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Evaluation of Alternative Navigation, Positioning and Timing Systems Based on Their Performance and Additional Characteristics

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Abstract

The aim of this paper is to provide performance assessment of Alternative Navigation Positioning and Timing (APNT) systems considered possible GNSS backup in European region. The performance of the APNT systems is assessed based on their performance characteristics such as accuracy, integrity, and by additional beneficial abilities, that could help by implementation or could provide different added value in terms of solving certain issues in the Communication, Navigation and Surveillance (CNS) domain.

Keywords

APNT, GNSS backup, Performance Assessment, LDACS, eLoran, Mode N, DME

1. Introduction

The dependence on Global Navigation Satellite System (GNSS) is increasing across different sectors including aviation. However, the power of the GNSS signal received on ground is comparable to "power emitted by a 60W light-bulb located more than 20,000 km away from the surface of the earth", according to the Airbus [1]. Hence, it may be easily affected by non-anthropogenic sources of interference such as atmospheric effects or a Signal-in-Space (SIS) error, as well as by anthropogenic interference caused by humans [1]. Loss of the GNSS signal of aircraft may result in a decrease of navigation performance causing not only decreasing the air traffic efficiency and increasing of additional costs, but also a serious threat to the air operations [1]. The International Civil Aviation Organization (ICAO) receives a large number of GNSS interference reports from different parts of the world annually [2]. In order to mitigate the impact of GNSS interference, Alternative Positioning Navigation and Timing (APNT) systems are being developed to substitute the function of satellite navigation systems in case of a GNSS unavailability. Several companies are involved in the development of these systems including Das Deutsche Zentrum für Luft- und Raumfahrt (DLR), Honeywell, EUROCONTROL, Thales Avionics, Deutsche Flugsicherung (DFS), etc. These companies offer different solutions of APNT systems which, undoubtedly, have both strengths and weaknesses. This paper deals with evaluation of the different solutions from the performance point of view including additional features useful by implementation of the systems. The assessed systems considered APNT candidates in European region, mostly developed within Single European Sky ATM Research (SESAR) projects [3], specifically L-band Digital Aeronautical Communication System (LDACS), enhanced LOng-RAnge Navigation (eLORAN), improvements of Distance Measuring Equipment (DME) and Mode N.

LDACS is being developed by DLR and focused primary on providing digital communication services ensuring sufficient transmission rate of datalink for the aviation needs in the future In addition the system also offers navigation capability, when the measurement of the slant range between aircraft and several LDACS ground stations is extracted from the communication data [4].

eLORAN is considered to be a substitution of the hyperbolical system Loran-C. eLORAN uses the existing infrastructure and low frequency band, however, it no longer operates on a hyperbolical principle, the position is determined from the difference of the time of the signal transmission and the signal arrival. Moreover, the eLORAN concept includes a significant number of enhancements compared to its predecessor, such as installation of atomic clocks into ground stations, possibility of transmitting data via data channel, introduction of various corrections to improve navigation services [5, 6].

Mode N represents a solution for a successive DME substitution and L band load release. The navigation function offers two modes; active mode similar to DME, and passive mode where an aircraft position is determined on-board calculating Time Difference of Arrival (TDOA) of signals received from different ground stations. Mode N uses the data transmission formats based on the Mode S specification in order to transmit information about location of the ground station in WGS-84 coordinates, antenna height, signal transmission time, station identification number or station status information [7].

SESAR project also proposes usage of DME upgrades for the APNT considered currently the short-term solution [3]. Firstly, DME Hybrid ranging may use one-way mode which is built on the existing ability of the DME to transmit pulse pairs without interrogation used for position update, and two-way mode used for periodic synchronization between aircraft and DME ground station. This hybrid method allows to significantly reduce channel load which results in the ability to provide information to the position of a larger number of aircraft. Secondly, the proposed improvement to the pulse rise time should mitigate propagation errors and increase the accuracy performance. Nevertheless, faster pulse rise time has a strong influence on the signal spectrum load and increase an adjacent channel interference. Finally, the Multi-DME algorithm upgrade focuses on providing on-board performance monitoring and alerting of undetected failure, in order to meet the (Required Navigation Performance) RNP requirements [3].

2. Approach to the APNT systems Evaluation

Given the above presented APNT systems, their performance has been assessed by evaluating the values of accuracy and integrity, which should be reachable according to the publicly available information. Since the APNT systems may be used as a backup for GNSS outage, the values were compared to the (Global Positioning System) GPS performance information. The performance characteristics of the systems were subsequently scored with one to three points. The accuracy is assessed based on the formula:

$$Accuracy\ change = \frac{GPS\ accuracy}{APNT\ sysem\ accuracy} * 100 \tag{1}$$

In case the accuracy of the APNT system has achieved a value lower than one third of the GPS reference value, i.e. 33.3%, the system will be evaluated by one point. If the system reaches one-third to two-thirds of the percentage of the reference accuracy, i.e. 33.3% - 66.6%, the system will be evaluated by two points. The accuracy higher then two thirds of the GPS system reference is evaluated by three points.

Similarly to the accuracy assessment, the integrity evaluation of the APNT systems is based on the comparison to the GPS reference value. The points are assigned according to numerical order of integrity risk. In case of integrity risk 10^{-5}, the system is evaluated by one point, in case of integrity risk 10^{-6}, the system is rated by two points, and integrity risk 10^{-7} is rated by three points.

In addition to the performance assessment, the following beneficial features of the systems have been chosen which may have a decisive influence in question of the APNT systems implementation or another added values in relation to the CNS domain:

- Feasibility of ground station implementation;
- Feasibility of avionics implementation;
- Feasibility of system standardization;
- L band load;
- Provision of communication service; and
- System range.

These characteristics are evaluated with maximum number of one point. In other words, these additional characteristics are considered secondary from the performance point of view, therefore, the score weight has been lowered.

3. Results of the APNT Systems Evaluation

In this section, the performance of APNT systems will be assessed on the basis of chosen evaluation criteria that may be useful when making decision on the introduction of a new APNT system. The evaluation is made by a comparison of values and information from publicly available resources. During the DME system assessment, the values of all improvements, described in first section of this paper, are considered.

3.1 Assessment of Accuracy and Integrity Performance

The accuracy of APNT systems is assessed by comparison with a reference value of GPS system. The GPS is considered the most common satellite navigation system used in aviation worldwide, and it provides a horizontal accuracy value of 7.8 m [8]. The percentage expression of the GPS and APNT accuracy comparison, according which the evaluation was made, are presented in Table 1.

According to the results from Table 1, it is clear that any of the APNT system does not achieve the GPS accuracy value, furthermore, it should be taken into account that the presented APNT systems accuracy may be strongly influenced by Dilution of Precision (DOP).

Similarly to the accuracy, the integrity assessment is based on the current GPS integrity risk value. The reference value of GPS is $1\text{-}10^{-5}$ [12]. As abovementioned, the integrity assessment is conducted in the form of scoring according to numerical order of integrity risk. The evaluation of the APNT systems integrity is presented in Table 3 below.

Values of accuracy and integrity of all APNT systems presented in this paper meet the most demanding requirements of Performance Based Navigation (PBN) for the navigation specifications RNP 0.3 [16]. This specification also requires another system performance which cannot be assessed by reason of the unavailability of these information.

3.2 Assessment of Implementation Feasibility

The main factor influencing that the system implementation may be facilitate is that the APNT system concept is based on the already existing one. This brings advantages by implementation of the ground equipment, the on-board equipment, as well as the system standardization.

3.2.1 Ground station implementation

LDACS ground infrastructure should be combined with the current (VHF Data Link) VDL Mode 2 ground stations [4]. Systems designed to use the existing ground infrastructure include eLORAN system which is based on existing LORAN-C, however the worldwide coverage would require construction of new stations [14]. Mode N is focused on the DME substitution and functioning on upgraded DME stations [7]. The last system focused on the use of the existing infrastructure is improvements to the DME system which has already had a large number of ground stations located around the world and their modernization is considered more feasible than in case of Mode N or eLORAN. [3]

3.2.2 Avionics implementation

Similarly to the ground equipment, the LDACS on-board avionics should be based on the current VDL equipment resulting in a multi-mode LDACS/VDL radio combined in a single avionics box [4]. In case of the DME system modernization, only the faster rise pulse could affect the on-board equipment change, and Multi-DME on the avionics software upgrade [3]. The advantage of the DME is that almost every aircraft is equipped by an on-board DME interrogator which is considered a prerequisite for facilitating the implementation. The LORAN-C avionics could be also used for eLORAN, but they has to be modernized [14]. In order to use the Mode N navigation services, aircraft should be equipped with specific avionics, which uses existing cabling and antenna. Two options offered for the of Mode N avionics implementation are illustrated in figure 1. [7]

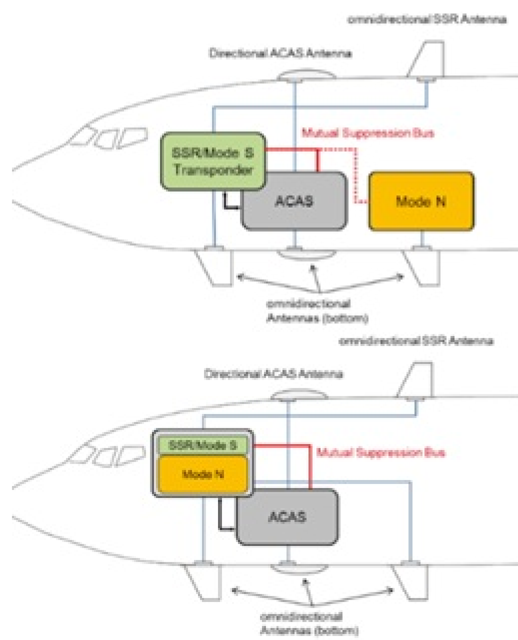

Figure 1. Mode N aircraft implementation options [7]

3.2.3 System standardization

The complexity of standardization can be affected by factors described above; whether the system is based on an existing one. For example, various DME enhancements requires just an adjustment of existing standards. A similar situation occurs with eLORAN, where is the possibility of using the Loran C standards with minimal changes [15]. Mode N uses existing ICAO standards for data formats for (Secondary Surveillance Radar) SSR Mode S, and may be based on DME ground infrastructure, that may significantly reduce the standardization time in comparison with a completely new system [7]. Conversely, a standardization process of LDACS is considered

Table 1. APNT systems accuracy assessment [7, 9, 10, 11].

APNT system	APNT system accuracy [m]	GPS accuracy [m]	Percentage expression of achieving the accuracy of the APNT system in comparison with GPS [%]	Evaluation
Mode N	40	7,8	19,5	1
eLoran	20		39	2
LDACS	20		39	2
DME*	47		16,6	1

Table 2. *DME Pulse Rise Time system values were considered for accuracy assessment.

Table 3. APNT systems integrity assessment [3, 13, 14].

APNT system	APNT system integrity [h^{-1}]	GPS integrity [h^{-1}]	Evaluation
Mode N	1-10^{-5} *	$1–10^{-5}$	1
eLoran	1-10^{-6}		2
LDACS	1-10^{-5}		1
DME	1-10^{-7} **		3

Table 4. *The Mode N system integrity value cannot be found in the available sources, therefore, the worst value of the introduced APNT systems is considered.
**Integrity was derived from the Protection Level of the Multi-DME system according to [15].

more comprehensive and time consuming with introducing completely new technology into aviation.

3.2.4 Evaluating of implementation parameters

The assessment of the ground infrastructure implementation is in accordance with the abovementioned evaluation of complexity for the ground stations implementation. In case the infrastructure uses the current ground stations with additional needs for upgrade, the system is rated at half of the maximum achievable rating of one point. In case of minimal changes in the ground infrastructure, the system is evaluated by the maximum number of one point, which was achieved only by DME. The assessment in terms of avionics implementation is performed similarly to the evaluation of the implementation of ground stations, i.e. according to the complexity of the feasibility of the on-board equipment implementation. For the last part of evaluation in terms of ground stations implementation, APNT systems are evaluated by one point on condition that the system has a basis to facilitate the standardization process, or by zero if the system is a completely new one. Points obtained by individual APNT systems are shown in Table 5.

3.3 Assessment of Additional Characteristics

Some of presented APNT systems provide a secondary system capability that represents an operational advantage. These factors are: release of the L band spectrum load, provision of communication service providing and provision of long range navigation.

Mode N is the only system that could reduce L band load, therefore, it is evaluated by one point [7]. However, there is a need to highlight that even if eLORAN does not reduce the L band load, it is still evaluated be 0,5 point due to its operation in another band [14]. Then LDACS is the only system that could provide communication service and it is evaluated by one additional point [4]. Finally, in the terms of provided range, there is only one system that is stands out in this point of view - eLORAN that enable to use its navigation function also above oceanic or remote areas. Therefore, one point is added to the eLORAN evaluation. [14, 17]

3.4 Results of Overall Assessment

The overall assessment of individual APNT systems with earned points is represented by Table 6.

According to the results, the highest score was achieved by eLORAN and DME. Nevertheless, the evaluation may be affected by lack of information, such as in case of determination of the Mode N integrity risk value. On one hand, LDACS has earned lower amount of points, but has an important added value thanks to the provision of communication service. On the other hand, the DME system with a high point gain does not bring any advantages in terms of secondary characteristic.

Table 5. Evaluation of Implementation Feasibility

	APNT system			
	Mode N	LDACS	eLoran	DME
Evaluation in terms of ground stations implementation feasibility	0,5 p	0,5 p	0,5 p	1 p
Evaluation in terms of avionics implementation feasibility	0,5 p	0,5 p	1 p	1 p
Evaluation in terms of system standardization	1 p	0 p	1 p	1 p
Overall evaluation of implementation feasibility	2 p	1 p	2,5 p	3 p

Table 6. Evaluation of Implementation Feasibility

	APNT system			
	Mode N	LDACS	eLoran	DME
Overall evaluation of Accuracy and Integrity Performance	2 p	3 p	4 p	4 p
Overall evaluation of additional characteristics and Implementation Feasibility	3 p	2 p	4 p	3 p
Overall evaluation of APNT system	5 p	5 p	8 p	7 p

4. Discussion

In case of the APNT system implementation, it is necessary to consider where the systems should be implemented. The various features of individual systems can be advantageous under different operating conditions. For example, eLORAN is considered suitable for remote and oceanic areas where the long-range characteristic plays the most important role. In other words, different factors such as traffic density in the deployment area or possibility for ground infrastructure placement, influencing accuracy of the position determination, need to be taken into consideration when deploying APNT systems. For example, on condition that the LDACS system is standardized and gradually introduced as an international standard to provide the digital communication service, its navigation function can be use as APNT worldwide. With regards to the DME system considered like a short-term solution for the GNSS back-up, with implementation of the various modernization of the system presented it promises sufficient performance also in a longer time horizon as resulting from the assessment. In order to facilitate operation of all CNS systems in the L band, the most comprehensive solution is offered by the Mode N solution.

5. Conclusion

The paper presents a comparison of four APNT candidates based on evaluation of their accuracy, integrity, and additional system features which may be beneficial by decision about their implementation. The results of the systems assessment show that all APNT systems met RNP requirements in term of accuracy and integrity provided. Considering the feasibility of the system implementation, the highest score was achieved by DME with its upgrades. According to the beneficial secondary characteristics, eLORAN provides the highest additional value. Altogether DME and eLORAN has received the highest number of points in the final evaluation compared to Mode N and LDACS. In particular, the values of the additional characteristics show that it is extremely important where the individual APNT systems are intended to be implemented, usage of each of them can be advantageous under different conditions of operation. Although the conducted evaluation of APNT systems provides an overview in terms of operational characteristics, the publicly available sources may not always include complete information. In addition, the implementation of systems in aviation is dependent on decision of international organizations which is made with consideration of another political and economic factors that could not be included in the paper.

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