

Different civil navigation systems and their application during different flight phases

Yiyang Zhang*

International Department, Urumqi Foreign Languages School, China

* Corresponding Author Email: chenhongmei@ssedu.com

Abstract. The paper introduces three types of civil navigation methods and two of their derived methods: Inertial Navigation System (INS), Global Navigation Satellite System (GNSS), and land-based navigation systems (PBN is the derived method). The paper interprets the principles and characteristics of these navigation systems and gives examples of some specific navigation panels used on the aircraft. Aircraft in this paper mainly refers to fixed-wing large modern passenger aircraft (from the 1970s till today, like the Boeing 747). Comparing the characteristics of different systems, the paper also illustrates the application of these navigation systems during the take-off, cruising and landing phases. At last, the paper proposes the future development of civil navigation systems.

Keywords: civil aviation, navigation, INS, GNSS, PBN, accuracy.

1. Introduction

Navigation refers to the capability to determine the current and intended position (relative or absolute) and adjust direction, course, and speed to reach the desired position [1]. In the early days of aviation, pilots mainly depended on visual landmarks, compasses, and some simple flight instruments, like the Sextant and artificial horizon to navigate [2]. However, with the development of the aviation industry, the increase in flight distance, the complexity of airways, and the efficiency requirement gave rise to these primitive methods that could not meet the demands, especially for civil aviation. Precise navigation is a significant technology for civil aircraft flights to be safe [3]. International Civil Aviation Organization (ICAO) defines the basic navigation service performance requirements, namely accuracy, integrity, continuity, and availability. Beneath these criteria, there are mainly three types of navigation systems used by civil aircraft at present: inertial navigation system (INS), global navigation satellite system (GNSS), and land-based navigation systems [4]. The earliest system was the land-based system, and then INS, finally GNSS. These advanced navigation systems prevent aircraft from disorienting and keep aircraft displacing along the correct route, making sure that the uncertainty of the aircraft's location is acceptable. These accurate navigation systems make the airways more complicated and denser, noticeably improving the efficiency of air traffic. As a result, air traffic control has become easier and air traffic accidents have been significantly reduced. Nowadays, all these navigation systems are integrated into the Flight Manager Computer (FMC), so the accuracy of navigation is even higher. The major research object of this paper is fixed-wing large modern passenger aircraft (from the 1970s till today). The paper interprets the principles of these navigation systems and compares the accuracy and reliability of different specific navigation methods. The paper also aims to summarise the application of INS, GNSS, land-based navigation systems, and their derived navigation systems (such as RNAV, and RNP) in civil aviation during different flight phases, for example, the take-off, cruise and approach phases. The paper raises questions about the future development of civil aviation navigation systems and provides some practical examples.

2. Different Navigation Types for Civil Aviation Aircraft

2.1. Land-based Navigation Systems

The overall principle of land-based radio navigation is that the onboard equipment receives the signals from a land-based navigational beacon (or station) and determines its position relative to that land-based navigational beacon [4]. There are various types of land-based navigational beacons. This paper will discuss the following beacons: Non-Directional Beacon (NDB), VHF Omnidirectional Radio Range (VOR), Distance Measuring Equipment (DME), and Instrument Landing System (ILS).

2.1.1. NDB

NDB, or Non-Directional Beacon, is a type of land-based radio transmitter that emits signals to help aircraft with navigation. An NDB station usually emits a signal between 190kHz and 1750kHz. Automatic Direction Finders (ADF) are installed onboard using NDB signals to find navigational paths [5].

The pilot can enter the frequency of the corresponding NDB, and the radio magnetic indicator (RMI) can indicate the relative direction of the ND.

The pilot cannot get the specific distance of the aircraft from the beacon. However, the advent of NDB stations was remarkable. NDB stations brought the world of civil aviation into the era of radio navigation.

2.1.2. VOR

VOR, or VHF Omnidirectional Radio Range, is a type of air navigation system that provides aircraft with its bearing relative to the ground station. Its working frequency is between 108.00MHz and 117.95MHz. The pilot can set a course to go across the beacon if the aircraft is equipped with a Horizontal Situation Indicator (HSI).

The needle will shift left or right relative to the direction it is pointing. That means the VOR station is on the aircraft's left or right side. However, the distance is still unknown.

2.1.3. DME

DME, or Distance Measuring Equipment, relies on equipment both on the ground and in the aircraft. It times the interval between the "interrogation pulse" from the transmitter and the "reply pulse" from the receiver to measure the distance [6]. It is always combined with a VOR station so that the pilot can get the correct position of the aircraft. The combination of a VOR station and a DME station is usually called a VOR/DME beacon. The FMC (if the aircraft has an FMC onboard) can select an appropriate VOR/DME beacon for many advanced airliners automatically, like the Airbus A320. Therefore, the pilot can get the location of the aircraft relative to the selected VOR/DME station almost all the time. Another combination is called DME/DME. As its name suggests, a couple of DME stations can also locate the aircraft.

2.1.4. ILS

ILS, or Instrument Landing System, comprises a localiser transmitter, a glideslope transmitter, and marker beacons. These components provide azimuth, vertical, and distance signals, respectively [7]. The aircraft must be equipped with an ILS unit receiver. The receiver can receive all the signals from the localiser and glideslope only by entering a single ILS frequency. The location of the aircraft concerning the localiser and glideslope is displayed on an indicator (like HSI or ND) in the cockpit and is utilized to land safely [7].

2.2. Inertial Navigation System (INS)

Inertial navigation can autonomously calculate a moving vehicle's position and velocity by using measurements of angular rotation and linear acceleration if inertial sensors are mounted on the vehicle (gyros and accelerometers). The first INS was created at the MIT Instrumentation Lab (eventually becoming the Charles Stark Draper Laboratory) for missile navigation [8]. A general way to operate

an INS is firstly entering the initial position of the aircraft, and then the INS will calculate the displacement vector of the aircraft by doing integral all the time and then adding the vector to the initial position. INS was widely used in about the 1960s, and it is still used as an important navigation system nowadays. There are mainly two types of INS: Gimbaled (or platform) INS, and Strapdown INS (SINS).

2.2.1. Gimbaled INS

In a gimbal INS, inertial sensors are installed orthogonally to a common base "platform" surrounded by concentric gimbals. They are interconnected to the platform and each other through ball-bearing shafts [8]. Delco Carousel IV-A (CIVA) INS was a kind of widely used gimbaled INS in the 1970s, and its Control Display Unit (CDU), was its Mode Selector Unit (MSU).

2.2.2. Strapdown INS

SINS replaces the gimbaled platform with a computerised analytical equivalent and straps the inertial sensors directly to the user vehicle [8]. Litton LTN-92 was a kind of SINS used in commercial aircraft in the 1980s.

2.3. Global Navigation Satellite System (GNSS)

The GNSS is an essential technology that provides information about space and time [9]. GNSS includes The United States' GPS, the European Union's Galileo satellite navigation system, Russia's GLONASS, and China's Beidou satellite navigation system (BDS). GNSSs use navigation satellites for navigation [4]. The navigation satellites emit signals containing position and time information all the time. An onboard GNSS navigation system can consume the signals from satellites, and then calculate the location of the aircraft using a triangulation method. At least three navigation satellites are required. Additionally, GNSSs support various other aircraft systems, including the aircraft clock, terrain awareness warning systems, and different surveillance functions of the aircraft [10]. GNSS was widely put into use in civil aviation in the 1990s. An example of a GNSS onboard navigation equipment is KLN-90B.

3. Advantages and Drawbacks of Different Navigation Systems

3.1. NDB

NDB is such a conventional ground beacon, and it has no significant advantages at present. The pilot can get the relative orientation of the aircraft from the beacon but without distance information. This means that the pilot cannot determine the accurate position of the aircraft by merely a single NDB station. The signal coverage of an NDB station is relatively small, and the signal is sometimes unstable due to special weather conditions, so the pilot cannot get the precise location of the station from RMI. However, the cost of producing an NDB station and installing it is not so high.

3.2. VOR/DME

VOR/DME are the most used land-based navigation stations currently. Its signals cover wider than NDB stations. For a high altitude VOR/DME beacon, it can provide signals up to 60000ft high, and a diameter of 240km [11]. This means that the performance of a VOR/DME beacon is higher at high altitudes than NDBs. The signals of VOR/DME stations are also more stable than those of NDB stations. As the combination of DME, the pilot can get the accurate location of the aircraft by one VOR/DME beacon. If a display instrument (like HSI or ND) is installed in the cockpit, the pilot can manipulate the plane flying towards or backward the VOR/DME beacon in a certain course precisely. However, VOR/DMEs are not available for some long-range flights or transoceanic flights because of the restriction on the number of VOR/DME stations. The installation of VOR/DME beacons is limited due to the terrain.

3.3. ILS

The most significant advantage of an ILS station is its precision. ILS is only for approach and land use, so its range is small. ILS provides 3D navigation, including track and height.

3.4. INS

Neither satellites nor ground stations are required for INS to locate the aircraft. As a result, INS can enable an aircraft to fly transoceanic routes without the support of ground beacons or satellites, so INS is the most stable way to navigate. The accuracy of a conventional INS is continuously decreasing with the increase in flight distance. To improve accuracy, some INS have introduced some techniques. For example, CIVA can update the position data by referring to a couple of DME beacons. If the aircraft is equipped with three CIVA systems, they can collocate to give a more accurate position. This technique is called triple mix.

3.5. GNSS

GNSSs have a high positioning accuracy, which can reach the metre level, and even less than a metre, therefore, are crucial in civil aviation navigation technology [4][12][13]. Many navigation satellites are about 20000km to 30000km high and transmit signals between about 1.164GHz and 2.492GHz [12]. Nevertheless, satellite signal propagation is impeded in certain terrains, such as canyons.

4. Performance-based Navigation (PBN)

PBN combines onboard equipment capabilities with satellite navigation and other technologies [4]. The way to navigate is not limited to the onboard navigation facilities, but the navigation ability and accuracy of the aircraft [4]. PBN is usually used on advanced aircraft. This kind of aircraft integrates INS, GNSS, and ground station receivers, and FMC synthesises these navigation data to give a consolidated location and monitor the accuracy. PBN consists of two elements: Regional Area Navigation (RNAV) and Required Navigation Performance (RNP). RNAV allows the aircraft to be within the coverage of the navigation signals, within the capability limits of the onboard navigation facilities, or a combination of both, along any desired flight path. The required performance navigation is derived from area navigation, which also requires the aircraft to have onboard navigation performance monitoring and alerting capabilities [14]. RNAV can be categorized as RNAV1, RNAV2, RNAV5, and RNAV10 (Table 1) [14]. RNP can be categorized as RNP AR APCH, RNP APCH, Basic-RNP1, and RNP4 (Table 2) [14].

Table 1. RNAV

PBN	Navigation systems	Required accuracy
RNAV1	GNSS, DME/DME, DME/DME/INS	1NM
RNAV2	GNSS, DME/DME, DME/DME/INS	2NM
RNAV5	GNSS, DME/DME, VOR/DME	5NM
RNAV10	GNSS, DME/DME, VOR/DME	10NM

Table 2. RNP

PBN	Navigation systems	Required accuracy
RNP AR APCH	GNSS, DME/DME	0.1NM
RNP APCH	GNSS	0.3NM
Basic-RNP1	GNSS, DME/DME	1NM
RNP4	GNSS	4NM

5. Application of Navigation systems

5.1. Take-off and Climb

The navigation systems used in take-off and climb periods mainly depend on the departure procedure. There are mainly two types of departure procedures: conventional and RNP (or PBN, or RNAV). The conventional procedure means the aircraft is not required to have PBN ability. The aircraft only depends on NDB, VOR, and DME to execute conventional procedures [15]. For RNP procedures, PBN is required. The specific PBN requirements are shown in the chart of the procedure, and the navigation systems needed are shown in Table 1 and Table 2.

5.2. Cruise

For most domestic inland flights, GNSS is the major navigation method when cruising, and some land-based beacons and INS are auxiliary. If the flight is long-range transoceanic, then the major navigation systems are INS and GNSS. For earlier aircraft, Boeing 747-200 for example, can cross the ocean only by using CIVA INS.

5.3. Approach and Land

ILS, or instrument landing system, as its name suggests, is designed especially for landing. It also provides navigation for the precise approach, because it can provide both the glideslope (vertical) information and localiser (horizontal) information, and its accuracy is high enough. ILS is the most used type of navigation when approaching. In addition to ILS, VOR/DME, NDB can also be the horizontal navigator. If the aircraft has an FMC, it can automatically reckon a glide path and guide the aircraft approaching based on the data of the altimeter. Furthermore, GNSS can also be a method to navigate the approach. However, only ILS can be categorized as a “precise approach”.

5.4. Application of PBN

Table 3 shows the application of different PBN levels [14].

Table 3. Application of PBN

PBN	Flight phases	PBN	Flight phases
RNAV1	Arrival, Departure, Initial approach, Go around	RNP AR PATCH	Approach, Go around
RNAV2	Inland cruise, Arrival, Departure	RNP APCH	Approach, Go around
RNAV5	Inland cruise	Basic-RNP1	Arrival, Departure, Initial approach, Go around
RNAV10	Transoceanic cruise	RNP4	Transoceanic cruise

6. Development Trends and Prospects

6.1. Possible new navigation system

A kind of novel navigation system is visual navigation. Visual navigation using cameras as part of a multi-sensor solution offers several advantages in such applications [16]. Using artificial neural networks, convolution, pooling algorithms and artificial intelligence training, visual navigation will be like a real pilot. Visual navigation aims to compensate for GNSS. All the navigation systems now applied in civil aviation are calculating the theoretical position of the aircraft all the time, but do not regard the specific practical conditions. The best way to get the real conditions is through vision. Visual navigation can make decisions according to the real situations it has “seen”. In civil aviation, visual navigation allows for automated take-off, landing, and taxing of aircraft. In 2020, Airbus’ ATTOL (Autonomous Taxi, Take-Off & Landing) system was successfully concluded [17]. Airbus has achieved autonomous taxiing, take-off, and landing of a commercial aircraft through fully

automatic vision-based flight tests using onboard image recognition technology - a world first in aviation [17].

6.2. Potential challenges for future navigation systems

There are still many significant challenges for visual navigation. Utilizing an appropriate error model for the specific task is one of the main challenges in monitoring the integrity of visual navigation, and real-time integrity monitoring is also challenging [16]. ATTOL system is also in development and still needs more experiments and tests.

7. Conclusion

Civil aviation navigation systems have matured over a long period, and today's aircraft can fly around the world with precise navigation equipment. An airliner today is equipped with all Land-based beacons, INS, and GNSS, and FMC can calculate the position of the aircraft and monitor the actual navigation performance at the same time. With the further development of the aviation industry, low-performance ground navigation stations like NDB will gradually disappear. More advanced and user-friendly navigation methods, such as visual navigation, will gradually make their way into the aviation industry. Civil aviation will become safer, more convenient and more efficient.

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