

4. Contemporary Air Navigation System

Ivan Ostroumov

National Aviation University Kiev, Ukraine

Navigation is an important feature of moving object, which is defined as the process of movement between two points of space. Depending on the type of space and the characteristics of the object, there are different types of navigation: air navigation, space navigation, marine navigation, submarine navigation, terrestrial navigation, underground navigation, information navigation, biological navigation, and others. Moreover, depending on the principles and methods used for navigation purposes, we can also distinguish: astronomical navigation, inertial navigation, radio navigation, satellite navigation, and others.

Generally speaking, air navigation is a process of aircraft movement from one point in airspace to another. Many years ago only a pilot was responsible for performing air navigation rules, but nowadays aviation is supported by various services and rules. From the current point of view, air navigation has become a complex system for air traffic planning, control, and guidance to guarantee safe aviation transportation.

Air navigation system provides all types of services that are used in aviation today to guarantee safety, continuity, and efficiency of aircraft navigation and air navigation infrastructure. Also, air navigation system is a complex of companies, personnel, infrastructure, procedures, equipment, rules, and data, that are used by airspace users during air navigation services, in order to guarantee the required level of aviation safety, continuity, and efficiency.

The main tasks of air navigation system are the following:

- design of flight trajectories (national and global air traffic routes, schemes of aircraft movement in airport areas) and requirements for flight performing (safe altitude, separation minimums, required navigation performance);
- development of navigation rules, that is setting up a defined list of actions for pilots during air navigation function performing in time of particular flight situation (for example rules of setting up pressure in barometrical altimeter, operation in case of communication loss, engine failure);
- air navigation data collection, processing, archiving, deleting and sharing;
- support of preliminary navigation calculations (angles and distances, ground speed, time of flight, fuel amount, safe altitudes)
- support pilots and other involved authorities in required air navigation data and knowledge sharing;
- data support of flight management systems, navigation systems, and other automatic systems of air navigation services.

Air navigation services are provided by different personnel. For example, airspace design of standard instrument for departure and arrival is supported by an air navigation service provider; support of digital air navigation data is provided by information technology specialists; an air traffic controller can perform air traffic control function (by issuing advisories for pilots) and can support air navigation information services (by sharing NOTAM data with pilots).

An important task of metrology is to determine the position of an object in space. Positioning is the process of determining location in space. For the purpose of positioning in space, a certain metric is introduced, which is fixed at a certain point. In this case, positioning is considered as determining the values of certain metric values relative to the reference point, which in most cases characterize distances.

Positioning in space is performed by measuring certain features or characteristics that occur under the influence of various errors. The measurement results obtained will differ from the true ones by the magnitude of the random component. Positioning errors are usually estimated using confidence bands that delineate a particular area in the space of a possible location with a given probability value. Mathematical statistics methods are used to evaluate confidence zones, or analytical dependencies are investigated, which usually express the influence of errors in the measurement equipment of space characteristics on the overall positioning error.

4.1 SURVEILLANCE EQUIPMENT OF AIR NAVIGATION SYSTEM

Safe air traffic management is grounded on maintaining safe separation minimums and strict rules following by each airspace user. Surveillance equipment of air navigation system is used to support the basics of ATC operation. Surveillance equipment is used to provide ATC information about current airspace users' locations.

Surveillance systems are developed rapidly beginning from the Second World War period. In common case, surveillance equipment can be categorized into two types: dependent and independent. Independent surveillance equipment uses sensors located on the ground surface that measure airspace user location directly in the system (or measure airspace user location from ground-based equipment). Dependent surveillance is grounded on airspace user location measurements, on board an aircraft, and then shares results with the help of digital data link to the ground to use in ATC loop. In this case, airspace user location depends on on-board positioning system.

Independent surveillance is grounded on wide usage of radars: Primary surveillance radars (PSR), Secondary surveillance radars (SSR), and passive radars. The term "Radar" was introduced in 1940 by the United States Navy as an acronym for RAdio Detection And Ranging.

Air Traffic Control uses radars to:

- monitor aircraft in relation to each other whilst they fly on routes, in control zones or in the airfield vicinity, and to vector the aircraft if necessary.
- provide radar talk-down to a given runway (Surveillance Radar Approach (SRA) or a military Precision Approach Radar).
- control and monitor aircraft on ILS let-downs, or during airfield instrument approaches.
- provide information regarding weather e.g. storm clouds.

Each radar performs surveillance function only within its coverage volume which is defined by maximal and minimal ranges. Multiple PSRs and SSRs are used in the surveillance network of ANSP for airspace users location to perform a basic function of ATM. For example, surveillance in Ukrainian airspace is supported by

36 PSR and SSR. Results of ATC radars availability assessment are represented in fig. 1. Data from different radars are processed in surveillance data processing system (SDPS).

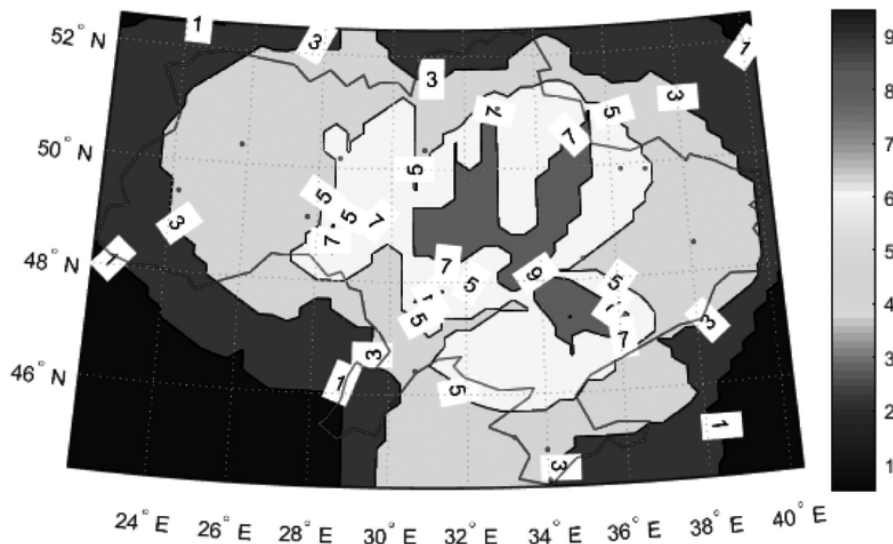


Fig. 1. Number of radars used to support surveillance in Ukraine

Continuously increasing amount of air traffic over the globe already reached limits of technical capabilities of SSR in Mode A and Mode C due to overlapping replies and interference at one interrogator caused by replies from a transponder responding to interrogations from another radar. Thus, nowadays mode S transponder is included in the minimum equipment list of any airspace user. Also, the main disadvantages of radars stimulated the development of dependent surveillance technology.

Nowadays dependent surveillance is mostly supported by Automatic Dependent Surveillance-Broadcast (ADS-B) concept that has been implemented in FAA and Eurocontrol airspace starting from 2005. According to ADS-B, user location is estimated by on-board equipment and shared with ATC and other airspace users by digital data link. To support surveillance function ANSP should deploy ground network of ADS-B receivers for receiving, decoding, processing, and sharing data transmitted from aircraft.

Multilateration is another localization approach that is frequently used in the surveillance domain. Multilateration is based on Time-Difference of Arrival (TDOA) method of localization and uses hyperbolic navigation principle [1]. Multilateration is grounded on usage of multiple synchronize receivers in the ground to receive navigation signal transmitting from ATCRBS transponder and detecting transponder location by hyperbolic navigation principle and fixing a time difference of signal coming at ground part of equipment [2,3]. There are two basic principles of multilateration operation: passive and active. Passive multilateration uses navigation signals transmitted by ATCRBS in mode 1090ES (ADS-B). Active multilateration includes a ground-based interrogator of Mode S, and uses reply signals for user localization in space. Typically, a multilateration system is used in the terminal area to support surveillance service in airspace closed to the airport.

4.2 ON-BOARD EQUIPMENT OF AIR NAVIGATION

The accuracy of planned flight trajectory maintenance by each airspace user directly affects air traffic safety. In accordance with the Performance-based Navigation (PBN), positioning system characteristics are represented by accuracy, integrity, continuity, and availability [4].

Accuracy is a difference between the estimated and actual aircraft position. Integrity usually is defined as a measure of trust which can be placed in the correctness of the information supplied by the total system.

Continuity is represented by the capability of the system to perform its function without unscheduled interruptions during the intended operation.

Availability is characterized by a portion of time during which the system simultaneously delivers the required level of accuracy, integrity, and continuity [5].

The values of these characteristics are defined in PBN specification that is implemented in each part of airspace and specifies the precision of an aircraft trajectory maintenance. It should be noted that integrity, continuity, and availability are probabilistic values that more closely describe the ability of the positioning system to perform its functions within the planned characteristics, respectively, depending on the value of each of the components.

Nowadays, different methods of aircraft position detection are available for airspace users. An overview of onboard positioning equipment is represented in Fig.2. Global Navigation Satellite System (GNSS) is the most commonly used positioning system because, in comparison with other systems, it can guarantee a high level of accuracy and availability regardless of aircraft position in airspace [6]. However, the effect of factors such as ionospheric delays [7], tropospheric errors [8], the interference of radio waves or unintentional jamming of signals reduces the positioning characteristics in a particular limited area or may cause a positioning system lock [9,10].

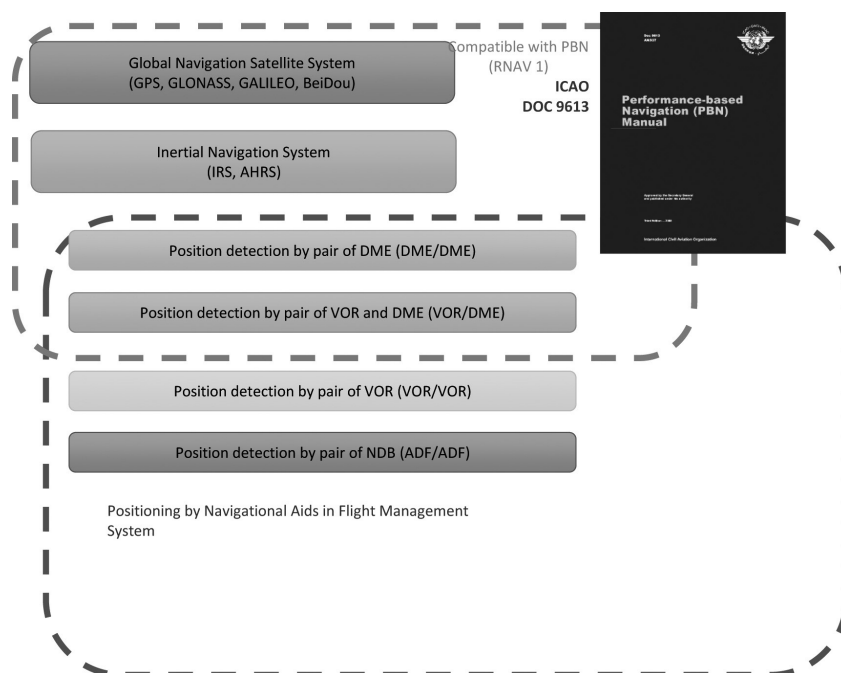


Fig. 2. Aircraft on-board equipment for positioning

In case of lack of positioning performance, Attitude Heading and Reference System (AHRS) can be used as stand-by equipment to continue positioning. Unfortunately, operation time of inertial navigation is limited by errors of positioning, which has additive behaviour and increase significantly with time. Thus, AHRS can be considered as a solution for a limited period of time, only. In case of error out of the required performance level, positioning by navigational aids can be initiated [11, 12].

Algorithms of positioning by navigational aids, operating in the Flight Management System (FMS) computer, use data from ground angular or/and Distance Measuring Equipment (DME), to estimate an aircraft location. According to the typical equipment list of civil aircraft, the FMS uses the optimal navigational aids pair [13] and automatically tunes the DME, VHF omnidirectional range (VOR) or Automatic Direction Finder (ADF) on-board sensors to perform measurements through the Radio Management Panel settings. Localization methods such as TOA (Time of arrival), AOA (Angle of arrival) or AOA/TOA may be used for positioning by navigational aids [12]. In case of TOA method, the distances are measured by Distance Measuring Equipment (DME). VHF omnidirectional range (VOR) or Automatic Direction Finder (ADF) can be used as angular data sensors for AOA method. The DME/DME and VOR/DME pairs are the most frequently used, while VOR/VOR and ADF/ADF are extremely rarely used due to significant errors of angle measurement by VOR and ADF equipment [12].

Onboard positioning system should meet numerous requirements for the characteristics of its operation, predefined in the RNP/RNAV navigation specifications [4]. Numerous advantages of RNP/RNAV procedures make them useful in the current airspace structure. Therefore, each positioning method corresponds to a certain airspace volume within which the requirements of navigational specifications approved by the Air Navigation Service Provider (ANSP) for defined airspace are met. An airspace air navigation service analysis takes a significant intention at SESAR project due to segmentation of ground navigational aids within European volume into the parts with particular boundaries and characterized by different performance level. The assessment task of the airspace area compliance with the requirements of area navigation is an important stage in the assessment improvement of flight safety [14,15].

The accuracy, integrity, and continuity requirements are set forward up to location data obtained from the onboard positioning system. The accuracy of navigational measurements is characterized by Total System Error (TSE), which must take a value within the permitted levels, depending on the type of navigation specification (Table 1), in 95% of the total flight time with longitudinal and lateral deviations [4].

Table 1. Performance requirements of navigation specification

Navigation specification	TSE, NM	Integrity
RNAV 10	10	10 ⁻⁵
RNAV 5	5	
RNP 4	4	
RNAV 2, RNP 2	2	
RNAV1, RNP 1	1	

According to [4], the main components of the TSE are the Navigation System Error (NSE), Flight Technical Error (FTE), and Path Definition Error (PDE):

$$TSE^2 = NSE^2 + FTE^2 + PDE^2.$$

The NSE value is estimated by the maximum value of mean squared deviation error of aircraft location detection within the 95% confidence band. NSE value depends on the type of navigation system and depends on the geometry of the ground stations location.

FTE characterizes the ability of a pilot or an automatic piloting system to follow a predetermined trajectory of flight. In the case of manual control, the FTE includes the indication or data interpretation errors. The FTE value for the various flight phases are shown in Table 2 [14, 4].

Table 2. FTE values according to the flight phase [14]

Flight phase	Control mode		
	Manual	Flight director	Autopilot
En Route Oceanic	2 NM	0.5 NM	0.25 NM
En Route Domestic	1 NM	0.5 NM	0.25 NM
Terminal	1 NM	0.5 NM	0.25 NM
Approach	0.5 NM	0.25 NM	0.125 NM

The PDE includes errors of aircraft trajectory settings in the FMS and other related components of the errors (database errors, air navigation chart errors, etc.). However, due to the usage of digital databases in FMS, the PDE is too small in comparison with the value of other components and it can be neglected.

The integrity of the navigation information is defined by the value of the probability of significant failure in the positioning equipped, which, according to [4], cannot exceed 10^{-5} per flight hour independently from flight phase. The requirements for the availability of ground navigational aids infrastructure or the segment of satellites for GNSS are also considered as a probability of a significant fault, which, according to [4], cannot exceed 10^7 .

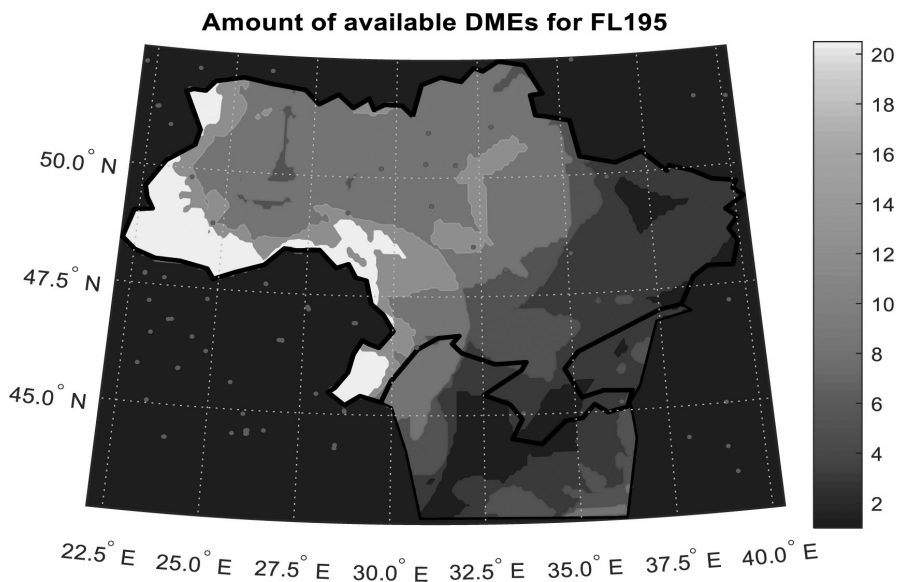


Fig.3. Amount of available navigational aids in Ukrainian airspace Fig.4. Airspace supported RNAV 1 requirements for positioning by DME/DME

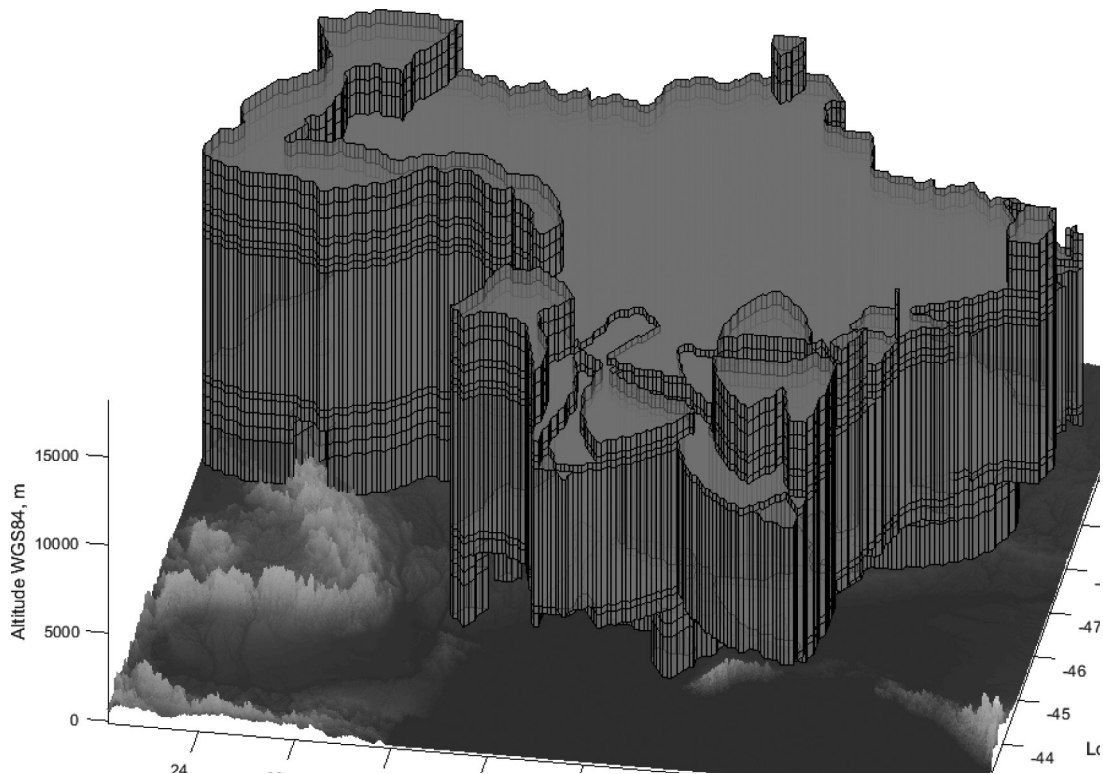


Fig.4. Airspace supported RNAV 1 requirements for positioning by DME/DME

In common, air navigation equipment includes GNSS, navigational aids (DME/TACAN, VOR, Non-Birectional Beacons), and Instrumental Landing System (ILS). All of these systems include two structural components: on-board equipment and infrastructure. In most cases, infrastructure equipment generate navigational signals that are used for positioning and navigation by on-board equipment. ANSP is responsible for infrastructure domain and airspace users for on-board equipment of aircraft. Performance of positioning depends on both parts of equipment. Thus, in order to guarantee high-performance of operation, ANSP has to provide continuous performance monitoring of ground networks of navigational aids and ILSs.

As an example, Ukrainian ground network of navigational aids includes 12 DMEs (in particular: BAH, IHA, IHR, IKI, IKV, KSN, KVR, ILO, ILV, STB, VIN, YHT) and 8 VOR/DMEs (BRP, DNP, IVF, KHR, KVH, LIV, ODS, SLV) [16] represented by high altitude and terminal types. For each type of navigational aid, there is a certain area of airspace within which the services of the navigational aid are guaranteed. The results of the availability assessment within Ukrainian airspace at FL 195 taking into account national navigational aids networks of the neighbouring countries: Poland, Slovakia, Hungary, Romania, Moldova, Russia, Belarus, and Turkey are shown in Fig.3 [14].

Results of performance analysis of Ukrainian airspace up to FL610 indicate 74.6% (Fig.4) its compatibility with RNAV 1 requirements for positioning by DME/DME that is a result of good geometry of DME ground network. This result cannot be significantly increased due to impossibility of navigational aids network development within sea regions

Ivan Ostroumov
National Aviation University Kiev, Ukraine
ostroumovv@ukr.net
ORCID 0000-0003-2510-9312