Implementing GIS for Air Navigation Aids Infrastructure Optimization

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ABSTRACT: Air navigation aids infrastructure for civil aviation is one of the key enablers for implementation of new air navigation concept called Performance Based Navigation (PBN), which will allow more efficient use of airspace and, therefore, increase capacity to accommodate increasing air traffic. To implement PBN, the air traffic service route in the designated airspace must be covered with navigation aids infrastructure to provide adequate navigation performance to aircraft operating in such airspace. Coverage of ground-based navigation aids such as Distance Measuring Equipment (DME) depends on the conditions of the terrain around the installation site. To provide sufficient navigation coverage while being cost efficient, the location and number of the navigation aids equipment has to be optimized taking into account terrain geometry, radio propagation, airport location, and existing navigation aids network. For this reason, Geographic Information System (GIS) plays essential role in determining optimal network of navigation aids equipment.

In this work, GIS platform for navigation aids infrastructure assessment and optimization is developed. The proposed platform enables cooperation between air navigation service provider and airspace users. The main goal is to support navigation aids planning with integrated and flexible tool. The platform is integrated with terrain and obstacle database, navigation aids database, and aeronautical information database (i.e. airspace boundary, air traffic services route, approach and departure procedures.). It is able to assess coverage of existing navigation aids network in 3-dimension in order to detect the coverage gaps. It also identifies obstructing obstacles or terrain. In addition, it optimizes number of additional equipment and associated installation site to satisfy required navigation performance. In this paper, architecture of the proposed GIS platform is described. Methodology to assess coverage of a given DME as well as mathematical formulation and spatial optimization algorithm for navigation aids network planning are presented. Finally, assessment and optimization results for navigation aids network in Thailand is presented and discussed.

1. INTRODUCTION

Navigation aids (NAVAIDs) is one of the most important system that allow aircraft to fly safely from departure to destination airport. Conventional aircraft navigation system relies on the location of ground-based NAVAIDs, such as VHF Omnidirectional Range (VOR), Distance Measuring Equipment (DME) and Instrument Landing System (ILS), to defined path that aircraft has to fly over. The accuracy of conventional navigation is a function of distance from the NAVAIDs.

With improvement of the capability of Flight Management System (FMS) to process navigation signal from multi sensors both ground-based and space-based (GNSS), the accuracy of navigation become much more accurate. This enables aircraft to fly with waypoints which is more flexible in design and more efficient. This new navigation concepted is referred to as Performance Based Navigation (PBN) concept. Figure 1 the conventional route defined by the location of NAVAIDs and splayed protection area and aircraft navigation in PBN concept, which aircraft fly waypoints and protection area is constant. To implement PBN, the air traffic service route in the designated airspace must be covered with navigation aids infrastructure to provide adequate navigation performance to aircraft operating in such airspace.

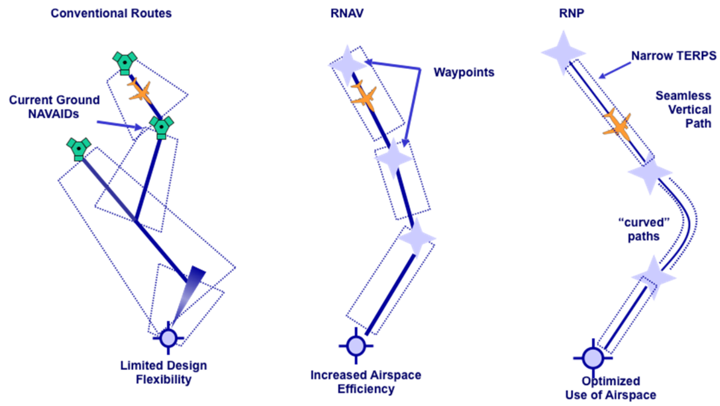


Figure 1 Conventional aircraft navigation and PBN navigation (RNAV and RNP)

Coverage of ground-based NAVAIDs depends on the conditions of the terrain around the installation site. To provide sufficient navigation coverage while being cost efficient, the location and number of the navigation aids equipment has to be optimized taking into account terrain geometry, radio propagation, airport location, and existing navigation aids network. For this reason, Geographic Information System (GIS) plays essential role in determining optimal network of navigation aids equipment.

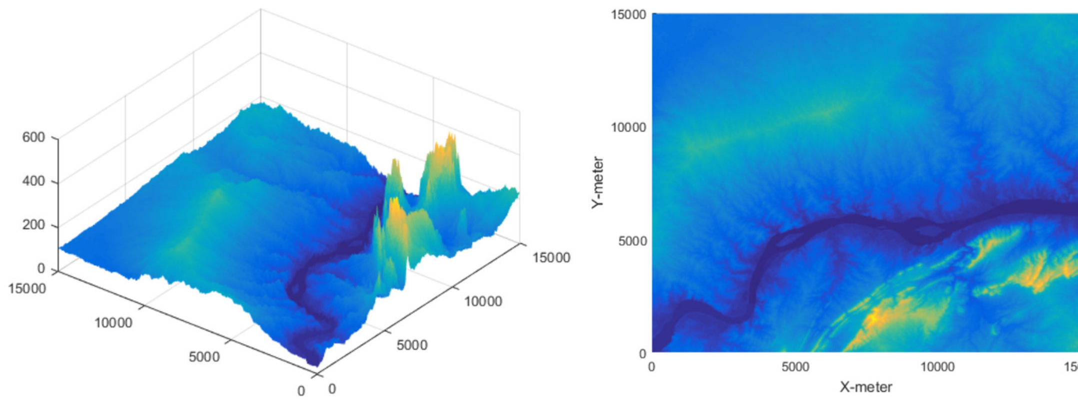
In this work, GIS platform for navigation aids infrastructure assessment and optimization is developed. The proposed platform enables cooperation between air navigation service provider and airspace users. The main goal is to support navigation aids planning with integrated and flexible tool. The platform is integrated with terrain and obstacle database, navigation aids database, and aeronautical information database (i.e. airspace boundary, air traffic services route, approach and departure procedures.). It is able to assess coverage of existing navigation aids network in 3-dimension in order to detect the coverage gaps. It also identifies obstructing obstacles or terrain. In addition, it optimizes number of additional equipment and associated installation site to satisfy required navigation performance. In this paper, architecture of the proposed GIS platform is described. Methodology to assess coverage of a given DME as well as mathematical formulation and spatial optimization algorithm for navigation aids network planning are presented. Finally, assessment and optimization results for navigation aids network in Thailand is presented and discussed.

2. RADIO FREQUENCY (RF) COVERAGE PREDICTION FOR A GROUND-BASED NAVIGATION AIDS

In this section, the numerical computational subroutine program to find the line-of-sight area between an airplane and around the navigation base station on an actual terrain in Thailand will be proposed. An altitude of an airplane, location of the navigation base station and real terrain data will be inserted into the proposed subroutine program. Moreover, the radio frequency (RF) propagation prediction subroutine will be implemented to find the radio frequency (RF) level of each an airplane location to ensure that the communication signal is enough. The electromagnetic field in the case of line-of-sight propagation will be focused in this paper. The computational of EM diffracted wave will be ignored in this paper. However, the EM diffracted wave at shadow zone will be added later.

2.1. Line-of-sight and shadow area searching.

In this section, the proposed algorithm to find the line-of-sight and the shadow area is proposed. The display of terrain, a line-of-sight and a shadow area calculation are performed by using MATLAB program. Firstly, the sampling actual terrain data in Thailand is loaded in to the subroutine. An sampling terrain data of 6,001x6,001 cells (block pixel) with the size of each cell of 30 meters are employed. The height above sea level of each cell represents the actual terrain surface. Figure 1 shows an example of sampling terrain data of 500x500 cells or 225 km^2 area. The perspective and top view are shown in Figure 2 (a) and Figure 2 (b), respectively.



(a) (b)

Figure 2 Example of sampling terrain data of 500x500 cells or 225 km^2 area (a) The perspective (b) top view

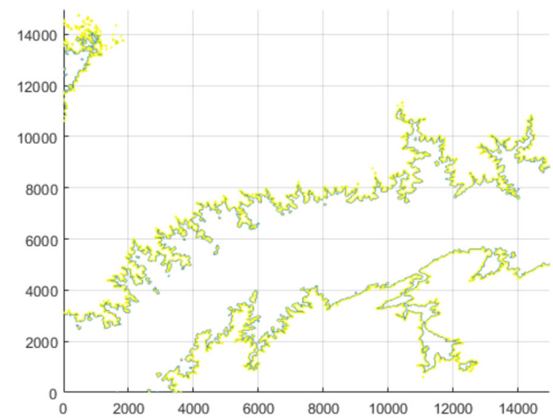
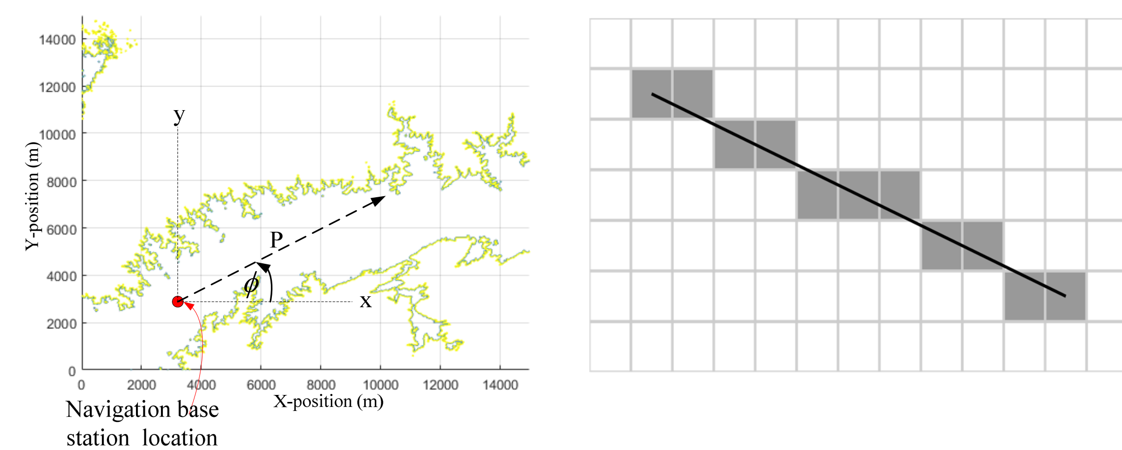


Figure 3 Contour area of mountain at an airplane flight altitude of 100 meters



(a) (b)

Figure 4 3D grid based line-of-sight search algorithm (Tx location and parameter) (b) Bresenham's line algorithm [2].

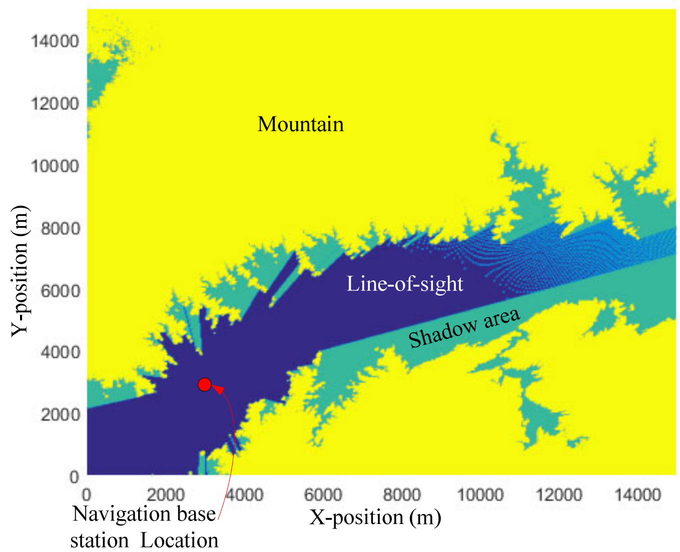


Figure 5 Results of the proposed searching subroutine of an airplane flight altitude of 100 meters.

In this paper, an example of airplane flight altitude of 100 meters is selected. Assumed navigation base station (X-position and Y-position) at data block of P(50,50) and P(100,100) are employed. In this case, the contour area of mountain at an airplane flight altitude of 100 meters is obtained by using the proposed searching subroutine as shown in Figure 3. Moreover, the line-of-sight area and shadow area will be calculated by using 3D grid based line-of-sight search algorithm namely Bresenham's line algorithm [2]. Figure 4 shows the 3D grid based line-of-sight search algorithm [2]. Parameter ϕ denote the azimuth scanning angle and P denotes the straight line between above base station location and an airplane at flight altitude of 100 meters. Bresenham's line algorithm selects the integer y corresponding to center of each pixel. It is closest to the ideal straight line as shown in Figure 4 (b). The slope of the line can be written as

$$m = \frac{\Delta y}{\Delta x} = \tan(\phi) \tag{1}$$

where the straight line equation can be written as

$$y = mx + b \tag{2}$$

By varying the parameter ϕ and x, the parameter y will be calculated by using Eq. 2 The searching process will be stopped at the terrain block pixel

Yellow color represents the mountain area (dangerous zone). Dark blue color represents the line-of-sight area (strong RF communication). Light blue represents the shadow area (weak RF communication).

2.2. EM WAVE PROPAGATION IN LINE-OF-SIGHT AREA

High frequency methods such as the Uniform Geometrical Theory of Diffraction (UTD), Physical Optic (PO) and other. Actually, those solutions are based on ray approximation. The UTD method [3] (i.e. High frequency method) is suitable for path-loss prediction of large communication area than other numerical methods. The prediction of the electromagnetic (EM) wave radiation (Line-of-sight) and scattering via the UTD method becomes very useful and important in solving problems related to network planning of modern radio wave communication systems. However, The electromagnetic field in the case of line-of-sight propagation will be focused in this paper. EM diffracted wave will be not included in this paper. In the line-of-sight area, the EM field can be calculated as

$$\bar{E} = \bar{E}^i + \bar{E}^d \tag{3}$$

where

$$\overline{E} = -jkE_0 \frac{e^{-jkR}}{R}, \tag{4}$$

where $\overline{E}$ denotes an complex electric field (V/m). $\overline{E}^i$ denotes an incident field of line-of-sight field. $\overline{E}^d$ denotes the diffracted field. The R denotes the distance between the base station and airplane. An example of calculated EM wave propagation in line-of-sight area in the case of cut plane height of 100 m and area of 500 x 500 cells with the cell size = 30 meters and the base station located at cell x=100 and y = 100 are shown in Figure 4. Normalized EM field shown that the EM field decays rapidly as a function of distance. Other example, EM field at cut plane height of 85 m and area of 500 x 500 cells with the cell size = 30 meters and the base station located at cell x = 50 and y = 50 are shown in Figure 5. Also, EM field at cut plane height of 85 m and area of 500 x 500 cells with the cell size =30 meters and the base station located at cell x =233 and y =166 are shown in Figure 6.

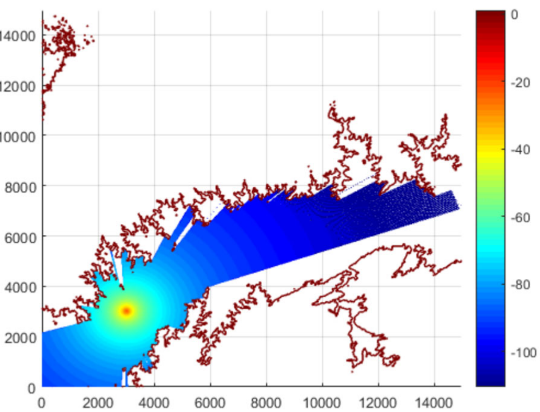
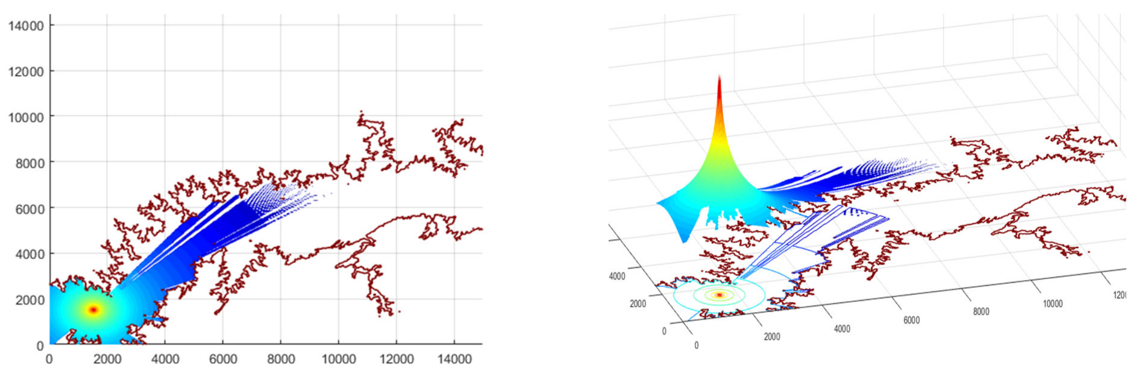


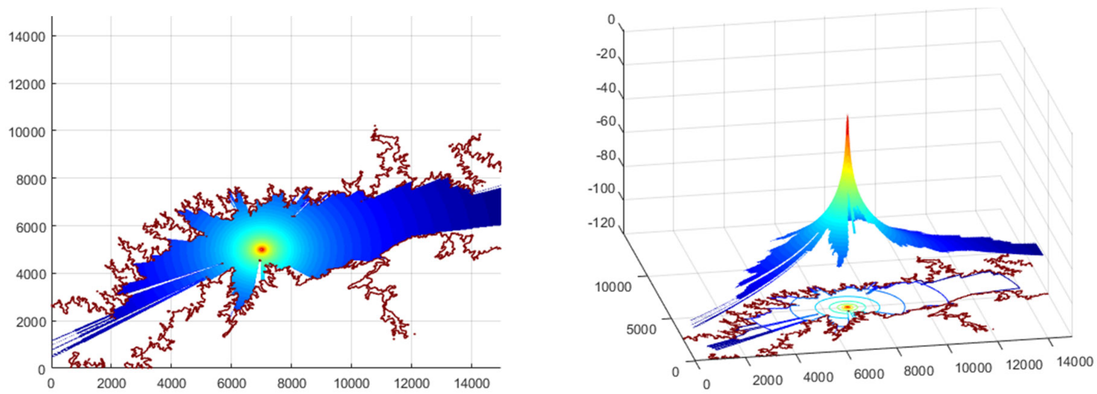
Figure 6 Calculated EM field of cut plane height of 100 m and area of 500 x 500 cells with the cell size = 30 meters. The base station located at cell x = 100 and y = 100.



(a)

(b)

Figure 7 Calculated EM field of cut plane height of 85 m and area of 500 x 500 cells with the cell size = 30 meters. The base station located at cell x = 50 and y = 50 (a) top view (b) perspective view.



(a) (b)

Figure 8 Calculated electric field of cut plane height of 85 m and area of 500x 500 cells with the cell size =30 meters. The base station located at cell x = 233 and y = 166 (a) top view (b) perspective view.

Finally, the proposed algorithm to find the line-of-sight and the shadow area is completed. The contour of EM line-of-sight field is mapped into the actual terrain data to provides a high accuracy of EM field information over the terrain. The weak communication area namely a shadow area is illustrated. The proposed subroutine program will be useful for the distance measuring equipment (DME) system.

3. OPTIMIZATION OF NAVAIDS INFRASTRUCTURE

To provide navigation service in PBN context, the airspace must have sufficient coverage of navigation signal according to requirements of the International Civil Aviation Organization (ICAO). The use of navigation system for PBN implementation can rely on a combination of VOR and DME that installed at the same location, denoted VOR/DME, which aircraft FMS compute their coordinate based on its range and radial angle from the VOR /DME. However, VOR/DME has limitation due to low accuracy of radial angle measurement. Another system that are used is to use two DME-s to determine coordinate of aircraft, denoted DME/DME. This method provides navigation accuracy about 1 km. In this work, we focus on the coverage of ground-based NAVAIDs, which depends on the conditions of the terrain around the installation site. To provide sufficient NAVAIDs coverage while being cost efficient, the location and number of the navigation aids equipment has to be optimized taking into account terrain geometry, radio propagation, airport location, and existing navigation aids network.

In this preliminary study, we consider the airspace at any given flight level (FL) as 2D grid where a_s is the airspace discretization step size. The input of the problem are:

- Air route network. The NAVAIDs system shall cover the route network in order to ensure the accuracy of navigation all along flight trajectory.
- Terrain data that provides altitude information at each 2D grid. In this work, the terrain data is in the form of Digital Elevation Model (DEM) with resolution of 30 meter. Therefore, we set the airspace discretization step a_s = 30 m.
- In reality, the installation site is limited due to accessibility, land ownership, lack of basic infrastructure, etc. Let $S=\{1,2,\ldots,K\}$ be the set of possible installation site, where N is the maximum number of installation site.
- Maximum coverage of each ground station. Each NAVAIDs equipment has different maximum coverage. This information is required for the determination of coverage.

The objectives of the optimization is to minimize the cost related to number of ground-based station. The decision variables are the number of ground-based station and the location of each ground-based station. In this case, we assign a binary decision variable s_i to each possible installation site such that $s_k = 1$ if the candidate station k is selected, 0 otherwise, $s_k \in S$.

The constraints that should be taken into consideration are:

- The route network must be covered by the signal from at least 2 installation sites all along the route. Let a_{ij} be the variable such that a_{ij} = 1 if the route network intersect with grid (i,j). Let c_{ij} be the number of ground station sites that its signal covers grid a_{ij}, therefore when $a_{ij} = 1$, $c_{ij} \geq 2$.

The formulation of our problem is the following:

$$\min_{s} \sum_{k=1}^{K} s_k$$

subject to

$$a_{ij}.c_{ij} \geq 2, \quad \forall i, \forall j$$

$$s_k = \begin{cases} 1, & if\ site\ k\ is\ selected \\ 0, & otherwise \end{cases}$$

Figure 9 illustrate the example of 2D grid airspace with possible installation site. The red circle shows maximum coverage area when the terrain obstruction is not considered. The light orange shows the grid that are covered by the signal and the dark orange shows the grid that are covered by signal from more than one station.

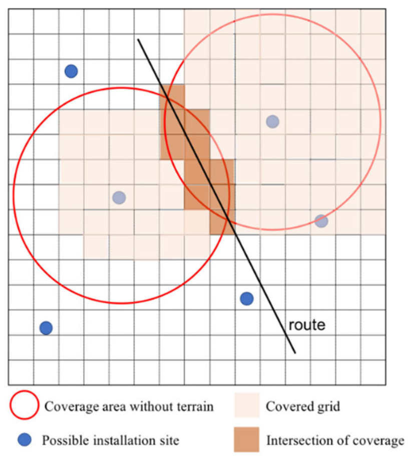


Figure 9 Example of grid airspace with candidate installation sites and signal coverage.

In this preliminary study, we test the proposed methodology with toy problem considering the airspace of Thailand with number of candidate installation site *K=6*. The maximum coverage of each station is set to 200 Nm. The route is simplified to be a straight line. The algorithm determines the DME station that must be installed in order to ensure coverage over the route as shown in Figure 10.

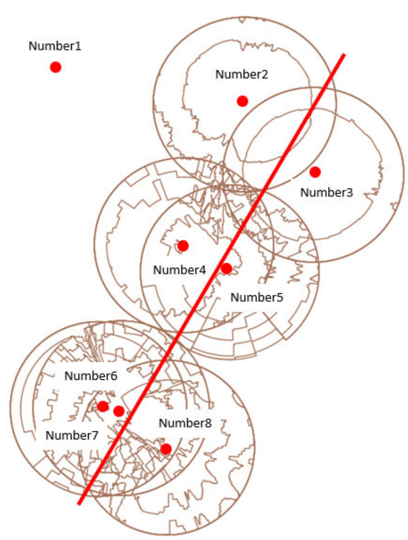


Figure 10 Experimental results.

4. CONCLUSION

In this work, a GIS platform for navigation aids infrastructure assessment and optimization is developed. The proposed platform is able to determine coverage of ground-based NAVAIDs station such as VOR, DME. An optimization tool to determine the number and location of NAVAIDs to be installed in order to cover the route is developed and preliminary result is presented. In the following of this work, the coverage assessment and optimization algorithm will be tested with realistic data and route network considering different navigation specification such as RNAV 1, RNAV 5, and RNAV 10. In addition to the number of station covering the route, the accuracy of the navigation also depends on the angle from the station, which will be taken into account in the future work.

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