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Main Threats and Solutions for Positioning by Navigational Aids Network

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Abstract. There are many systems on board of civil airplane for coordinates-measurements. Global Navigation Satellite System is used as a primary positioning sensor. As a stand-by, positioning by navigational aids can be used in case of malfunction of the primary system. Both positioning systems, except inertial navigation system, are grounded on signals measurements and data transferring via communication channels. In paper we study the main threats that can affect communication channels between different parts of navigation equipment and analyze its potential impact into positioning performance. We discuss interference of radio waves, unintentional jamming and spoofing threats, threats of usage not valid air navigation data and missing optimal pair of navigational aids due too poor standard service volume model. As a result, a possible solution for each of these threats detection and minimization of their impact is proposed, based on improvements of data processing inside of Flight Management System.

Keywords: navigational aid, threat, communication, positioning, DME, VOR, FMS, GNSS, unintentional jamming, spoofing, database.

1 Introduction

Airplane navigation is a key element of successful transport system operation that supports the safety of aviation. Navigation function includes tasks of safe airplane movement from one point of airspace to another by the most effective three-dimensional trajectory. In this case, detection of airplane location or positioning in space within predefined reference frame is important component of aviation safety. In common case, positioning systems use direct data transmission from network of radio beacons to airplane with further data processing. An airplane positioning system may use Time of Arrival (ToA), Time Difference of Arrival (TDoA) [1], or angle of arrival (AoA) [2] methods for coordinates detection. All of these methods use radio communication channels for navigation signals transmission. Different systems use different radio spectrums [3]. Performance of positioning depends on quality and continuity of navigation radio signal fixation at the receiver. Thus, all factors that can influent communication line within navigation system degrade the accuracy of positioning significantly. Appearance of these factors has different nature and result in

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different forms [4]. Mostly it depends on communication line structure and channel type [5]. For example, Time Division Multiple Access (TDMA) and Frequency-Division Multiplexing (FDM) has different nature of threat influence at one of the channels of navigation system. A simple noise at operation radio frequency of navigation system can lead to total lock in case of TDMA usage, but in case of FDM can slightly reduce performance of positioning. Therefore, the way of threat influence on operation of positioning system via communication line can be different, depending on localization method used, particularities of measurement sensor structure, and communication channel operation.

Performance of navigation detection makes Global Navigation Satellite System (GNSS) extremely popular in a variety of civil aviation applications. But, multiple threats [6] that can act at communication line into transmission of navigation data can degrade performance of positioning and even can lead to positioning lock. In case of lack of positioning performance, an Attitude Heading and Reference System (AHRS) can be used as a stand-by equipment to continue positioning function. Unfortunately, operation time of inertial navigation is limited by errors of positioning, which has additive behavior and increase significantly with time. Thus, AHRS can be considered as a solution for limited period of time. In case of error out of required performance level, positioning by navigational aids can be initiated [7]. Both, GNSS and positioning by navigational aids data depend on success data transmission in communication channel. Threats, that can affect the transmission line can reduce positioning performance. In our research we would like to study the main threats that can affect positioning function from communication network side.

2 Treats in communication line of Global Navigation Satellite System

GNSS is one of the most useful positioning systems in the world. Global coverage and stable availability makes GNSS useful in various applications. Today GNSS is realized in GPS, GLONASS, GALILEO, and Beidou with various augmentation subsystems. GNSS includes a set of synchronized transmitters located at Earth's orbit. Each satellite in constellation transmits navigation signal at specific communication channel. The distance of communication line between transmitter and receiver in communication channel is very significant for transmitting power. In case of GPS, space segment is located in 20180 km from user receivers. A transmitter of satellite for L1 supports power in 21.9 W (13.4 dBW) [8], satellite antenna gain for the worst case of user location supports 13.4 dBW. Thus, power of navigation signal from satellite is above 26.8 dBW. Radio wave propagation in free space takes 184.4 dBW. Total atmospheric and polarization mismatch losses take 3.9 dBW. Finally, in user segment we are getting navigation signals with power level of −158 dBW, approximately. The power level of these signals is too small and may be easily affected by intensive noise or interference in communication channel. Also, large spatial variation of ionosphere delay and fluctuation of power oscillation in troposphere [9] effect power budget of communication line and finally degrade performance of positioning by GNSS dramatically.

The interference of radio waves is another important problem of GNSS. Improper functioning equipment can be a source of noise that can affect communication line of navigation system by means of interference. Numerous reports and papers [10, 11, 12] are describing events all over the world with improper functioning of transmitting equipment with the wrong settings that affect GPS positioning capability.

Continuous growing of GNSS value in positioning market makes widespread and implementation of positioning service in different human activity and multiple commercial applications. In opposite side, at the private security level, widespread GNSS functionality creates basics to introduction and rapid world-wide spread of specific systems for navigation signals jamming. We do not want to cover military side of this problem where jammer is used for deliberate generation of noise at radio frequency of communication line at predefined volume, but we would like to focus on private person level. Today in global market a variety of low power jammers with an effective operation range from a few to hundreds meters is available. Small size, low battery supply, and low price for such kind of equipment make it popular for drivers of logistical companies, taxi, and other delivery services (see **Fig. 1**). By the principle of operation all of these equipment generates a simple noise at spectrum of GNSS. Usage spectrum of GNSS for transmission of anything including simple Gaussian noise is a violation of radio spectrum law, that makes usage of jammers under the law. However, low power of transmission results in 5-10 meters of effective operation radius for positioning system lock and makes real problem for their detection with stationary radio spectrum controller stations, make them totally undetected.

Fig. 1. An example of low power jammers

From another side, usage of jammers close to airport area may affect accuracy of positioning systems used for airplane landing or take-off, navigation during taxi; operation of ground services and even affect operation of different augmentation systems (LAAS, WAAS, EGNOS, GBAS). Statistic of events of such equipment usage told us about problem of "unintentional" usage of jamming equipment. It means that the primary reason to use this equipment is to provide locking of private user receivers and it does not directly affect aviation operation. According to numerous studies, a problem of unintentional jamming is one of the most important threats of GNSS in near future.

The main source of jammers' location may be highways, lanes, roars, parking lots, and other places of possible car location. A highway can be considered as the most unpredictable, due to limited time of appearance and continues changing the power of transmission at point of positioning. In this case, appearance of unintentional jamming can be considered in terms of queuing theory and a Poisson process with further consideration at navigation performance level. The impact of unintentional jamming in positioning process can be different according to variety of equipment and jammed radio spectrum. The jammer can be oriented to transmit noise at spectrum only one of GNSSs. However, positioning system on-board of airplane can utilize omni-constellation principle and use navigation signals from wide vary of radio-spectrum. In this case, loss of navigation data from one of GNSSs can reduce positioning accuracy, but do not lock positioning functionality at all.

One of the possible solutions for problem of interference or unintentional jamming in GNSS can be found by usage of an adaptive antenna array [12]. In this case, an antenna array can change the directional characteristics of its gain function dynamic during operational mode. The operation of the adaptive antenna array follows three main steps. At the first a presence of valuable level of noise is detected. With the help of electronically rotated gain function of antenna, direction to the threat location can be detected in relation to the antenna array. At the final step antenna array generates an adaptive gain function pattern in order to minimize receiving power from threat direction. Unfortunately, adaptive antenna systems are not popular in civil aviation, due to economic reasons and have mostly a military application.

3 Positioning by navigational aids

Positioning by navigational aids usually is grounded on usage of data from VHF omnidirectional range (VOR), Distance Measuring Equipment (DME), or Automatic Direction Finder (ADF) in order to detect airplane position [7, 13, 14]. According to the minimum equipment list of a common civil airplane, there are two sets of each of these sensors. Operation of these sensors usually is controlled by Flight Management System (FMS) via Radio Management Panel (RMP) (see **Fig. 2**). Algorithms of positioning by navigational aids are processed in FMS. FMS includes an air navigation database, that contains technical data about navigational aids around the world. During a positioning cycle, FMS analyzes the airspace around, taking into account extrapolated airplane trajectory and data about ground navigational aids in order to detect an optimal pair of navigational aids. At this stage, a binary integer linear programming can be used to find a solution to the optimization problem [15]. Frequencies of optimal pair of navigational aids are used by RMP for tuning sensors DME, VOR, or ADF. Results of measured distances or angles come back to FMS for solution a system of navigation equations [14].

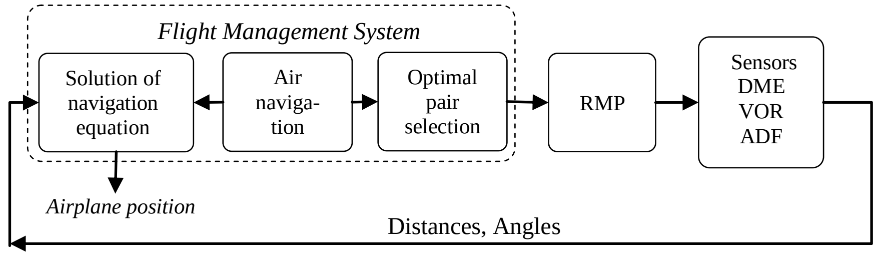

Fig. 2. A cycle of positioning by navigational aids

According to poor accuracy of positioning by AoA method, pairs of ADF and VOR are not used very often. But, DME/DME that utilize ToA method, and VOR/DME (utilize AoA/ToA methods) are considered as main alternative positioning approach in civil aviation [14, 16].

Let's consider a sensor structure and the importance of a communication line for measurements in VOR and DME (see **Fig. 3**).

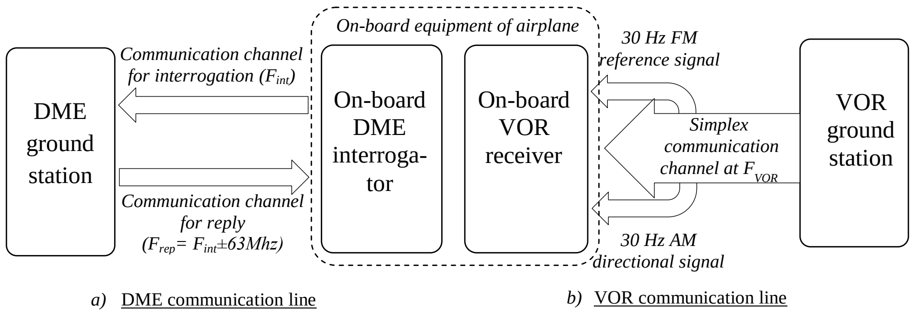

Fig. 3. Communication lines of navigational aids

3.1 Distance Measuring Equipment

DME uses interrogation principle to measure distance from airplane to ground-based navigational aid. DME operates in the UHF band between 960MHz and 1215 MHz with1 MHz spacing that supports 252 channels [3]. On-board equipment interrogates ground DME station at frequency of particular channel. As interrogation signal DME uses two pulse pairs that are specified to have a Gaussian envelope and are amplitude modulated. The time distance between pulses in pairs is different for different channels 12 μs (X channel) and 36 μs (Y channel) [17]. The time frame between pulse pairs is unique for each interrogation and is used in system to identify own reply from DME. The ground station of DME receives and validates interrogation signal. After detection of valid interrogation pulses ground station generates reply signal in the 50 μs delay (for X channel) [17]. DME reply signal is the same as interrogation signal but has a carrier frequency in 63 MHz offset. During 50 μs delay period and 10 μs margin DME ground station is frozen for any interrogation. During measuring interrogator does not know possible time of returners and have to wait up to 2.5 ms to guarantee operational radius in 200 NM.

Slant distance in DME is calculated by measuring the time frame between sending interrogation and receiving reply on-board of airplane and known constant speed of radio waves propagation (c=3e8 m/s).

3.2 VHF omnidirectional range

VOR ground transmitter operates within 108-117.95 MHz frequency range in the VHF band (particularly 40 channels in 108-112MHz and 120 channels in 112-117.95 MHz) [3]. Navigation signal of VOR includes two sub-signals amplitude and is frequency modulated. The frequency modulated reference signal (30 Hz) is Omnidirectional and produces constant phase regardless of a receiver's bearing from the VOR. Amplitude modulated variable phase signal (30 Hz) is directional signal, created by electronically rotated antenna pattern [17]. The on-board receiver of VOR extracts both sub-signals in amplitude and phase demodulators with further counting phase difference. The phase difference in VOR is the same with magnetic bearing angle from a ground station.

4 Threats of positioning by navigational aids

Both VOR and DME use communication lines in the measurement cycle (see Fig.3). DME communication handshake requires two communication channels at different frequencies. VOR uses only one frequency for transmitting all required for navigation data with AM and FM separation. Thus, ground navigational aids network operation requires some amount of VHF and UHF bands spectrum. Communication channels at these frequencies may be simply affected by interference or jammed. Also, radio waves at this spectrum are propagated at direct line of sight, thus communication line can be guaranteed only within specific operational volume, constructed taking into account technical characteristics of equipment and radio waves propagation model.

4.1 Radio Frequency Interference

In general, a thereat of Radio Frequency Interference (RFI) is caused by the presence in the communication channel of one radio frequency another than information signals. In this case, all other signals can be considered as a noise for particular data transmission channel. RFI can be produced by any device that conducts or radiates radiofrequency energy. Also, source of RFI may be caused by natural phenomena, such as lighting or solar flares. As a threat to navigational aids, RFI usually is caused by improper functioning of radio-transmitting equipment. In some cases RFI may be a result of multipath behavior of radio wave propagation, caused by radio waves multiple reflections from high artificial constructions or natural elements of relief (such as trees, hills, and mountains). Presence of multipath can change operational volume of radio transmitting equipment significantly and lead to unintentional interference with availability area of navigational aid. Computer-based simulation of radio frequency mitigation with near-located transmitters is required to study and prevent a navigation lost, taking into account elevation and environmental models.

4.2 Jamming and spoofing of navigation functionality

Jamming of navigational aids can be considered only as an illegal activity and can be found in different military applications. In order to provide effective noise jammer it is required a valuable level of transmitting power to effect airplane receiver that is located at high altitude. National stationary radio frequency monitoring stations can easily detect location of jammer and limit transmission power. Thus, jamming of navigational aids is not a "real" threat for civil aviation applications according to safety statistics.

Spoofing is another important threat that may take place in case of targeting action on airplane navigation system. Spoofing is an illegal act of influence via communication channel on some navigation system in order to replace actual transmission data with outdated data. Usage of wrong data in navigation algorithms will result in a malfunction of equipment. In this case spoofing is much more significant threat than jamming, because navigation equipment can not detect historical changes in signals and continues its operation with generation of wrong data.

VOR communication line is a simplex that makes this navigational aid sustainable for spoofing acts. But, DME is not protected according to unencrypted data transmission in the communication channel. Also, DME uses omnidirectional antenna patterns with high transmission power, that makes receiving and detection of airplane interrogation easy.

One of the most challenging tasks is to detect presence of wrong navigation signal. In case of DME, a comparison of predicted distance and measured is the only solution. Big difference between them indicates about presence of abnormal data and should initiate a new measurement cycle or be a cause for changing DME frequency. For navigational aid data prediction dead reckoning method, linear extrapolation, or different regression models can be used.

Similar to GNSS an adaptive pattern array is a possible solution in case of detected direction of jamming/spoofing source of a radio signal that can be implemented in onboard equipment of DME interrogator and VOR receiver.

4.3 Air navigation Data Base error

Algorithms of airplane position estimation by AoA and ToA are grounded on solving a system of linear or nonlinear navigation equation with exactly known navigational aids location [14]. Moreover, during measurement process FMS needs actual channel or radiofrequency of DME or VOR. Coordinates and other technical data related to each navigational aid are held inside of air navigation database in FMS memory. The outdated database may cause a serious threat for the whole positioning process. In common case, coordinates are changed not very often, while operational channel may be changed. Usage of not valid data may cause spending a lot of time in process of navigational aid pair selection, due to multiple interrogations of unused channels and dismissing actual operation ground facility. Monthly air navigation database updating helps to keep navigational aids data valid to support worldwide navigation. Also, some FMS supports automatic database updating via wireless connection.

4.4 Threats of positioning related to availability area

Navigational aids can perform services only within their operation volume. This volume is a result of communication line support between an airplane and ground-based equipment. Geometry and shape of navigational aid service volume is a result of antenna pattern, antenna gain functions, radio waves propagation models in free space, influence of tropospheric oscillation, technical characteristics of equipment, Earth surface and altitudinal artificial construction influence into radio waves propagation.

Common FMS may use standard service volume of navigational aid in positioning algorithms or using DME in a searching mode, sequential requesting all channels. Standard service volume defines space inside which signals of navigational aid can be fixed on board of airplane with enough level of signal/noise ratio for supporting communication channel data exchange. However, results of real signal/noise study, obtained during flight inspection of airspace, indicate two times wider service volume in comparison with standard shape. Thus, services of navigational aid may be available out of standard service volume, but there is no guaranty of required minimum level of signal/noise. Positioning algorithms of FMS which uses only standard service volume in optimal pair procedure may miss numerous pairs with potentially better performance. Interference and jamming also affect the service volume of navigational aid cutting a volume of acting electronic equipment. Thus, usage of not complete volume data is another threat for positioning by navigational aids inside of FMS.

As a solution for this problem an application of advanced algorithms of navigational aids availability estimation taking into account technical characteristics of communication equipment and influence of Earth into radio waves propagation may be considered [18]. At least oscillation in troposphere, diffraction and refraction models should be applied. A line of sight screening within length of communication line inside of digital elevation model data can be considered as a simple diffraction model. More advanced diffraction models can consider individual characteristics of surface and support bending and attenuation of radio waves due to edges. Unfortunately, availability of navigational aids for the whole airplane trajectory can not be solved by analytical approach, due to complexity of task. A list of available navigational aids can be reached by applying an iterative approach [18] dividing investigation airspace into elementary particles. In this case, dimensions of elementary particle define the accuracy of approach. The boundary of 3D group of elements with the same characteristics creates an operation volume of navigational aids.

According to regulation [16], an airplane navigation system has to follow performance requirements within investigated airspace. Accuracy of positioning system depends on geometry of navigational aids ground network [13, 14] that should be taken into account at availability estimation level. Performance regulation specifies the value of Total System Error (TSE) that should be reached. TSE includes two basic components: Flight Technical (FTE) and Navigation System (NSE)Errors [16]. NSE utilizes an accuracy of positioning system. Estimation of availability volume of navigational aids network has to be performed taking into account required level of TSE. The TSE value for Ukrainian controlled airspace is defined by RNP/RNAV 1 at level of 1NM [19, 20]. Results of estimation of availability volume of positioning by national navigational aids network are represented in **Fig. 4** and **Fig. 5**. Ukrainian navigational aids consist of 12DMEs (BAH, IHA, IHR, IKI, IKV, KSN, KVR, ILO, ILV, STB, VIN, YHT) and 8 VOR/DMEs (BRP, DNP, IVF, KHR, KVH, LIV, ODS, SLV) [21].In computer-based simulation we use coordinates of navigational aids locations together with their technical characteristics, Digital elevation model of relief for frame between 23° and 40° of latitude; 43° and 52° of longitude [22].

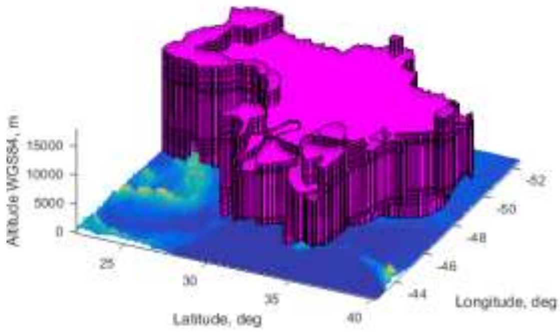

Fig. 4. Airspace volume of DME/DME availability for positioning by optimal pair

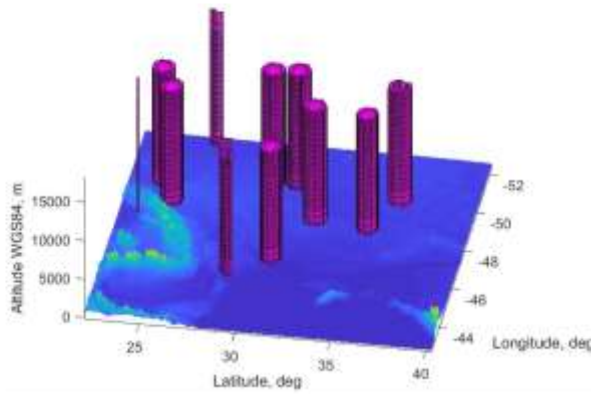

Fig. 5. Airspace volume of VOR/DME availability for positioning by optimal pair

Also, results of navigational aids availability estimation can be represented in the form of cutting volume at particular flight level in case of study some gaps in airspace performance.

5 Conclusion

Operation of DME and VOR navigation equipment is grounded on successful data transmission in radio communication channels. Threats that can affect communication lines between ground navigational aids network and airplane reduce performance of positioning dramatically due to reduced number of navigation parameters. We consider influence of possible interference from malfunction of ground radio equipment, unintentional jamming and spoofing problem, air navigation database error and availability area estimation model as main threats. Interference and jamming can be easily detected by level of noise on board of airplane and switch to use another ground station. Spoofing problem is not common according to intentional behavior in military application, however the easiest solution to this problem can be found by simple correlation estimation between actual and predicted navigation signals. Application of more advanced simulation of radio waves propagation models and accurate technical data reduce an error related to wrong decision of optimal pair of navigational aids for positioning.

Obtained results indicate that protection of positioning algorithms can be applied at software level of FMS by applying particular algorithms of threat detection and avoiding usage of damaged navigation data in positioning process.

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