National Aviation University of Ukraine
Air Navigation Systems Department

Performance analysis of positioning system by navigational aids in three dimensional space

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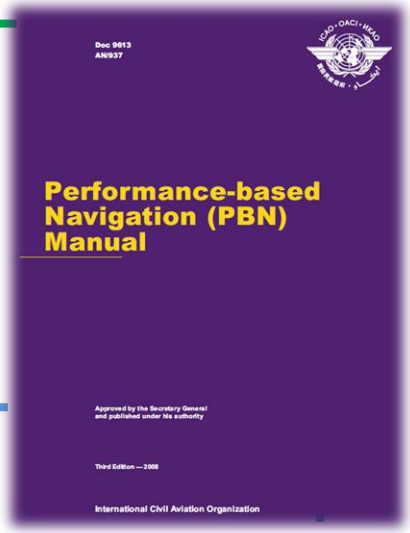
Aircraft on-board equipment for positioning

Global Navigation Satellite System
(GPS, GLONASS, GALILEO, BeiDou)

Inertial Navigation System
(IRS, AHRS)

Compatible
with PBN
(RNAV 1)

ICAO
DOC 9613



Position detection by pair of DME (DME/DME)

Position detection by pair of VOR and DME (VOR/DME)

Positioning by Navigational Aids in Flight Management System

Errors of Global Navigation Satellite Systems

- large spatial variation in ionospheric delay
- **Interference from ground based radio equipment**
- **jamming of radio waves**
- Refraction from obstacles (multipath error)
- Geometric factor of the satellite segment

Interchange of NAVAIDS data of on-board equipment

Flight management system

DME A

DME B

VOR A

VOR B

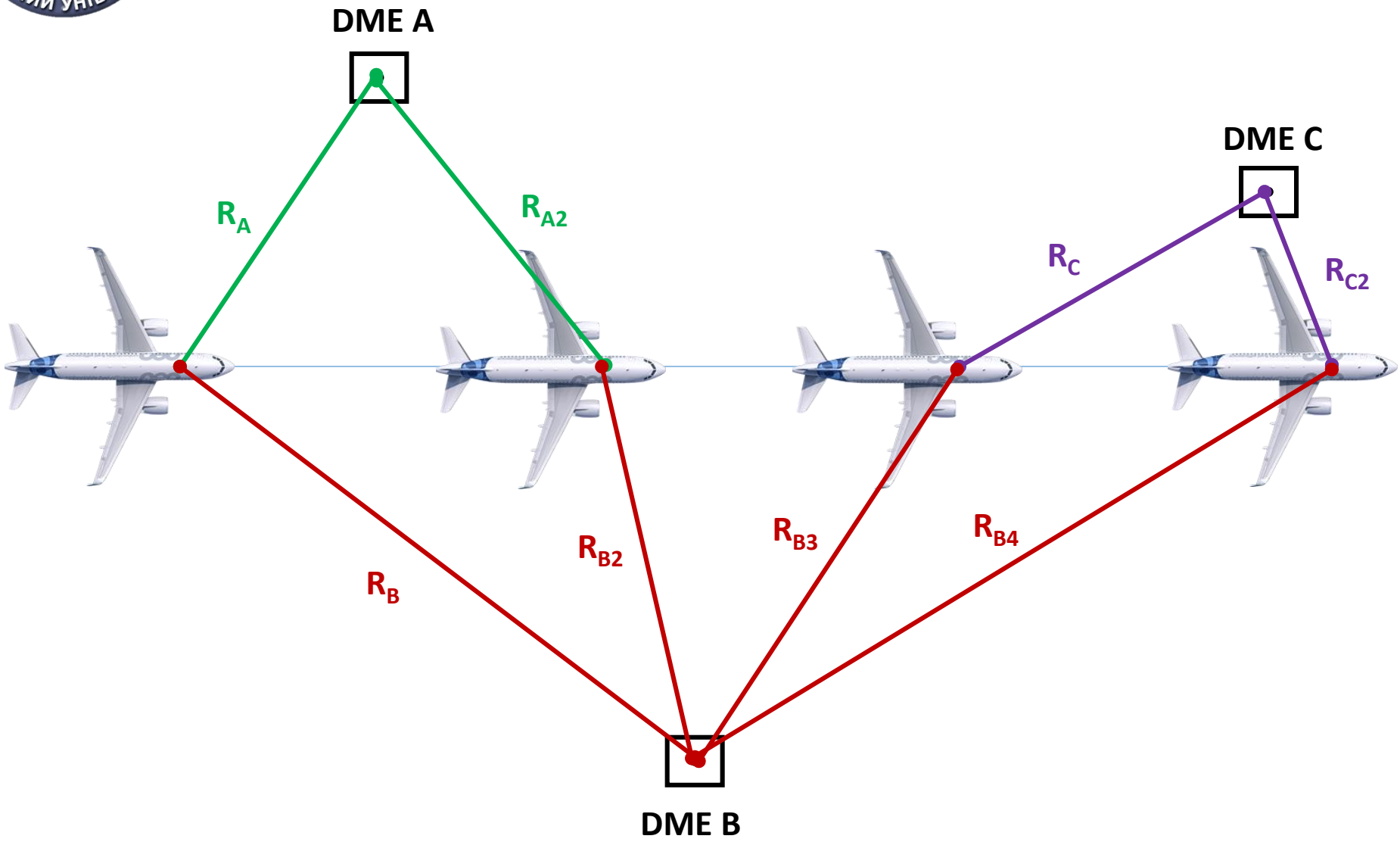
ADF A

ADF B

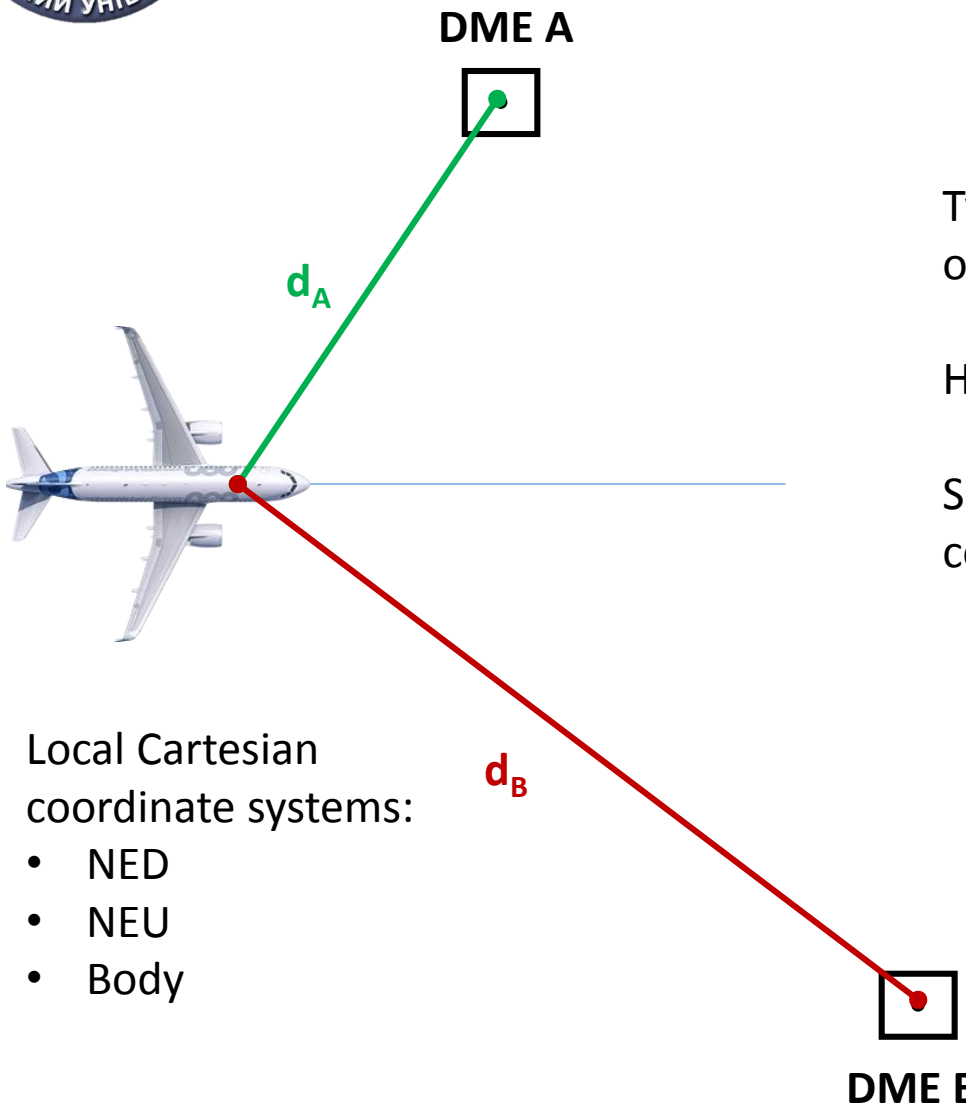
Radio management panel

Only pair of DME/DME equipment is in use for positioning function.

DME/DME



DME/DME (TOA) positioning method



Two ranges from Two DMEs support only Lateral Navigation (LNAV)

Horizontal distances are used for LNAV

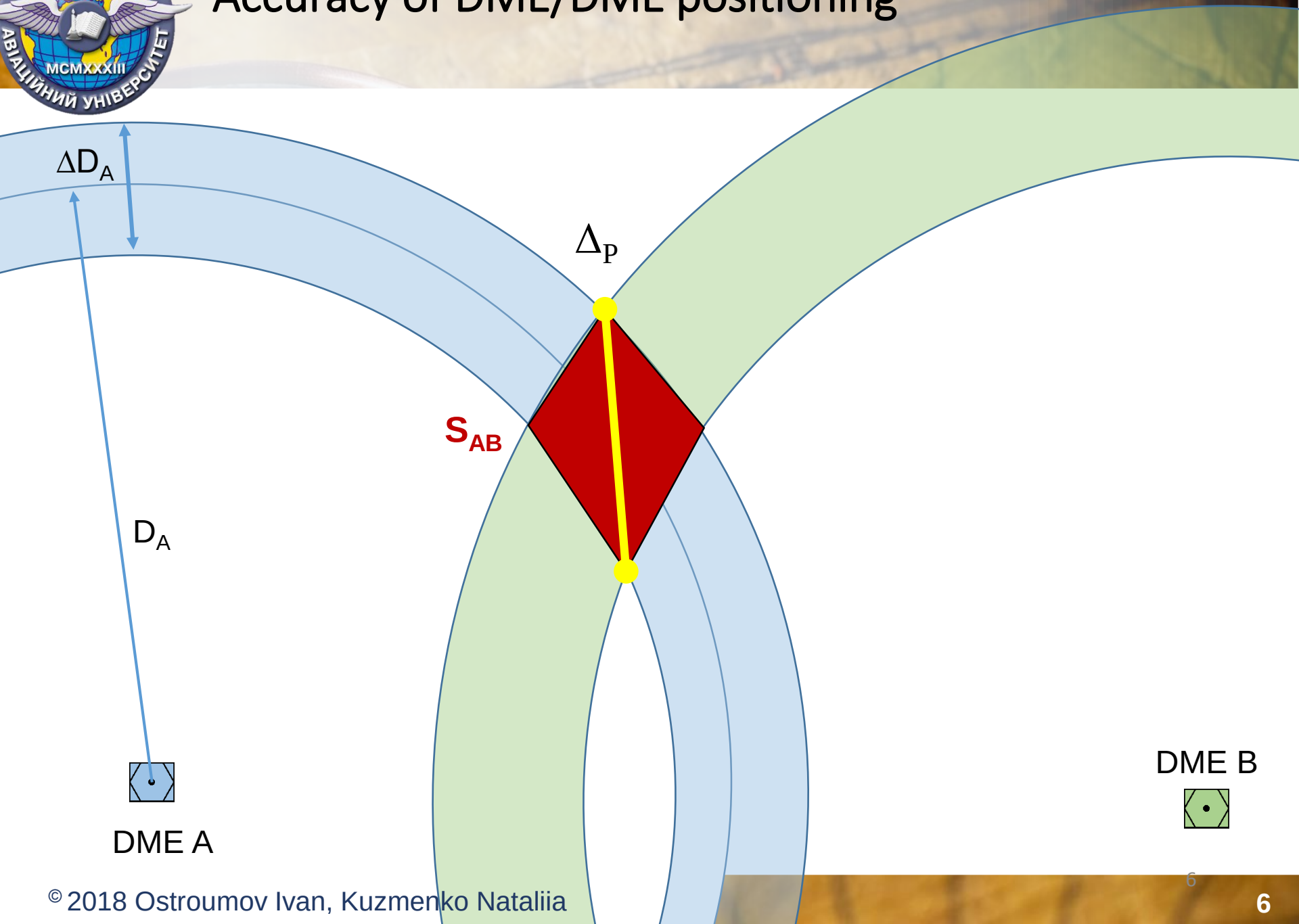
Slant ranges from DME (d) should be converted to horizontal one (d_h)

Local Cartesian coordinate systems:

- NED
- NEU
- Body

$$\begin{cases} d_{hA}^2 = (x_{DMEA} - x)^2 + (y_{DMEA} - y)^2 \\ d_{hB}^2 = (x_{DMEB} - x)^2 + (y_{DMEB} - y)^2 \end{cases}$$

Accuracy of DME/DME positioning



Accuracy of DME

$$\sigma_P = \frac{\sqrt{\sigma_{DMEA}{}^2 + \sigma_{DMEB}{}^2}}{sin(\alpha_{AB})}$$

$\sigma_{DMEA,B}{}^2 = \sigma_{sis}{}^2 + \sigma_{air}{}^2$

$\sigma_{sis}{}^2$ – Signal in space error

$\sigma_{air}{}^2$ – Error of airborne interrogator

σ_{sis} = 0.05 NM

RTCA DO-189:

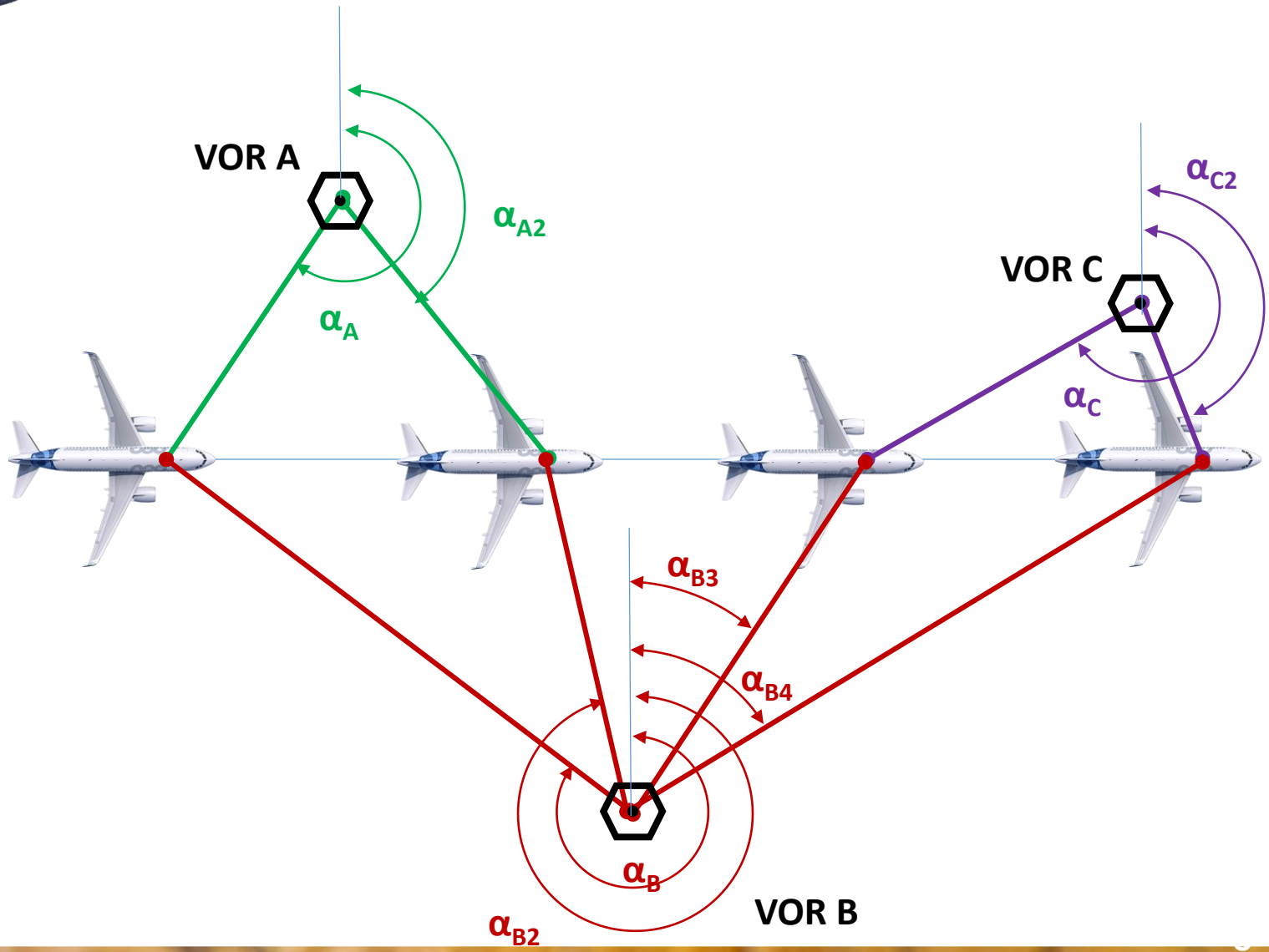
σ_{air} = 0.085 NM

AC90-100A and ICAO DOC-9613:

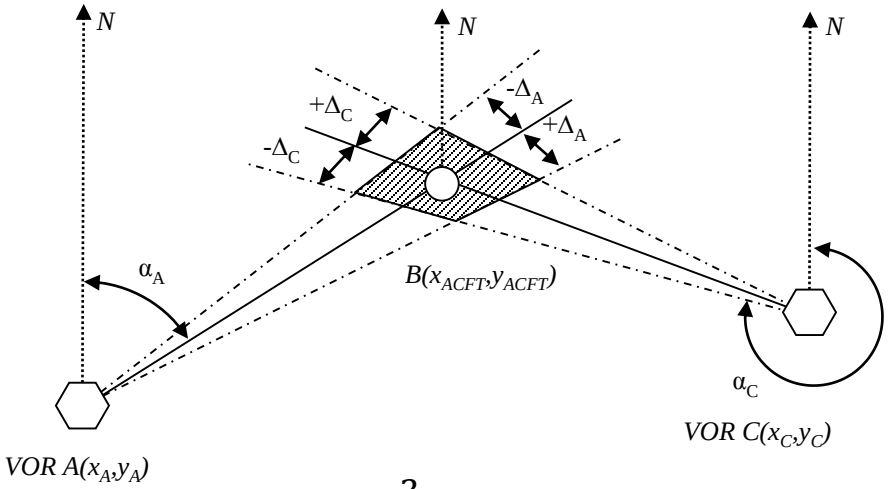
σ_{air}=max{0.085NM; 0,125% R},

$$\sigma_P = \frac{\sqrt{2\sigma_{sis}{}^2 + \sigma_{airA}{}^2 + \sigma_{airB}{}^2}}{sin(\alpha_{AB})}$$

VOR/VOR



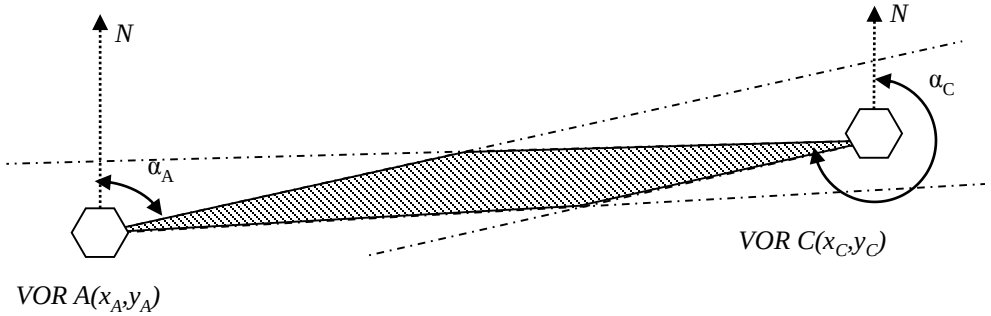
Error of positioning in VOR/VOR

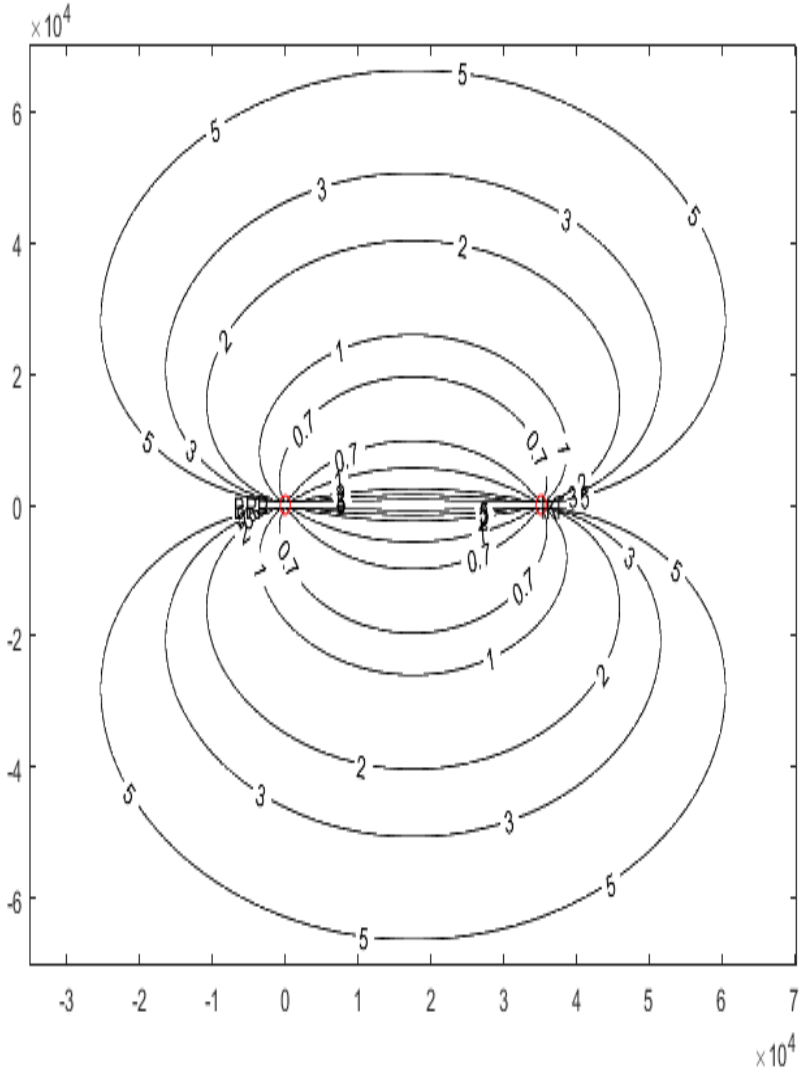


$$\sigma_p^2 = \frac{\sigma_\alpha^2}{sin^2\,(\alpha)}(d_A^2 + d_B^2)$$

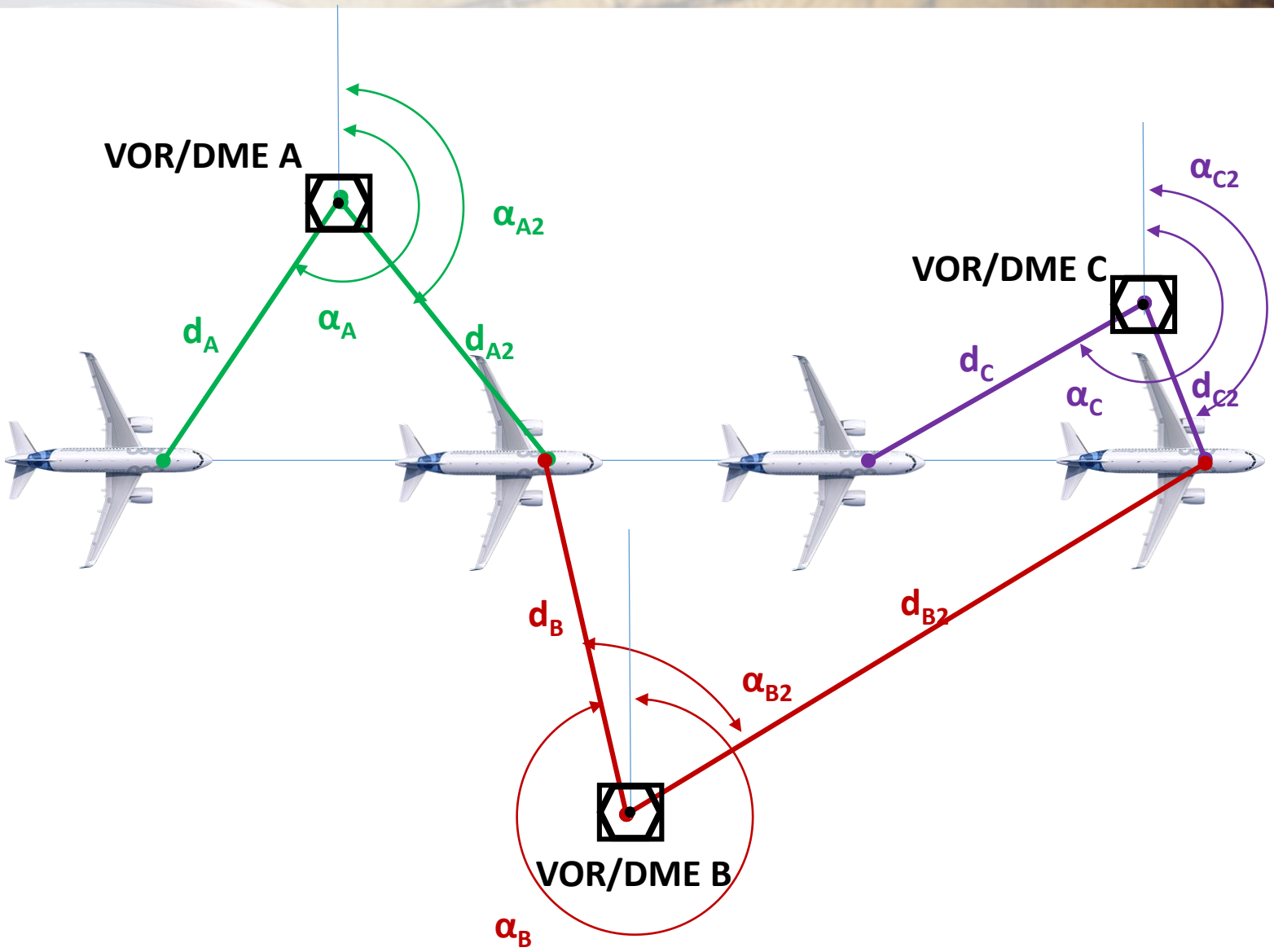
Where:

$$d_A = \frac{d\,\sin(\alpha_B)}{\sin(\alpha_A + \alpha_B)} \qquad d_B = \frac{d\,\sin(\alpha_A)}{\sin(\alpha_A + \alpha_B)}$$

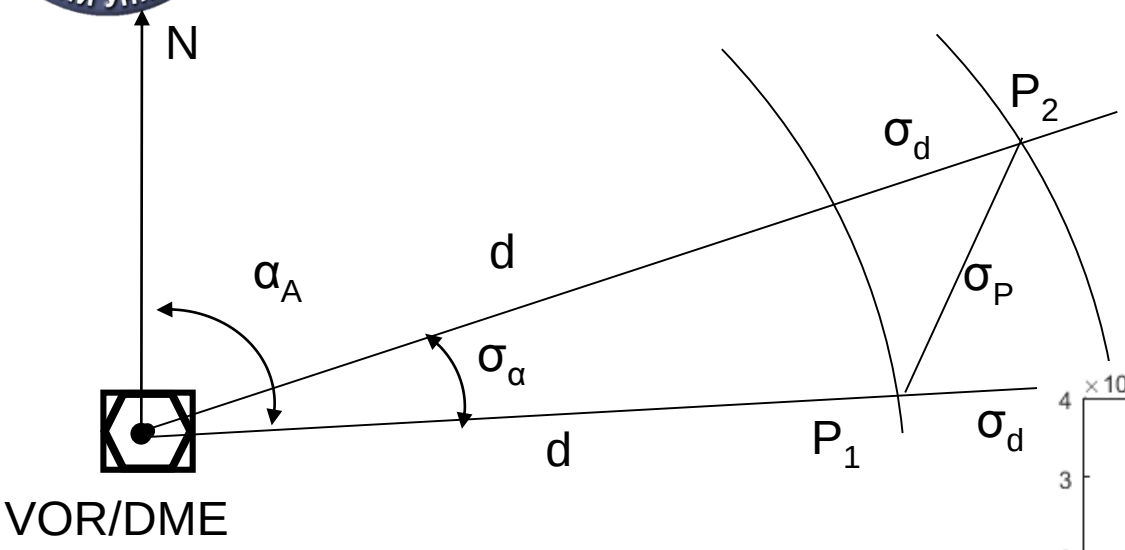




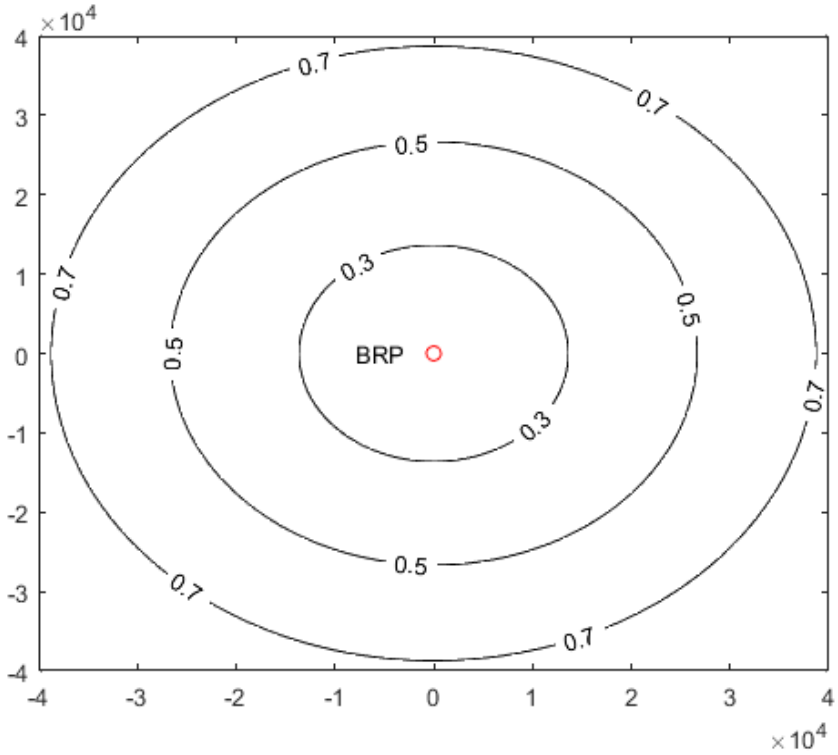
VOR/DME



Error of positioning in VOR/DME



$$\sigma^2_p = \sigma^2_{DME} + D^2\sigma^2_{VOR}$$



Standard Service Volumes

Ground stations classification

T (Terminal)

From 1000 feet (305 m) AGL up to and including 12,000 feet (3,658 m) AGL at radial distances out to 25 nm (46 km).

L (Low Altitude)

From 1000 feet (305 m) AGL up to and including 18,000 feet (5,486 m) AGL at radial distances out to 40 nm (74 km).

H (High Altitude)

From 1000 feet (305 m) AGL up to and including 14,500 feet (4,420 m) AGL at radial distances out to 40 nm (74 km).

From 14,500 feet (4,420 m) AGL up to and including 60,000 feet (18,288 m) at radial distances out to 100 nm (185 km).

From 18,000 feet (5,486 m) AGL up to and· including 45,000 feet (13,716 m) at radial distances out to 130 nm (241 km).

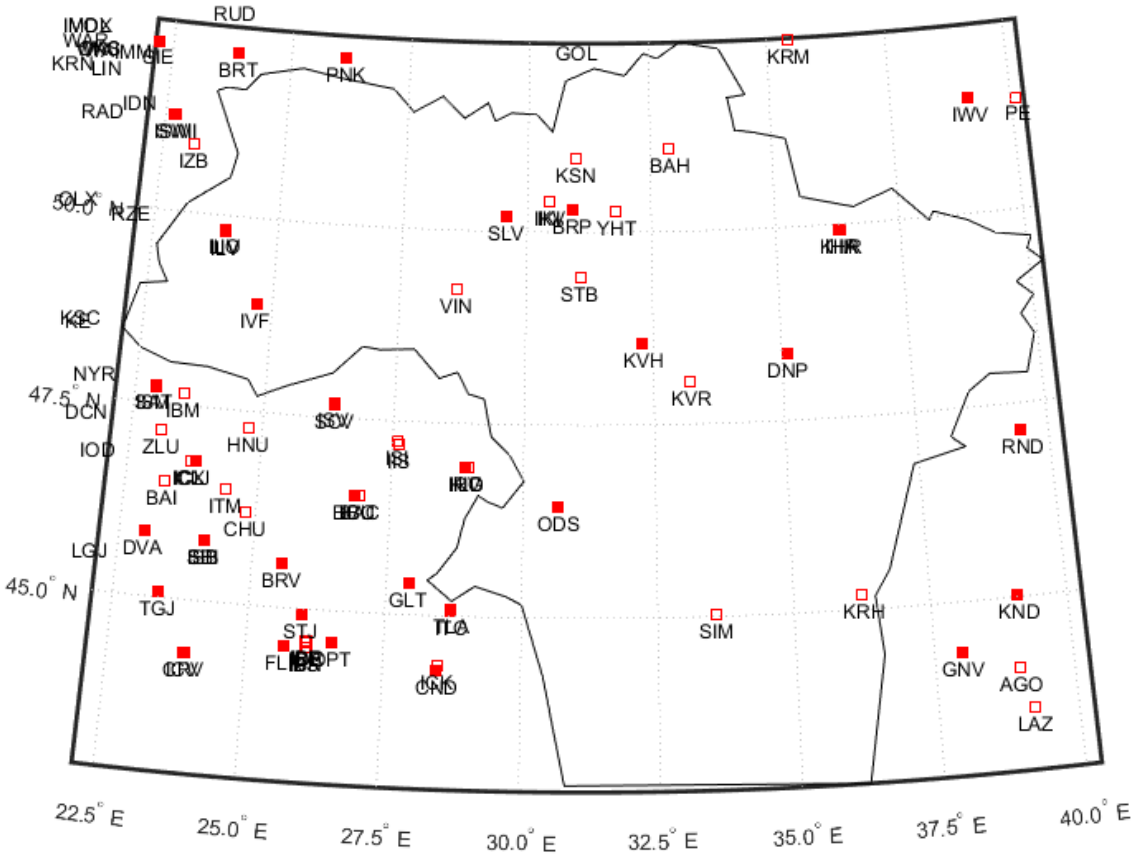
AGL – Above Ground Level

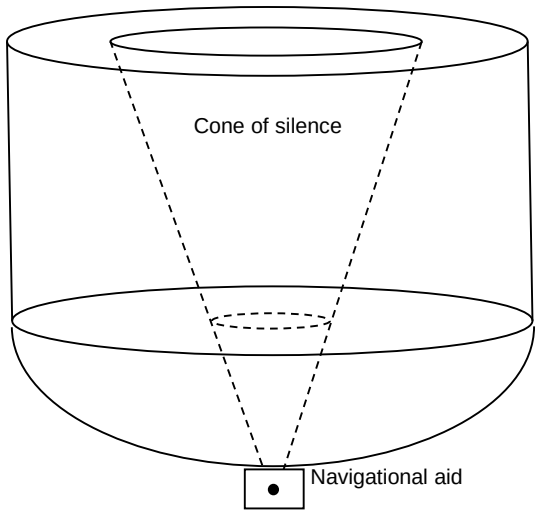
FAA AC 00-31A

Ukrainian National Navigation Aids Network

DME: BAH, IHA, IHR, IKI, IKV, KSN, KVR, ILO, ILV, STB, VIN, YHT

VOR / DME: BRP, DNP, IVF, KHR, KVH, LIV, ODS, SLV



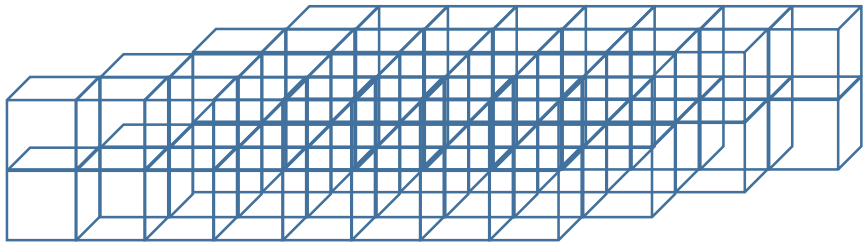


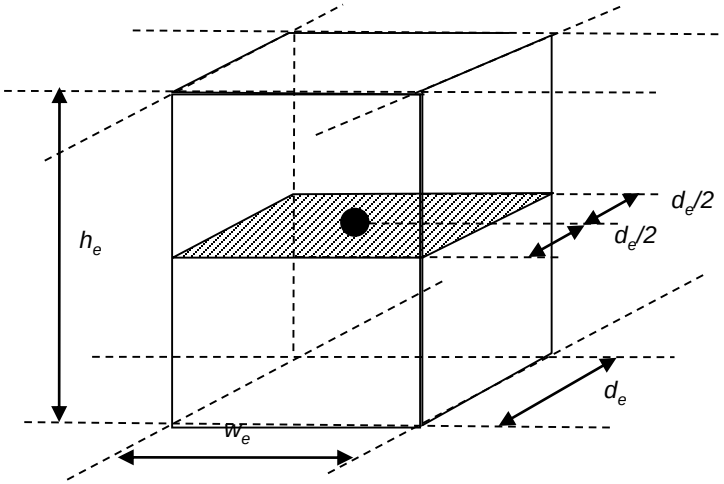
Standard service volume of Terminal navigational aid

Performance estimation

1. Iterative approach with dividing air space into elementary cell
2. Area of investigated airspace is 853412,1 k km^2
3. Models of NAVAIDS service volume estimation
   - Cylindrical models by AC 00-31A, + approach, + en-route
   - Radio waves propagation; for antenna “dbs5100” DME; relief model included
   - DEM: SRTM (February 11-22, 2000) 3 arc sec (possible 1 arc sec)

6. Altitudes from ground up to FL 610 that corresponds to the highest flight level used for civil air traffic





Data fusion

Fusion of simulation results into a single space model is possible according to one of three approaches

A. Construction of a space model in the form of a set of elementary cells (usually cuboids). The main disadvantage of this method of space representation is a big amount of elementary cells, which complicates computation and leads to difficulties in visualization.
B. Selection of groups of adjacent elementary cells and approximation of their contour by surface. However, it is quite complicated task for computation, since increasing accuracy of calculations can lead to internal holes that are difficult to be separated from contours of a cell group.
C. Construction of a space model by the method of contour layers is the most optimal method of three-dimensional simulation. It is based on altitude layer consideration with the allocation of contour lines corresponding to certain conditions with subsequent approximation of the group of contour lines at different layers by a surface.

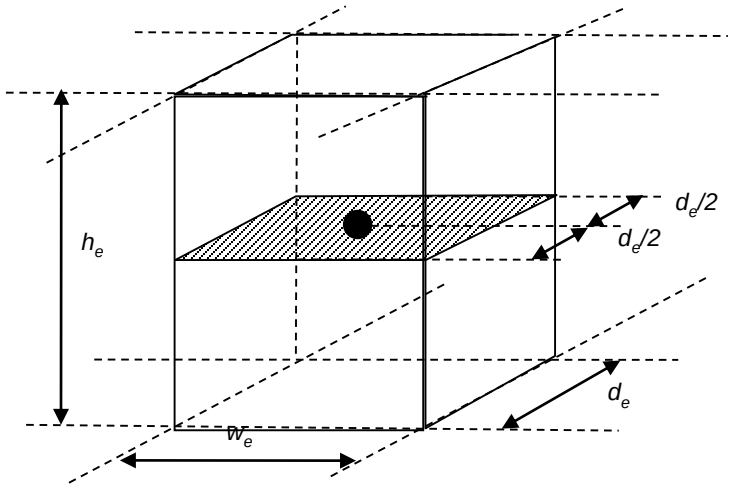
Verification

cell size :

d_e=6.77 km, w_e=4.97 km, h_e=177 m.

Horizontal plane includes 25354 elementary cells with 100 altitude layers within Ukrainian airspace.

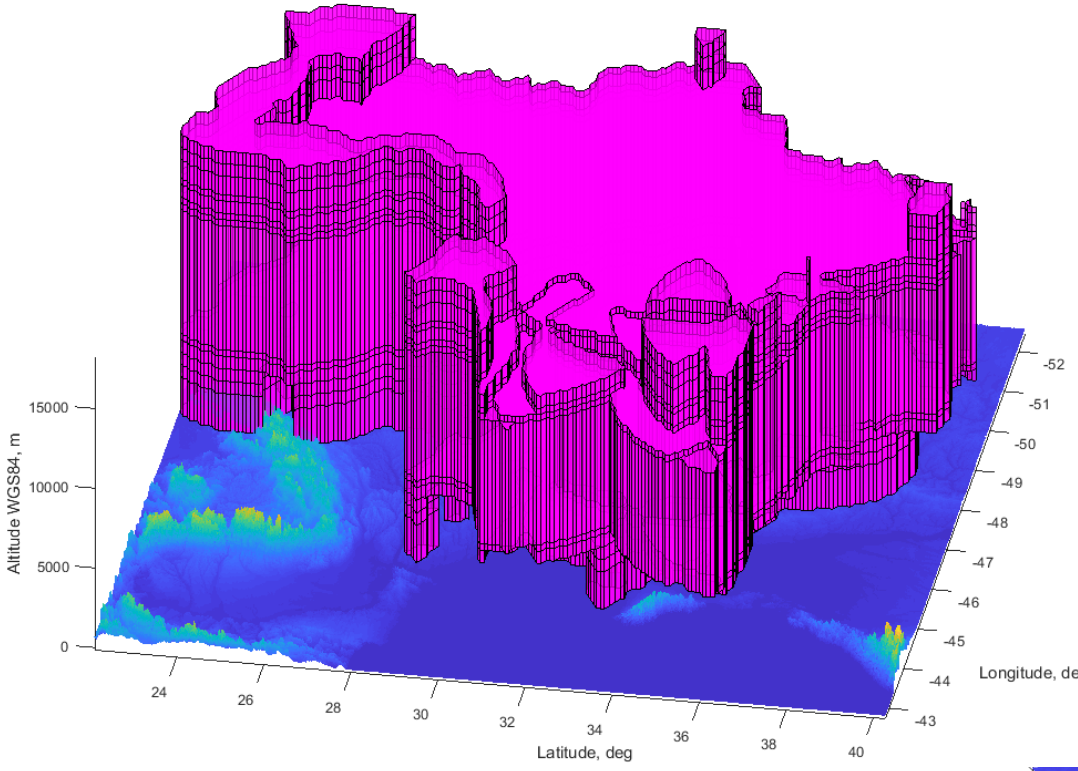
Total area of Ukrainian territory is 8.5×10^5 km^2 and 1.5×10^7 km^3 of airspace volume.



Results of performance analysis of Ukrainian airspace according to area navigation specifications for different positioning approaches in percentage of space volume

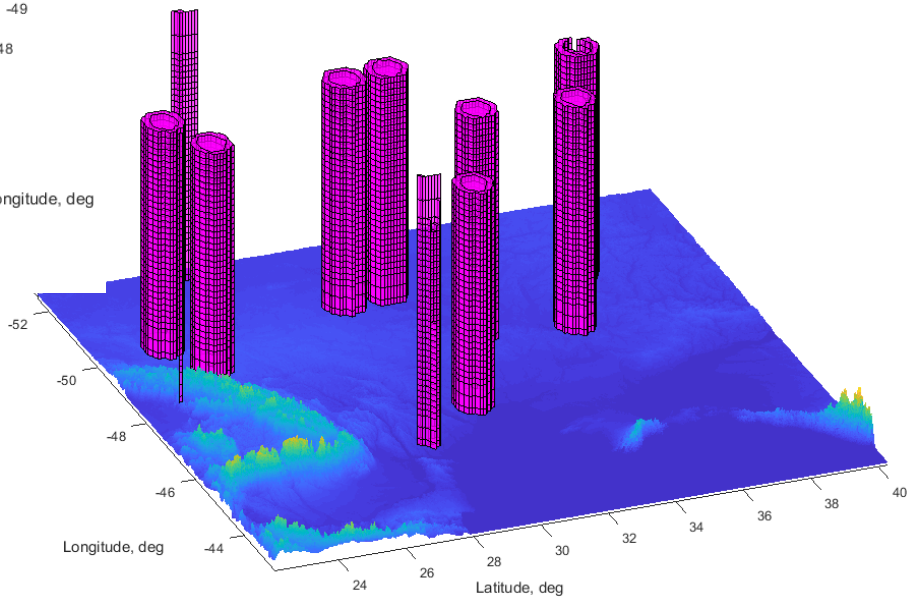
RNAV	DME/DME	VOR/DME	VOR/VOR
RNAV 1	74.6%	4.58%	0%
RNAV 2	74.78%	26.64%	0.78%
RNAV 5	74.78%	70.38%	32.5%

Verification RNAV 1

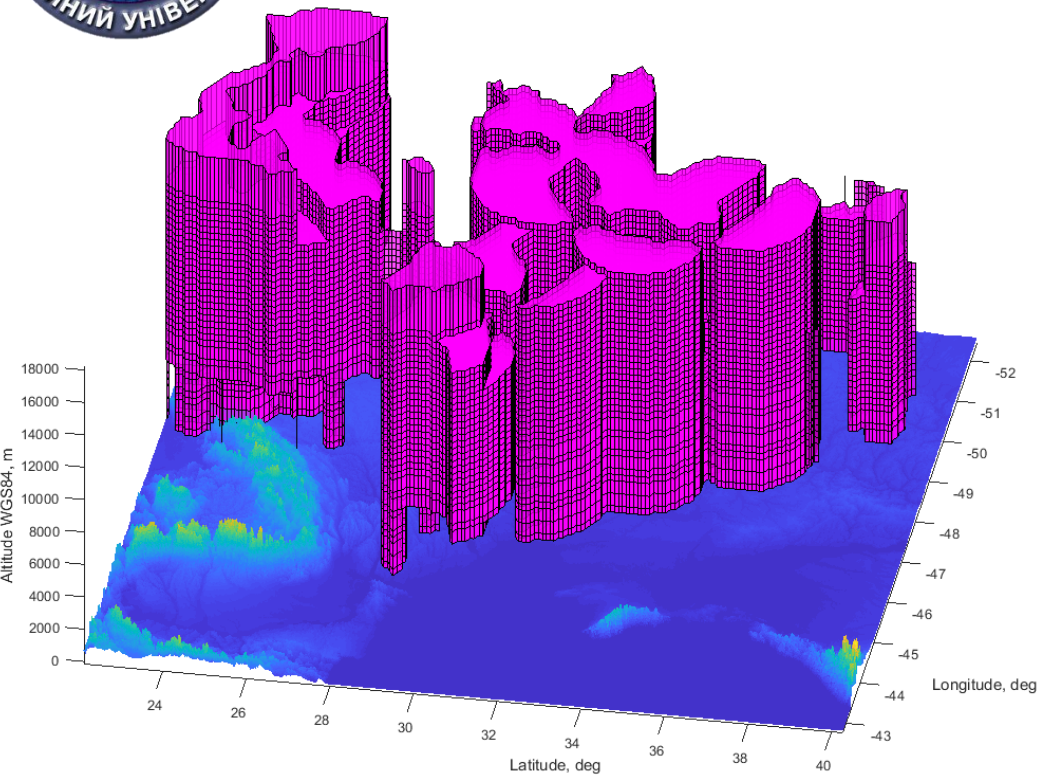


DME/DME

VOR/DME

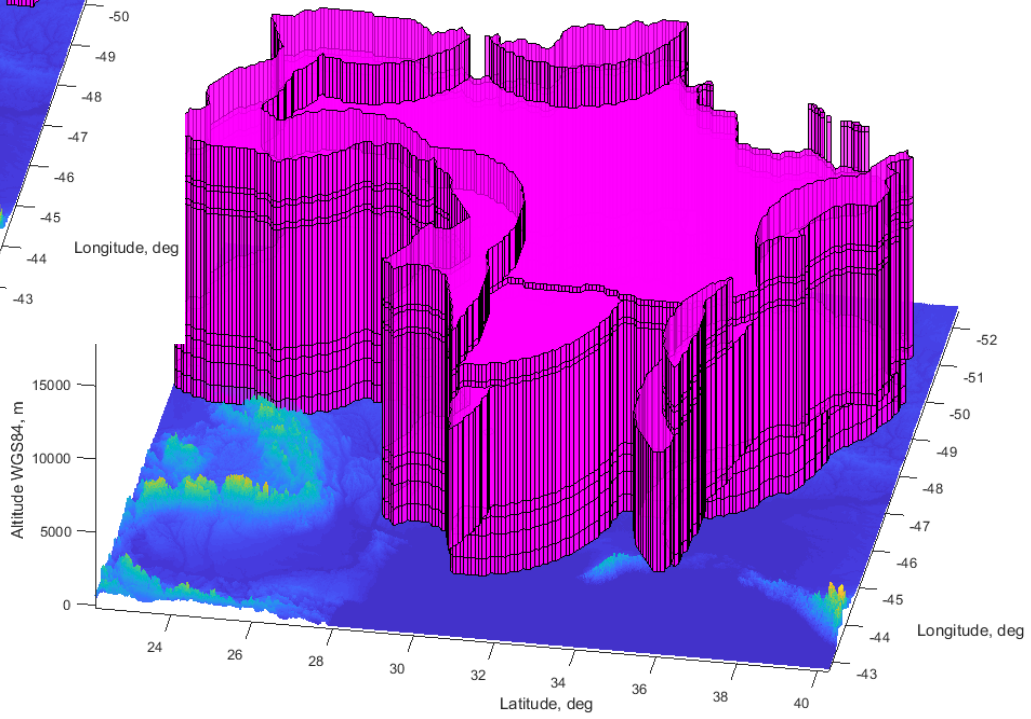


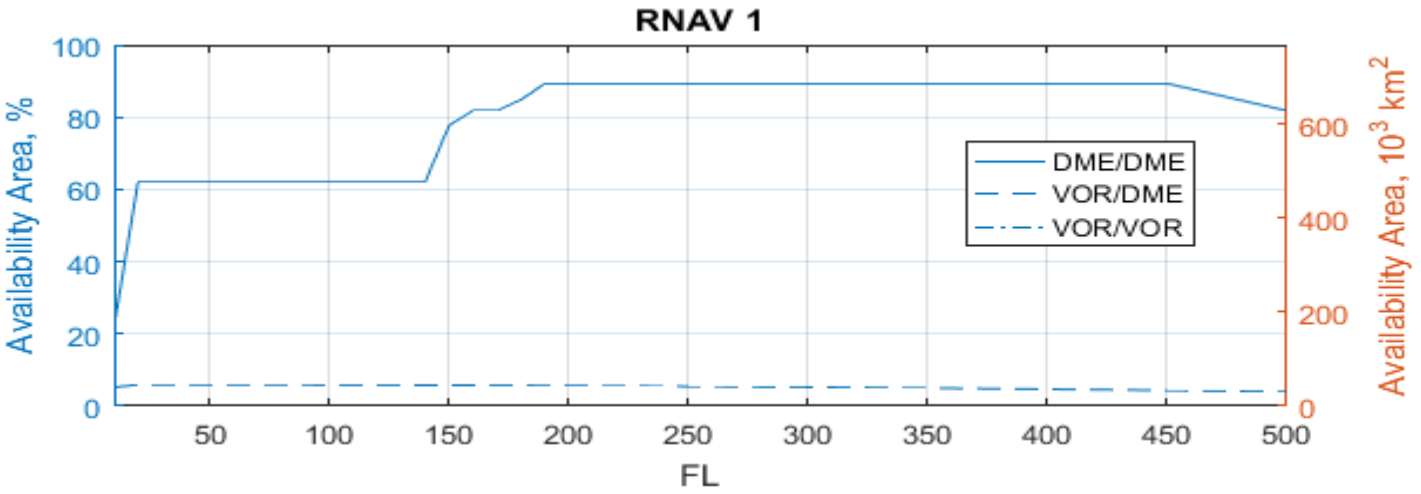
Verification RNAV 5

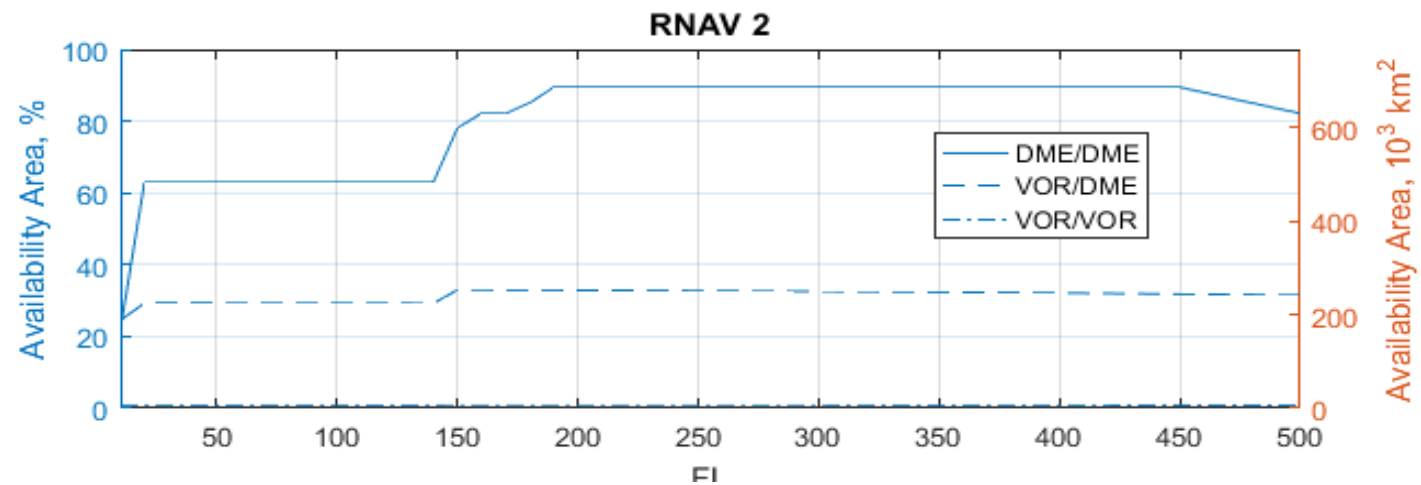


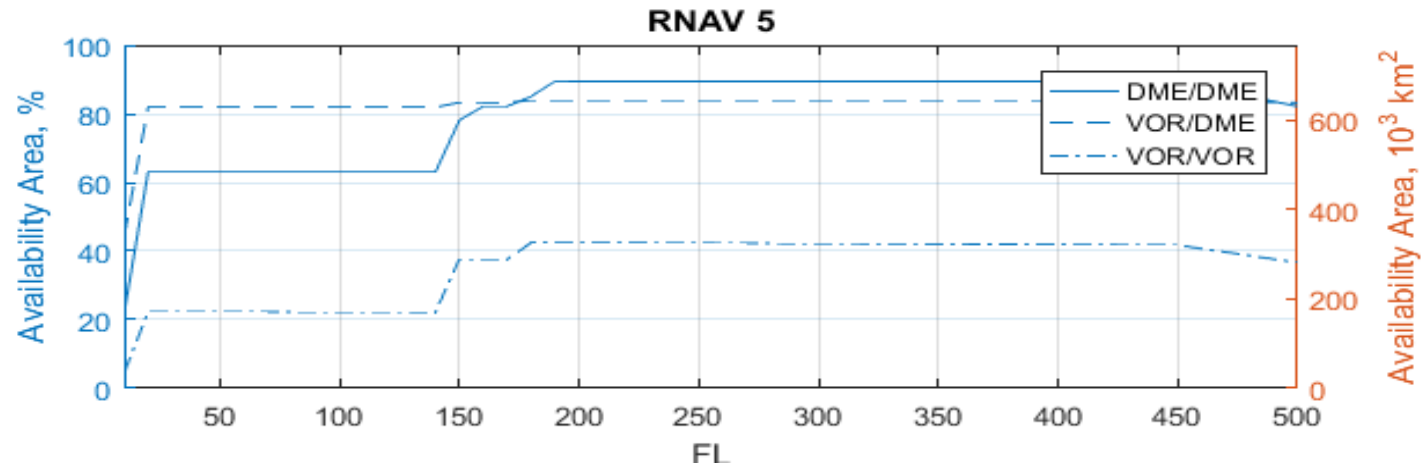
VOR/VOR

VOR/DME









Conclusions

Represented approach of positioning system performance analysis in 3D space helps to estimate and investigate volumes of different area navigation specifications support according to PBN concept.

Results of performance analysis of Ukrainian airspace up to FL610 indicate 74.6% its compatibility with RNAV 1 requirements for positioning by DME/DME that is a result of good geometry of DME ground network. This result can not be significantly increased due to impossibility of navigational aids network development within sea regions. VOR/DME service supports RNAV 1 only in 4.58%, but supports RNAV 5 in 70.38% of airspace. VOR ground network does not satisfy performance characteristics of RNAV 1 due to low accuracy of positioning. However, RNAV 5 is supported by VOR/VOR positioning within 32.5% of Ukrainian airspace.

Obtained 3D volumes help air space users and air navigation service provider for better understanding of potential gaps in positioning system services and to develop strategies of navigational service improvement in order to guarantee required level of flight safety. Also, obtained 3D models of space indicate airspace volume within usage of different alternative to GNSS positioning systems, such as DME/DME, VOR/DME or VOR/VOR.