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STATE OF THE ART IN AIRPORT NAVIGATION

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I. Abstract

The general increase in air traffic and the complexity of modern airport layouts have conducted to think about new technologies to assist pilots during maneuvers on airport surface. Some airport navigation applications have been developed in recent years. The current technologies plot the estimated aircraft position on the airport map. In good visibility condition, this information helps the pilot to navigate on the airport. These applications contribute to the reduction of the taxiing time and runway incursions. Nevertheless, this information is not sufficient to navigate in low visibility condition. This paper introduces the state of the art in airport navigation, with the current functions available to assist pilots, and also the additional applications envisaged to improve the airport navigation in low visibility condition. Current constraints and limitations of airport navigation development are highlighted.

II. Introduction

In a recent ICAO (International Civil Aviation Organization) press release [1], a 6.3% increase in the number of passengers has been assessed between 2009 and 2010 (data assessed by the 190 states members of ICAO). This increase implies more aircraft traffic on the airport surface. Important effort is done to design new A-SMGCS (Advanced Surface Movement Guidance and Control System) architecture and functions that will enable an efficient and safe management of the traffic at the surface of the airport, in all weather conditions. In this context, the definition of new airborne navigation capabilities during taxiing operation is a prospective topic in civil aviation. Obviously, the development of new navigation applications requires to take into account this particular environment which results from operations performed on airports with complex layouts and high traffic density.

Some applications have already been developed to support aircraft navigation on airport. These applications are used for situational awareness. This paper reviews possible ideas to improve the airport navigation capabilities. To implement these concepts, requirements, not yet elaborated, are needed. This paper investigates the rationale for the definition of new navigation requirements to support the future airport navigation functions.

The paper organization is as follows. Section 2 provides the state of the art in airport navigation, which illustrates the different applications available nowadays. Section 3 describes the operational applications envisaged in the future to assist pilots to navigate safely on the airport surface. These applications include airport navigation in low visibility condition (airport in LVP – Low Visibility Procedure – conditions). Section 4 discusses the difficulties to develop airport navigation applications according to current constraints and limitations. Section 5 introduces means and sensors which are appropriate to provide aircraft position estimate.

III. State Of The Art In Airport Navigation

Today, pilots use paper copies of airport maps to navigate on the ground. Before departing, they anticipate the arrival reading the map associated to the destination airport to prepare the airport navigation. This step is long and laborious due to the complexity of some airports. Moreover, there are many airport manuals documenting an airport and it is difficult to maintain the documentation up to date.

After landing, pilots receive instructions, called clearances, from the ATC (Air Traffic Control) to go to their final destination. Clearances indicate the path to follow using taxiway nomination. Some signs and visual ground aids can help the pilot to locate himself but he has no overview on the airport surface.

To reduce the crew workload and to help the pilot to make decisions, systems dedicated to maneuvers on the ground have been developed. These systems plot the estimated position of the aircraft on electronic maps displayed to the pilots.

Two existing systems currently used in civil aviation providing airport navigation applications through different display interface, are presented. These systems, the EFB (Electronic Flight Bag) developed by Jeppesen and the OANS (Onboard Airport Navigation System) developed by THALES, are implemented on Boeing and Airbus aircrafts.

III.1 EFB

The Electronic Flight Bag is developed by Jeppesen [27] to increase efficiency during aircraft operations. The EFB, composed of hardware and software, provides an integrated information management both in the air and on the ground and is available in three different configurations: Class 1, Class 2 and Class 3[2]. In 2008, Jeppesen was granted FAA approval for its AMM application for Class 2 EFB devices [27].

EFB may incorporate rapid updating like NOTAMS (Notice To Airmen) updates and route information.

The aircraft position estimate is depicted on a detailed AMM (Airport Moving Map) on the EFB head-down panel. This display of the estimated position enhances safety and security. Only the aircraft own position is displayed on the taxi-moving map. This position is represented by a blue triangle as depicted in the Fig. 1.



Figure 1: EFB taxi moving map [3]

The EFB also depicts the name associated to each taxiway. Hence, the pilot has a better idea of its course on the airport surface and can anticipate. A zoom on the map is also available.

The accuracy of the maps over an entire airport is about 3-5 meters [3].

III.2 OANS

The OANS dynamically displays on Navigation Display the airplane position (Fig. 2) over a high-resolution geo-referenced airport moving map, using an Airport Mapping Database (AMDB) [4] to facilitate taxi maneuvers, particularly at large airports. AMDB is developed according to RTCA DO272 and EUROCAE ED99 and RTCA SC-193 / EUROCAE WG-44. The OANS offers to pilots an easy access to the information presented on the Navigation Display through a unique Cursor Control Device. During Flight operations, the OANS allows the flight crew to consult the airport map and to prepare the navigation on the selected airport. All needed information to perform taxiing operation from and to the gate is displayed on the head-down panel.

The OANS also provides contextual information for implementation of the Brake To Vacate (BTV) and Runway Overrun Protection (ROP) functions [4].

By providing the crew with appropriate alerts, the system becomes an important means to avoid potential

Runway Incursions and navigation error, such as take a wrong taxiway, on airport surface.

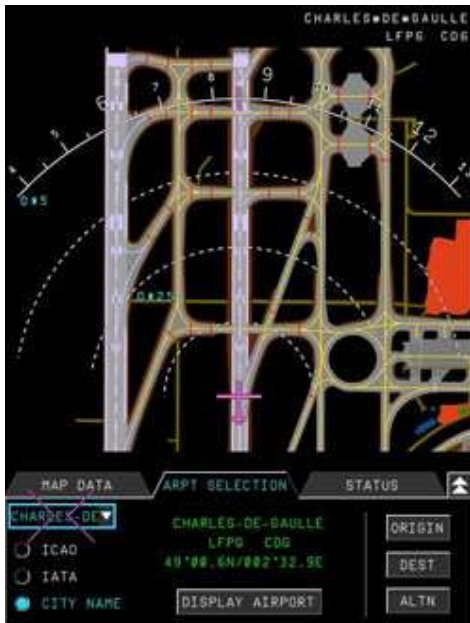


Figure 2: OANS display [4]

IV. Airport Navigation Application and Related Human Machine Interface

Research is currently investigating a number of new capabilities to assist the pilot during taxiing operations for navigation management and control of the aircraft.

The mid term new concepts concern two types of domains, guidance¹ and steering applications. For both guidance and steering applications, two different display technologies, EMM (Electronic Moving Map) or HUD (Head Up Display) are used to provide the navigation and control information to the pilot.

Final stage of research also investigates the capability to design system enabling a complete automation of the aircraft control during taxi operations.

IV.1 Guidance application

A guidance application will provide the pilot with indications for navigation over the airport surface in accordance with the ATC routing instructions.

¹ Use of guidance terminology is as per A-SMGCS concept definition: it corresponds to the management of the navigation on the airport surface during the taxi operation.

Current airport navigation applications just indicate the name of the taxiway. To improve efficiency, future applications will display clearances on the display so that the pilot can drive the aircraft according to these clearances. The path to follow will be underlined with a specific color or symbols.

Some alarms onboard could be defined to give more details to the pilot. Currently, if the pilot does not follow his cleared path, he is alerted only by the ATC (Air Traffic Control). This process takes time and may be replaced by an alarm that occurs when the aircraft does not follow the path given by the clearance. In the same idea an alarm may occur when the aircraft is detected in an area not allowed for his category. In addition, on the map might be placed some others mobiles for which the positions are provided by various A/C or ATC surveillance systems, that could interfere with estimated position. If a conflict is detected an alarm can warn the pilot.

IV.2 Steering application

Steering application will allow the pilot to drive in all weather condition using steering indications relative to synthetic vision. A virtual 3D image of the aircraft in the airport environment from the pilot perspective is generated from aircraft position and orientation, and displayed to the pilot. Inside the image, indications can be added showing the flight path as well as steering control information so that the pilot can optimally drive its aircraft during taxi operations.

IV.3 EMM

Current airport navigation capabilities are supported by the use of head-down or panel-mounted EMMs.

Graphically, the EMM depicts the airport layout including labeled taxiways, runways, and concourses. Current applications depict the position of the aircraft referenced to the airport map. Foreseen evolution is to add a number of additional contextual information for the management of the airport navigation operation.

For example, indication of the path to follow according to the clearance onto the map would reduce the crew workload. The cleared taxi route will be represented graphically and the own ship icon will be updated in real time and will depict the location of the own ship relative to the airport features and the cleared route. It is then expected that the EMM would improve navigation by clearly depicting the current estimated

position of the aircraft relative to the cleared taxi route to the next navigation decision point [13].

IV.4 HUD

The HUD presents symbols and displays flight information on a combiner glass. The information appears in the pilot's forward Field Of View (FOV). In current-day commercial aircraft, HUDs are typically mounted in front of the left seat, for use by the captain only. The HUD improves situational awareness in providing trajectory related symbols. These symbols are superimposed on to the pilot's actual external visual cues (horizon, runway ...).



Figure 3: Example of HUD in an aircraft cockpit [4]

New functionalities such as the Enhanced Vision System (EVS) and potentially the Surface Guidance System (SGS) in conjunction with the OANS as well as the Synthetic Vision System (SVS) are envisaged. The HUD system could be used because it provides a flexible platform to support these new functionalities [4].

The name of the taxiway displayed on the map is not sufficient for SGS due to the complexity of large airports. Another idea to reduce the crew workload is to indicate the cleared taxi route. Nevertheless, in low visibility condition, this information is not sufficient for the pilot. He knows where he must go on but he cannot see the taxiway. To solve this problem, a 3D visualisation of centerline and edges of taxiway could be superimposed to the real images sensed by the eyes of the pilot through HUD.

The real environment vision can be deteriorated by visibility conditions. The elements displayed on the HUD can become the main source of information to help the pilot to do ground maneuvers.

The HUD can be employed in two different ways. First, it can be used like EMM to provide guidance

information for the pilot. In low visibility condition, the HUD can provide steering information.

IV.5 Autotaxi

In the final stage of airport navigation, automatic control of the aircraft will combine the guidance and steering capability to enable an automatic control of the aircraft on the airport surface. It is also called autotaxi. Some studies have been done about automatic control of the aircraft on the ground considering actuators but all make the assumption that the aircraft position is known without errors.

V. Positioning Requirements for airport navigation

The common point for all these new functionalities is the need for the knowledge of the aircraft current position. This position is mandatory to generate the 2D map or 3D virtual reality displayed to the pilot (corresponding to its current perspective from the Airport Mapping Database) and to compute guidance and steering information. Therefore there is a direct relationship between the expected performance of the position and the way the new concept will be operationally used and implemented.

It seems natural to consider that the position must have

- Sufficient accuracy so that the displays are truly referenced with the actual situation of the aircraft,
- Sufficient integrity so that reliable guidance or steering information can be computed for safe navigation or control.
- Sufficient continuity so that the system can be used without undesired service disruption
- Sufficient availability so that the new functions provide reliable level of services

Also, it may be felt that these navigation performance will be modulated by the operational condition in which the system will be used. Integrity requirements on position will not be the same if the system is used for situation awareness, or if it's used for navigation/ or control of the aircraft. As well, integrity requirements will not be the same if mitigation can be provided through independent ATC surveillance, or through visual reference by the pilot.

Precise requirements on aircraft localization service on the airport surface, in terms of accuracy,

integrity, continuity and availability, have not been completely expressed by existing standards.

The main difficulty is the definition of the operational context for the use of such capability, incorporated and consistent with a global A-SMGCS vision.

The collision of two B747 on the ground at Tenerife has conducted ICAO to provide guidance material for the navigation system used on the ground. The document ICAO DOC 9476 about SMGCS (Surface Movement Guidance and Control System) was published in 1986 [15]. The basic principle of SMGCS is based on “see and be seen”. In the 90’s, the ICAO develops the A-SMGCS concept to take into account new technologies and to cope with the air traffic increase and the airport complexity.

A-SMGCS is mainly an ATM system which considers four main connected functions:

- Surveillance function concentrates and displays to the controllers the position and the identification of all aircrafts and vehicles on the airport surface.
- Routing function designates the most efficient route to follow for each aircraft or vehicle.
- Control function detects the conflict between moving aircrafts and provides to each aircraft the constraints and alerts relative to its followed path.
- Guidance function gives indication to the pilot to follow the assigned route.

Fig. 4 illustrates relationships between A-SMGCS functions

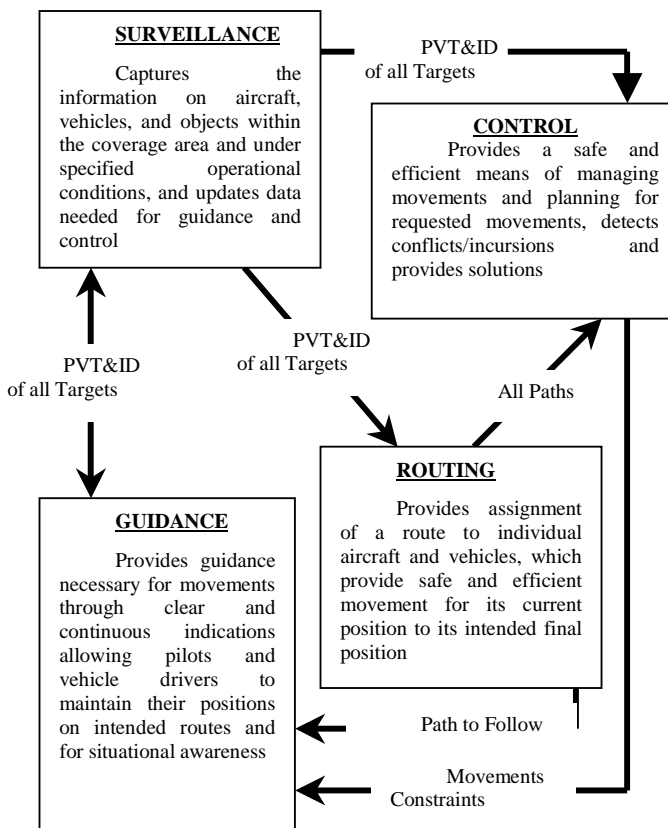


Figure 4: A-SMGCS functions relationship [5]

General objective of the A-SMGCS functions is to provide and organize the means for an efficient and safe traffic of the different mobiles on the airport surface.

A pragmatic strategy has been defined by EUROCAE WG411 in [25] for a progressive deployment of A-SMGCS taking profit of existing infrastructure existing at the airport surface or on board aircrafts. Four different level of maturity have been defined (see table 1).

Table 1: The different level of maturity of A-SMGCS [25]

Level	Surveillance		Control		Route Planning	Guidance	
	Users	Mobiles and area covered	Users	Conflicts detected	Users	Users	Type
I	Strict application of SMGCS						
	Surveillance						
	Controller	All Vehicles in the manoeuvring area All aircraft in the movement area					
II			Control			Guidance	
	Controller	All Vehicles in the manoeuvring area All aircraft in the movement area	Controller	RWY incursions		Drivers	Airport Static Map & mobiles position on a screen as an option
III					Route planning		
	Controller All participating mobiles	All Vehicles in the manoeuvring area All aircraft in the movement area	Controller Equipped mobiles	All conflicts	Controller	Pilots Drivers	Airport Dynamic Map (with runway status...), mobile position on a screen Automatic switch of a ground signals
IV							
	Controller All participating mobiles	All Vehicles in the manoeuvring area All aircraft in the movement area	Controller All participating mobiles	All conflicts + Conflict Resolution	Controller Equipped mobiles	Pilots Drivers	Airport Dynamic Map (with runway status...), mobile position & route from route planning function on a screen Automatic switch of ground signals

The implication of the airborne navigation means such EMM only appears at the latest stages of A-SMGCS deployment for guidance, but there are not yet quantitative/ or qualitative performance allocation requirements that clarifies how this function contributes to the performance objectives of the A-SMGCS system.

An allocation of the TLS (Target Level of Safety) (Fig. 5) between the different functions is generally agreed by the community at the top level of the function, but lower level allocation between the different actors contributing to the function is not possible because there may be different types of architecture for A-SMGCS.

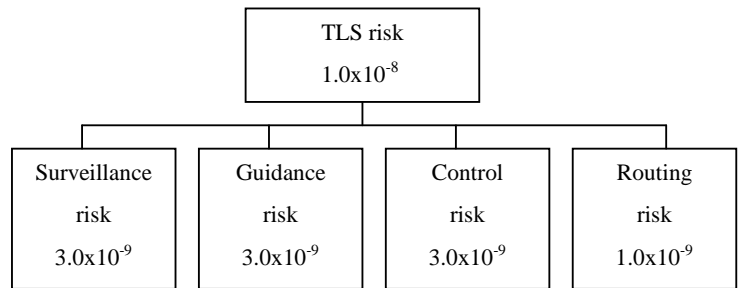


Figure 5: A-SMGCS Target Level of Safety [5]

In DO 247 [5], RTCA has investigated and developed further requirements for an architecture where airborne GPS receiver contributes to A-SMGCS architecture both for guidance and surveillance through the use of ADS-B.

The methodology retained for this allocation splits the top-level risk adjusted by a factor

representing the ratio between fatal accident and incident, between different operational phases (stand/gate, taxiway, apron). Risk allocation for guidance function is depicted in Fig. 6.

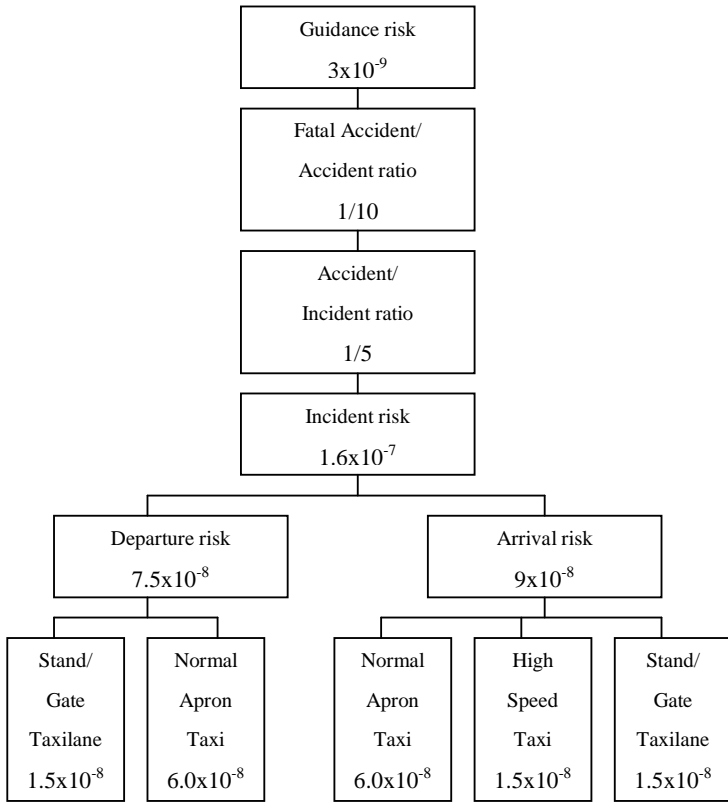


Figure 6 : RTCA Allocation [5]

But with the same methodology, other allocations for guidance have been proposed in the literature, [6] as depicted in Fig. 7.

The same Target Level of Safety (TLS) – 3×10^{-9} – and the same guidance allocation – 3×10^{-8} – are taken into account but the final allocation for the operational phases differ from one to another.

DO247 was written to show GNSS benefits for aviation users and to encourage exploitation of GNSS to support key operational operations, particularly airport surface operations. In this architecture, the airborne GNSS receiver becomes a key actor of the global architecture system and it has been demonstrated that performance of a GPS augmented by a LAAS augmentation supporting CATIII could also support the A-SMGCS architecture.

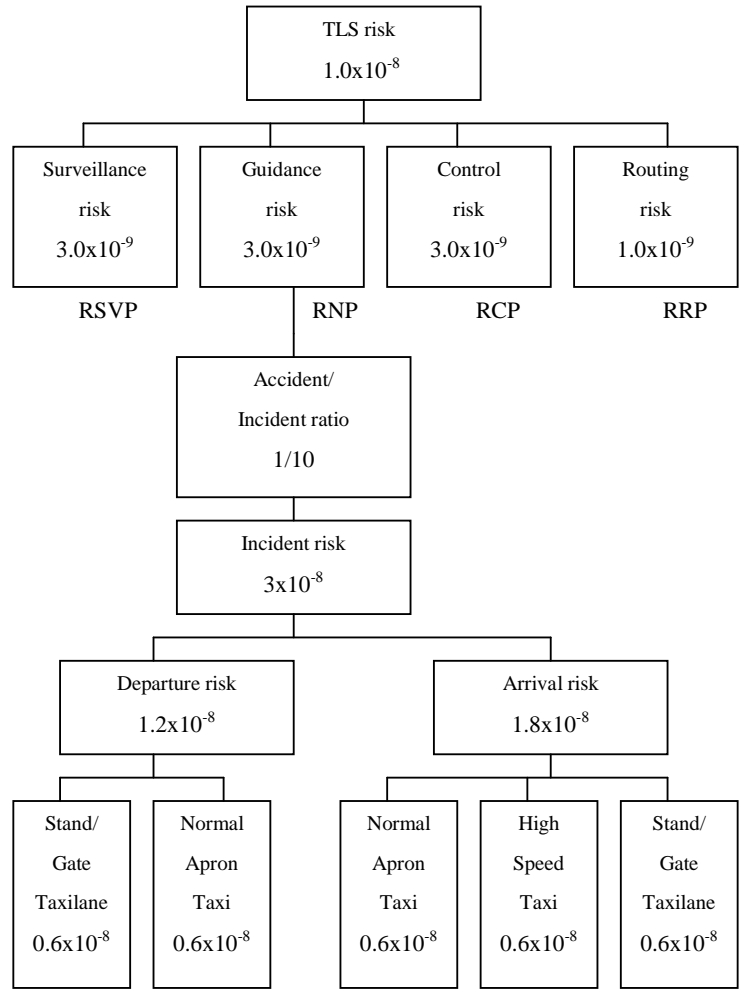


Figure 7: RSP allocations – Guidance function [6]

Some European studies, such as EMMA2 (European airport Movement Management by A-SMGCS, part 2) [18], ANASTASIA (Airborne New and Advanced Satellite techniques and Technologies in A System Integrated Approach) [19], and currently SESAR (Single European Sky ATM Research) [20] and ALICIA (All Conditions Operations and Innovative Cockpit Infrastructure) [21] are focused on the problem of aircraft localization on airport surface.

Some results of these studies or few papers [6] [7] present requirements for navigation system on airport surface. Table 2 presents the navigation system performance requirements introduced in [7].

Table 2: Surface Movement Signal-In-Space Navigation System Performance Requirements [7]

Accuracy	Integrity			Continuity	Availability
SIS accuracy (2 σ)	Alert Limit	Integrity Risk	TTA	Continuity Risk	
0.5 m	1.3 m	1.4E-7/ 90s	1s	7.5E-5/ 90s	TBD

From these different studies, it can be seen that there does not exist unique approach to derive requirements for an airborne localization system contributing to an A-SMGCS. Different approaches lead to different set of performance requirements.

Nevertheless, the common characteristics of these different set of performance requirements seems to show that the highest level of accuracy, integrity and continuity might be required to support the airport navigation applications.

Major issue is that such type of requirements are the limit of what current technology can provide, and the precise knowledge of the required performance will be the key element for the design of the system providing localization information.

VI. Aircraft positioning

Currently, a modern aircraft generally provides for in-flight navigation multi-sensor navigation system compliant with the requirements of the different area navigation specifications defined by the ICAO PBN (Performance Based Navigation) manual [24]. It is intended that these navigation means will be the basis for the delivery of the position supporting airport navigation applications.

This section recalls the characteristics and limitations of GNSS (Global Navigation Satellite Systems) and inertial navigation systems which are the primary candidates to compute airplane position.

VI.1 GNSS

Global Navigation Satellite Systems (GNSS) are global coverage satellite systems that provide position, velocity and time (PVT) services and provide a certain performance level in terms of

accuracy, availability, continuity and integrity. The satellite-based element is composed of three distinct parts, also called segments: the space segment, the control segment and the user segment. In the future it is planned that there will be several constellation providing signals on several frequencies available for civil aviation. Currently, only GPS L1 is used.

GNSS positioning is based on the trilateration. A user needs to track four satellite signals from the same constellation to determine the position. The pseudorange, between satellite and receiver, may be obtained using two types of measurements: the code and the carrier phase measurements.

Every single frequency GNSS measurement (pseudorange, phase, Doppler) is affected by a number of errors.

The main contribution is due to propagation phenomena. GNSS signals cross the atmosphere which is divided into several layers, and which affect the signal propagation.

In flight, ionosphere is the main source of raw GNSS errors for an airborne receiver. Then follows troposphere and multipath [17][23]. Corrections of these errors are necessary to achieve a precise aircraft positioning.

Ionosphere error can be eliminated using dual frequency measurements. If a single frequency receiver is used, error models such as the Klobuchar model can be used [22]. Troposphere delay can nowadays be accurately modeled.

To make GPS single frequency have a sufficient accuracy, integrity, continuity and availability for the most stringent civil aviation applications, augmentations are implemented that provide the user with additional information. Augmentations systems can be local (GBAS), regional (SBAS).

GBAS consists of a ground-based transmitter that sends corrections (ephemeris, ionosphere, troposphere, satellite clock corrections...) directly to users [8]. GBAS is currently dedicated to support CAT I precision approaches. As a consequence, it covers at least the final approach segments and the corresponding runways. Corrections are sent via VHF data link, so that VHF signal may not necessarily cover all the runway surfaces and taxiways and could be affected by multipath.

SBAS is a wide coverage augmentation system in which the user receives augmentation information from a satellite-based transmitter [8]. SBAS system, like WAAS (Wide Area Augmentation System) in US, EGNOS (European Geostationary Navigation Overlay System) in Europe, MSAS (Multifunctional Satellite Augmentation System) in Japan, transmits corrections. A large network of ground stations allows to estimate satellite ephemeris, clock corrections, ionospheric corrections and to estimate reliable model parameters. Performance (accuracy, availability, integrity) of GPS is improved. Modern GNSS receivers are generally capable of SBAS accommodation. However, SBAS satellites are geostationary so the satellite visibility condition depends on the general location of the airport at the earth surface, and on the location of the aircraft on the airport. For example, it will be more difficult to have SBAS correction for an airport situated on the north or on the south of the earth.

On ground, signal masking caused by buildings and natural obstructions and multipath can also deteriorate GPS signal. The impact of these effects can result in loss of signal tracking (partially or totally) or/and tracking error. Tracking errors can result in position errors. Multipath is the largest contributor on pseudorange error on airport surface [16][25].

The antenna environment (buildings, metal surfaces, water bodies, the ground...) creates multipath (see Fig. 8). In our case, the main factors are buildings and surrounding traffic [16][25]. A lot of parameters influence multipath error. So, it is difficult to have an error model for multipath in airport surface.

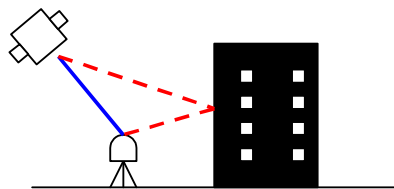


Figure 8: Example of multipath - Reception of two signals from the same transmitter

Important characteristic of GNSS is also the sensitivity of the performance to the disposition of satellites from the user perspective. At least, a limitation of GNSS is the number of satellites required to provide position services. To provide PVT services a minimum number of four satellites is necessary. Moreover, if a Fault Detection RAIM (Receiver Autonomous Integrity Monitoring) is used to monitor integrity a minimum of five satellites is required, and a minimum of six satellites is needed for FDE (Fault Detection and Exclusion). These requirements might be difficult to achieve in airport environment when buildings may mask the satellite. Airport navigations phases on apron or near the gates can be affected by this phenomenon due to the proximity with buildings.

Due to these limitations (multipath, loss of tracking), GNSS performance may not be sufficient for airport applications. Other sensors must be used on airport surface to provide reliable aircraft position estimate. One of the most employed is Inertial Navigation System (INS).

VI.2 INS

An Inertial Measurement Unit (IMU) is composed of 3 accelerometers (1 per 3D axis) and 3 gyrometers (1 per 3D axis). With the addition of a computer, the IMU becomes an INS. This computer computes position and velocity of the vehicle. Attitude of the vehicle is given by integration of gyrometers measurements, velocity is given by integration of accelerometers measurements, and with another integration, position is obtained. INS does not require external signals contrarily to GPS.

However, the estimates provided by an inertial sensor drift with time. It is due to the integration of the raw data to yield position. Any small error in the measurements is amplified after integration. The inertial sensors are unsuitable for accurate positioning over a long period of time, but short-term accuracy is good and acquisition rates can be high.

Inertial Measurement Unit and GNSS are generally used in combination due to their complementarities [14] and hybridization algorithms have been developed to provide 100% availability of positioning information with

performance compliant to the most stringent RNAV (aRea NAVigation) operations.

However, the performance achieved by current algorithms will not be sufficient to support the intended airport navigation functions, considering the specific environment of taxiing operations.

Therefore, other algorithms, sensors or means used to navigate in other applications such as terrestrial vehicles or robots will be envisaged to reach a better aircraft localization in these particular conditions.

The most popular sensors employed to navigate in the literature are wheel speed sensor [9], RFID (Radio Frequency Identification) [10], camera [11], Wi-Fi [12].

VII. Conclusion

After a review of the state of the art of the current airport applications currently available on the market, ideas to improve these applications have been introduced (display of the path to follow, display of the centerline). To develop these functions, the heart of the problem is to provide an aircraft position estimate with a high level of accuracy and integrity. The drawbacks (multipath, signal masking, drift) of current sensors (GNSS and INS) used to generate an aircraft position onboard show that other sensors are necessary to navigate safely on airport surface. To determine what kinds of sensors are required, performances of aircraft localization must be known. Actually, no standard delivers requirements for airport navigation system (in good as in low visibility condition).

As introduced in D0247, performance requirements for airport surface must be validated before performance standards like MOPS and MASPS can be finalized.

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