significant improvement in spatial distributions of parameter availability and performance of network service.

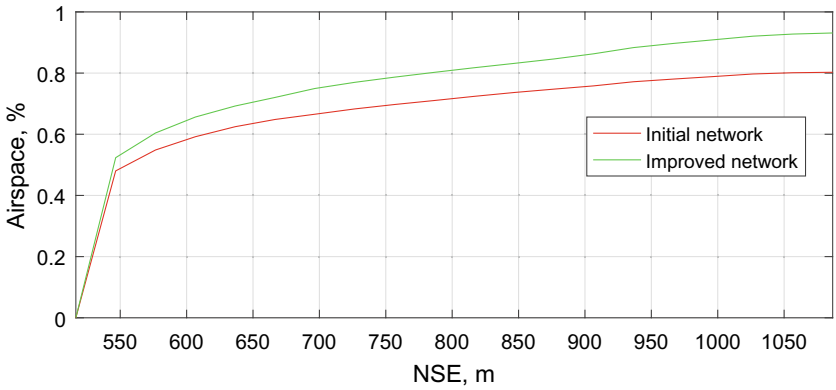

Fig. 7. Results of improved network positioning performance in NSE.

5 Conclusions

Network optimization is one of the core tasks of modern air transportation development in order to improve the safety of civil aviation. Improvement of positioning performance by navigational aids could be reached by adding new nodes in the existing network. H3 library provides a new step in tools for geo-data analysis with easy access to cell properties calculation. In comparison with existing methods, proposed algorithm uses a reduced number of recalculation at each candidate point analysis, which requires recalculation only effected cell with no need for recalculation of the whole grid of cells. In addition, different precision levels of hexagons could be used for rough scanning and precise tuning results.

Results of network improvement depend on quality of existing network configuration. Nodes type and the type of each addition navigation aid have a direct impact on the overall optimization process. Proposed algorithm provides resource efficiency distribution within navigation aids network to support modern trends in civil aviation development.

Practical application of the proposed method for Ukrainian navigational aids improvement shows that one additional node could significantly improve overall network performance for considered polygon of airspace.

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