Chapter 3. Conventional Navigation and Standardization in Civil Aviation (Sherman Lo)

History of aviation navigation

TO DECIDE ON TERMINOLOGY

1) Glide slope vs glide path Glide path is general, glide slope is the device
2) Radio navigation vs radio navigation x
3) DME beacon or transponder

3.1 Introduction:

The prior two chapters detailed GNSS and its use for aviation. However, aviation navigation has a rich history prior to the introduction of GNSS and satellite navigation. So-called conventional navigation aids such terrestrial radio and inertial navigation systems form the backbone of the airways around the world and still remain the primary source of navigation for most aircraft and aviation operations. Many terrestrial systems will continue to play a vital role in aviation navigation in the next 50 year. Conventional navigation aids, such as inertial navigation, also will play an important role in a GNSS primary environment. The development of these systems also provided technologically and institutionally experience which helped make aviation one of the safest modes of travel. This experience did not come for free. The history of aviation is written in blood [1]. Tragedies and accidents often provided the understanding needed and motivations for major advancements and regulations. As we further develop GNSS to serve an increasing number of aviation operations and users, we should use these hard earned lessons to guide these advancements. This chapter examines the history of key aviation navigation systems to better understand our navigation infrastructure and as well as the lessons learned in developing and implementing them. We take for granted that aviation is one of the safest means of travel. This outcome is by no means preordained. In fact, aviation fatalities were commonplace in the early days of aviation. Experience from these hard learned lessons, which resulted in equipment, operational and administrative improvements, over time has exponentially improved aviation safety. Figure 1 illustrates this point and shows the fatal accident (fatalities) rate on US commercial carriers over time [2]. The figure shows a logarithmic decrease in fatalities with a zero value indicated by 10^{-6}.

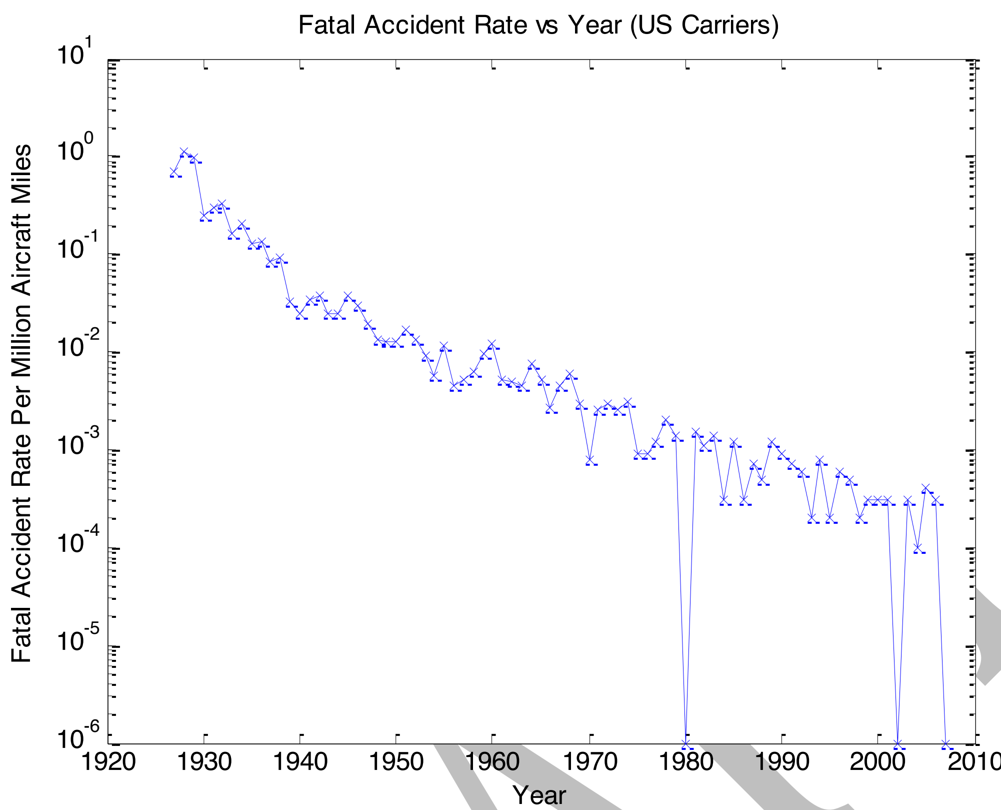


Figure 1. Fatal Accident Rate (Per Million Aircraft Miles) vs Year for US Carriers; a value 10^{-6} represents 0. Data from [2]

This chapter is organized as follows. Section 3.2 is the main section of this chapter and it covers a selected history of aviation navigation and conventional navigation aids. We will examine the history of conventional navigation aids through the development of three key systems: instrument landing system (ILS), distance measuring equipment (DME), and inertial navigation systems (INS). The history also highlights some of the challenges faced and the lessons learned in creating and standardizing conventional navigation systems. Aside sections details the technical operations of these key systems. Section 3.3 discusses the role of conventional navigation systems as GNSS becomes more and more prevalent in aviation. Section 3.4 overviews the different standards documents and bodies and their relationships. DME standards both for European and US are used to illustrate the relationships. Section 3.5 concludes the chapter with some closing thoughts.

3.2 Aviation Navigation: A Selected Examination of the First 100 Years

Navigation and aviation are intrinsically tied. The fundamental purpose of flight is to get from one point to another. Visual aids were sufficient in the earliest days of powered flight to support short trips in clear weather. However, as the desired distances and operational conditions increased, precise navigation became paramount. In the initial decades following the 1903 Wright brothers flight, few navigation aids were available for early pilots and pilots used whatever was readily available such as magnetic compass and using roads and railways. The latter is a practice that is still followed today by some visual flight rule (VFR) pilots for whom flying IFR facetiously means "I follow roads". Bonfires were often lit for lighting during night and low visibility conditions [3]. However, accident rates remained very high and this ad hoc navigation system would not serve air commerce. To fully realize the capabilities of commercial air services, aviation and the air space needed more organization, coordination and regulation. This was initiated in the United States (US) by the Air Commerce Act (1926) which chartered a bureau to oversee aviation. This act established the first agency to oversee and regulate aviation in the US, the Aeronautic Branch, later renamed the Bureau of Air Commerce (BAC), within the Department of Commerce.

3.2.1 The Instrument Landing System (ILS)

At this time, aviation use was rapidly growing, with air travel nearly doubling each year from 6 million miles in 1927 to 25 million miles in 1929. Mail delivery and other commercial enterprises meant that aircraft operations would need to proceed even in inclement weather and conditions. A key need was a means to land in poor visibility conditions. It became apparent that more advanced navigation aids were needed to guide aircraft through landing and that without it, safe and reliable operations were not possible. For example, from July 1924 to July 1925, there were 750 forced landings with 77 % caused by weather [4]. Prior to his Atlantic crossing, Charles Lindbergh nearly lost his life trying to find a place to land at night. Many concepts were proposed in the US and Europe to solve this problem. The concept of a radio navigation aid, later known as the instrument landing system (ILS), providing "blind landing" represented a paramount goal.

The first tests of radio based landing were conducted in 1929 using low frequency (LF) signals. It had a localizer providing horizontal guidance and marker beacons indicating location along the course. These initial tests showed that vertical guidance is vital and the glide slope, an instrument indicating the desired glide path, became a fundamental element. Hence ILS is primarily composed of three separate radio frequency (RF) components – localizer, glide slope and marker beacon [SEE ASIDE]. A basic system with these elements was tested in 1931. By 1933 both the National Bureau of Standards (NBS) and the United States (US) Army were developing and testing versions of instrument landing systems.

These further tests clarified the essential characteristics of ILS and its components, specifically the need for: 1) approach lights, 2) a *straight line* glide path (generated by the glide slope equipment), 3) a higher than LF frequency signals and 4) a means to detect and intercept the localizer. In 1935, the BAC started testing its own system. With several competing technological efforts and three key components, it should come as no surprise that it took many years of adjudication, discussions and further testing and development before an ILS standard was adopted.

Of course, the NBS, US Army, US Navy and BAC were not the only stakeholders. Private industry, in particular, commercial aviation had immense economic motivation for all weather operations. So in 1935, Rex Martin, the Assistant Director of the BAC, encouraged the formation of the Radio Technical Commission for Aeronautics (RTCA) "to prosecute a continuing study of radio problems as they affect air navigation. [5]." Although, the RTCA had no legal authority, by building consensus amongst its members including manufacturers, airlines and other governmental stakeholders, it would have "authority of agreement". This is important as the Bureau also lacked any power to create standards – it could only recommend. Furthermore, it could neither enforce nor procure operational equipment.

Still, by 1939, there was still no consensus on what technology ILS should use. The glide slope technology was a particularly sticking point. The system being developed by the BAC, which, in 1938 was reorganized into the Civil Aeronautics Authority (CAA), used very high frequency (VHF) and could not produce the straight, long (6 mile) glide paths desired by the US Army. Hence the Army favored microwave technology which had the promise of producing the desired glide paths. This disagreement reached the highest ranks and President Roosevelt, in May 1940, abrogated a compromise (the National Academy of Sciences report on blind landings) whereby the CAA system would be operated as an interim standard while research continued on a final system.

3.2.1.1 Developing the Components of ILS

Compared to glide slope development, the beacon and localizer elements proceeded with much less controversy and change. The initial ILSs used three beacons to indicate distance to the runway. In 1937, the RTCA recommended the use of 75 MHz transmissions with the ability to identify the beacons aurally and visually. As the aircraft passed over each beacon, cockpit instruments would alert the pilot of the beacon it was overflying. The CAA, unlike the BAC, had the authority to procure equipment. And so, in 1939, the first permanent installation of these marker beacons was made.

Also, in 1937, the RTCA established the basic operating frequency and characteristics of the runway localizer [6]. The runway localizer was to operate in the ultra-high frequency band (UHF) around 100 MHz and provide a straight course. The stated goal of the RTCA in establishing these characteristics was to provide guidance and develop a CAA installation to get "more experience under conditions approaching service conditions." It was not meant to settle on a system or technology. The approach seemed sensible as there were still many competing systems (e.g. Sperry), frequencies (e.g. microwave), and antenna implementations being developed and tested. However, the circumstance of the world trumped intent. The coming of World War II expedited the deployment and adoption of the CAA VHF localizer and established it as the *de facto*, though not *de jure*, ILS standard for horizontal course guidance. Deployment started in 1941 as the US Army had a pressing need and wanted an immediate and ready solution. In this regard, the CAA localizer system had several advantages. It was suitable for horizontal guidance, its VHF technology was mature allowing for rapid deployment and it could be made portable. All these factors led the US Army to adopt this (and the CAA beacon solution) to form the horizontal guidance component of its portable SCS-51 system. With the SCS-51, one finally had a system that achieved necessary properties targeted by the most demanding ILS customer, the US Army

While adopting the localizer, the US Army continued research means of generating a better glide path. It held out for a microwave based system which would enable very straight and long approaches. It took over the CAA system which was UHF system with a 93.7 MHz constant intensity glide path. The system was not suitable as it produced a curve glide path. The Army contractor replaced this system with a system that multiplied up the localizer frequencies to 330 MHz for transmission on the glide slope antennas. This system simplified the equipment, allowed for straightening of the glide path and performed well enough for the US Army Signal Corp to procure 350 units as the glide slope component of SCS-51 system. Still, this was felt to be a temporary solution until microwave technology became sufficiently mature. Again, the momentum of the wartime procurement also resulted this being the adopted glide slope system, settling the ILS design debate.

Despite the capabilities and significant wartime deployment of SCS-51, there was still no consensus on the adoption of a landing system. In immediate years after the war, the debate on landing system broadened from a discourse on how to technologically implement ILS to one on how to provide a guided approach. The ILS concept was challenged by an alternative landing method called ground controlled approach (GCA). The controversy set different aviation stakeholder against each other.

GCA used radar to provide guidance information to ground personnel who would then instruct pilots on how to maneuver. This system used compact microwave hardware on the ground and required no instrumentation on the aircraft or additional pilot training. This was very attractive to general aviation as represented by Aircraft Owners and Pilots Association (AOPA). It was also attractive to the US Navy which could put it on aircraft carriers. However, it required a skilled ground crew and took control out of the pilot's hand which made it an anathema for the CAA and the air lines pilots association (ALPA). The fights over GCA versus ILS resulted in vitriolic public debate, a contested congressional hearing, and finally in congressional elimination of CAA landing aid funds for its adamant stand against GCA.

Fortunately, a compromised was worked out. The key was understanding that GCA and ILS could be complimentary and could help overcome some of the deficiencies of each system. The issue was turned over to RTCA, which was seen as a technical organization and hence a less biased arbiter. RTCA Special Committee (SC) 31 published a report in January 1948 arguing for having both ILS and radar in the form of precision approach radar (PAR, the radar surveillance component of GCA) and airport surveillance radar as part of an integrated airspace infrastructure.

Testing that resulted from the ILS/GCA debate also helped to ensure that runway lights became an integral component of ILS. Strangely enough, despite early indications, the need for runway lights was not a strong consideration during the initial development of ILS [4]. Wartime experience and uproar from private pilots finally brought about the adoption of a standard lighting arrangement at every ILS runway in the 1950s.

3.2.1.2: ASIDE/INSET Technical Details of ILS OPERATIONS

ILS consists of three major components: localizer, glide slope and distance indicator

The ILS localizer consists of an antenna array that transmits signals on a VHF carrier frequency. These localizer frequencies and their corresponding glide slope frequencies are seen in Table 1. The array is constructed such that the antennas generate two carrier modulated signals. One is modulated at 150 Hz signal and dominates right of the centerline (as seen by an approaching aircraft) and the other, modulated at 90 Hz, dominates the right. The aircraft measures the depth in the difference of modulation (DDM) between the signals which indicates the horizontal deviation of the aircraft from the ideal. The ideal path is one where the difference is zero. On the aircraft, the deviation from the ideal center (where the two signals are balanced) is indicated on the ILS instrument by dots of deflection from the centerline. The full horizontal beam width ranges from 3 to 6 degrees and is set such that the beam is 700 feet wide at threshold. This is shown in Figure 2. To support different runways and approaches, forty different VHF carrier frequencies (108.1-111.95 MHz) are allocated. Each frequency is matched to one of the 40 glideslope carrier frequencies thereby forming the 40 ILS channels.

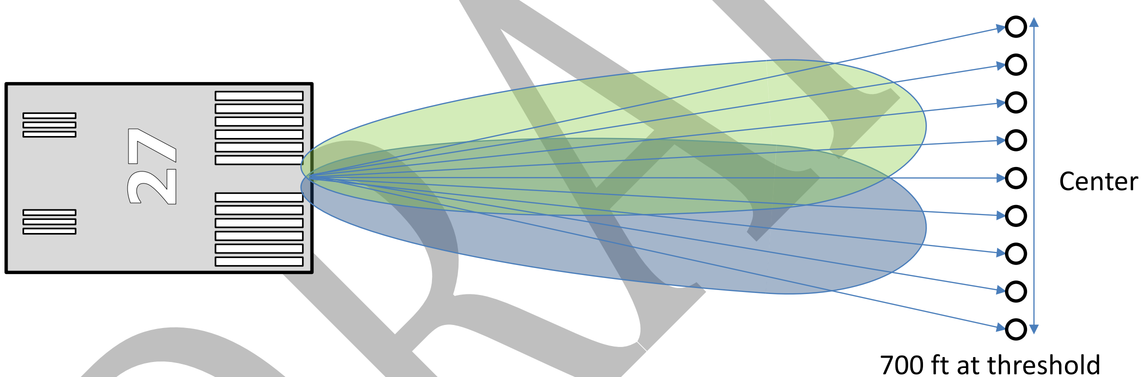


Figure 2. ILS Localizer for a 5 degree wit

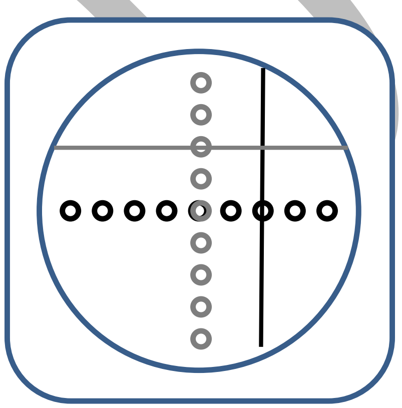


Figure 3. ILS Avionics Cockpit Guidance Display

The ILS glide slope works in a similar manner to the localizer. Two modulated signals on the same carrier frequency are transmitted about the ideal glide path which is typically 3 degree from the ground. Each ILS glide slope operates on one of 40 UHF carrier frequencies between 329.15-335.0 MHz. Like localizer, the carrier is modulated with either a 90 Hz or 150 Hz tone with the 90 Hz tone being dominant above the glide path. The beams are typically generated by co-located antennas on an aerial on the side of the runway. The beams typically range from about 0.7° below the glide path center to 0.7° above. The ILS instrumentation indicates the results by showing where the aircraft (center) relative to the ILS centerline (cross hair, zero deflection on glide slope and localizer). The deviations of the aircraft with respect to the glide slope and localizer is indicated to the pilot in one central display on the aircraft. This is shown in Figure 3.

Table 1. Corresponding Localizer & Glide Slope channels frequencies

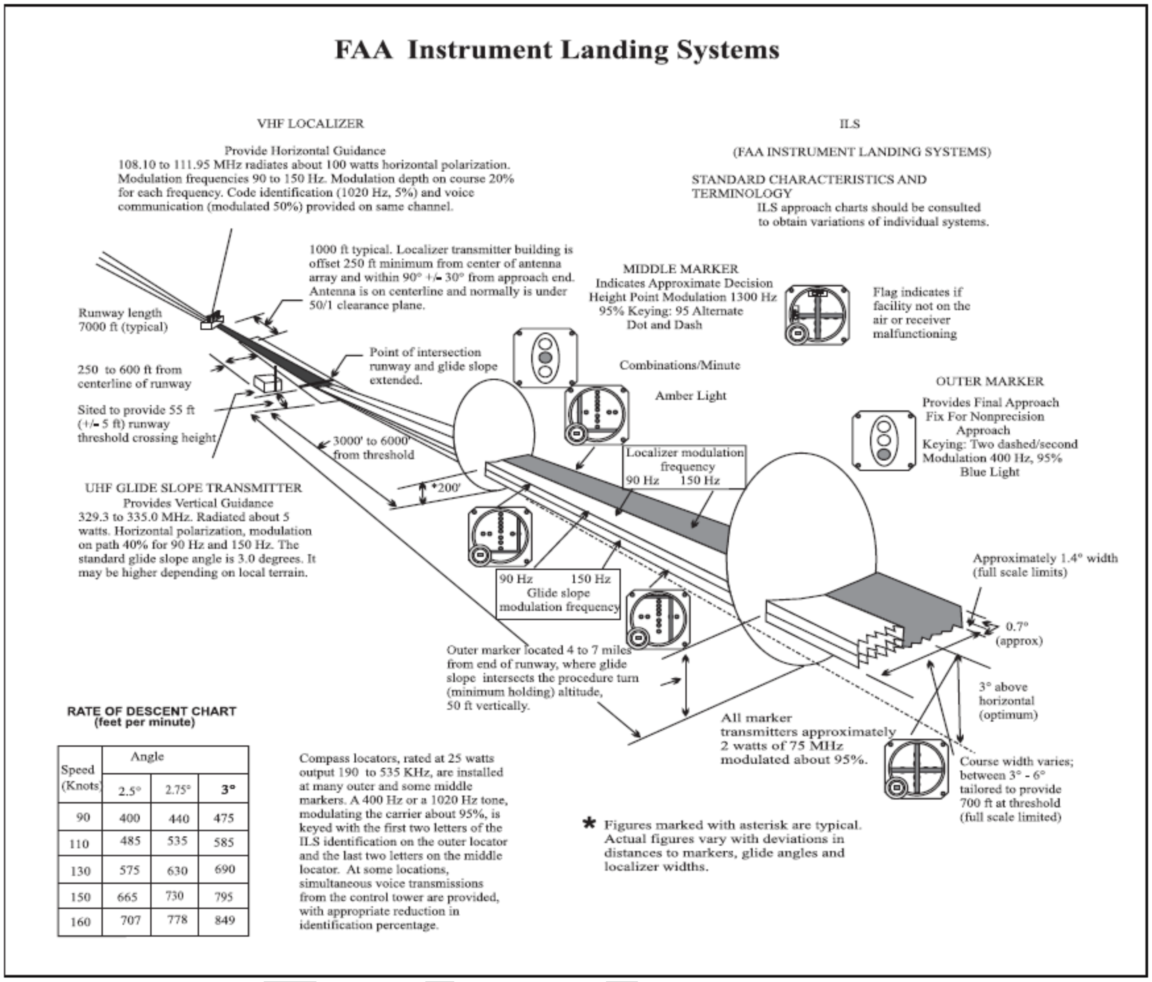
Localizer	Glideslope	Localizer	Glideslope	Localizer	Glideslope	Localizer	Glideslope
108.1	334.7	109.1	331.4	110.1	334.4	111.1	331.7
108.15	334.55	109.15	331.25	110.15	334.25	111.15	331.55
108.3	334.1	109.3	332	110.3	335	111.3	332.3
108.35	333.95	109.35	331.85	110.35	334.85	111.35	332.15
108.5	329.9	109.5	332.6	110.5	329.6	111.5	332.9
108.55	329.75	109.55	332.45	110.55	329.45	111.55	332.75
108.7	330.5	109.7	332.2	110.7	330.2	111.7	333.5
108.75	330.35	109.75	332.05	110.75	330.05	111.75	333.35
108.9	329.3	109.9	333.8	110.9	330.8	111.9	333.1
108.95	329.15	109.95	333.65	110.95	330.65	111.95	332.95

To indicate distance along the approach, three marker beacons, the outer, middle and inner marker, are typically used. They all transmit using a 75 MHz carrier. When the aircraft is over the marker, standard ILS avionics indicate the situation both aurally and visually. In newer ILS, a low power (LP) terminal DME is used in addition to or in place of the markers and provides continuous indication of distance to the runway. LP DMEs are also more desirable as, unlike the markers, they do not require land off airport property.

The outer marker is furthest away from the runway and represents location of the final approach fix (FAF). It can be located 4 to 7 miles from the runway threshold with the typical distance being 4.5 miles. The marker can be identified aurally via Morse code of “dashes” on a 400 Hz tone at 2 Hz. The onboard ILS instruments flash blue to indicate when the aircraft is over the outer marker. In some airports, it is collocated with a non-directional beacon (NDB), a simple ground transmitter that avionics can use to determine direction to the transmitter, to aid in capturing the ILS (recall this was important feature to ILS).

The next marker is the middle marker which is located at roughly the missed approach point (MAP). The MAP is typically around 3500 feet from the runway. The middle marker is aurally identified via 1.3 kHz Morse code tone of “dash-dots” at 2 Hz. It is visually identified by a flashing amber light. The inner marker indicates that the runway threshold is approaching. It is aurally identified by a 3 kHz Morse code tone of “dots” at 6 Hz. It is visually indicated by a flashing white light.

Figure 4 shows these components as presented in the FAA Aeronautical Information Manual (AIM).



Speed (Knots)	Angle 2.5°	2.75°	3°
90	400	440	475
110	485	535	585
130	575	630	690
150	665	730	795
160	707	778	849

Figure 4. Instrument Landing System (FAA AIM) 0

3.2.2 International Civil Aviation Organization (ICAO)

At around the same time that the US Army ILS and other wartime navigation systems were being installed, progress was being made on the creation of an international organization to help harmonize aviation technical and legal standards. In December 1944, the Chicago Convention was signed by 52 nations and created the International Civil Aviation Organization (ICAO). The organization was provisional until half the signing nations ratified the convention and hence initially termed Provisional ICAO (PICAO). The stated purpose of the ICAO is for nations to agree:

“on certain principles and arrangements in order that international civil aviation may be developed in a safe and orderly manner and that international air transport services may be established on the basis of equality of opportunity and operated soundly and economically [8]”

The PICAO became permanent organization with the ratification of the Chicago Convention on March 1947 and became the ICAO the following month. By the end of the year, the ICAO became an official agency of the United Nations. The creation of the ICAO came just in time to standardize ILS internationally and to adjudicate adoption of the rho-theta concept, where by collocated ground beacons provide range (rho) and angle (theta) measurements to enable positioning and navigation. DME technology was designed to support the range element of the concept.

3.2.3 Distance Measuring Equipment (DME)

To use the initial ILS, one needed the ability to find the ILS and the airport itself. Radio navigation systems were also needed for cross country flight. Unfortunately, few radio navigation aids were available. Early radio navigation (1939) used four course ranges – four lanes to and from a given ground beacon [9]. However, these early radio navigation systems had several limits. They used LF which was becoming crowded communication band. They could only handle low traffic volume which was a severe limitation as air traffic rapidly increased in the 1930s and 1940s. LF is also susceptible to interference from precipitation static - charge build up and discharge that often occur during rain. Thus the reliability of these systems degraded during inclement weather – the times they are most needed. This led to the development and implementation of navigation based on collocated range and angle (rho-theta) measurements from DME and VHF Omni-directional Ranges (VOR), respectively.

The road to DME, much like ILS, was neither straight nor easy. First there was a debate over the adoption of rho theta system. VOR development was initiated in 1937 and the first practical VOR demonstrated at ICAO in late 1944 [10]. However, within ICAO, debate raged over the utility of VOR versus Gee, a hyperbolic radio navigation system [4]. Gee had the benefit of providing positions allowing an aircraft to operate anywhere in the airspace, what is now termed "area navigation" whereas VOR would constrain aircraft to specific airways. Paraphrasing E.R. Queseda in [10], rho-theta has the advantages of simple presentation, simple identification, ease in obtaining a track or a position fix, could be used without a computer or complex displays, single site installation and simple avionics. In short, it was simple to implement, equip and use. In May 1948, a RTCA special committee laid out the use of a rho-theta systems for aviation with no additional calculation. VOR and rho-theta eventually won the day due to its simplicity and its wide spread installation during the war. It was adopted by ICAO in 1949.

Even with the rho-theta concept based on VOR-DME being adopted, the design of the DME system was still unclear. Fundamentally, DME is a ranging system where an aircraft interrogates the DME ground station and receives a reply in response. The true range to the ground station is determined from the round trip time. The design of that transmission, like glide slope, was the source of significant debate and resulted in several competing designs.

Starting in the early 1940s, the CAA funded several developments for a ranging system. It was decided that a frequency of about 1000 MHz, later identified as 960 to 1215 MHz, should be used due to the better properties of the frequency and congestion at lower frequencies. The initial system being specified by RTCA Special Committee 21 (SC-21) was a 50 channel system. A separate RTCA committee (SC-22) indicated that 100 channels were needed. So, the SC-21 concept was reworked and several techniques were combined so that 100 channels could be provided using 20 radio frequencies (10 for interrogation and 10 for reply) with the frequencies separated by 2.4 MHz. For each frequency, 10 channels were accommodated through a pulse multiplex method whereby a different spacing between pulse pairs is used to indicate each channel. Hence two different channels share a common frequency for either interrogation or reply. But the channels are designed so they do not share both interrogation and reply frequencies. Geographic separation is used so that nearby stations do not generate on or near frequency interference with each other. By 1948, the CAA issued a contract for the first 15 such ground transponder devices with another contract for 450 Model DTB DME issued in 1950. By 1956, 276 Model DTB were installed [9].

At about the same time, the US Navy was developing Tactical Air Navigation (TACAN) which was a complete rho-theta solution providing both bearing and distance. The TACAN design allowed for a small portable azimuth system which was critical for carrier based operations as it was impractical to implement VOR on a ship. This became a US military standard as the US Air Force also adopted the system. The TACAN system operates in the same frequency range as the previously describe DME and had 126 channels separated by 1 MHz. TACAN beacon used pulse pairs with the two pulses separated by 12 microseconds.

This, of course, presented a problem as the two systems used the same spectrum and were not interoperable. Not only is this inefficient operationally but contrary to the Common System concept. This is the philosophy that US air traffic control and navigation should use a common system capable of supporting both civil and military requirements. The only deviation comes in the case of special military needs. The Common System concept became established through a series of legislation following World War II. In 1945, the Air Coordinating Committee was established to coordinate all interested US governmental agencies.

The establishing of the Common System concept made finalizing on one standard inevitable. That resolution came in the 1956 with US VORTAC decision which established VOR TACAN as the standard. For military users, TACAN would provide azimuth and range. For civil users, VOR would provide azimuth and TACAN or TACAN compatible DME would provide range. This essentially meant that the original DME standard used by Model DTB would have to be phased out. This original standard became designated ICAO type non-standard measuring equipment (NSME) with the DME standard being the one enunciated by the US VORTAC decision.

DME continued to evolve but these are mostly incremental changes to the original TACAN design. Additional codes, described in the Description section, have been added to support more capacity and services. However, today's DME would be well recognized by users of the original TACAN. For additional details and information concerning evolution of the DME pulse, see [9][11]

3.2.3.1 ASIDE/INSET: Technical Description of DME

DME works on the principle of round trip ranging whereby the range is determined by measuring the time it takes for a transmission to go from an aircraft to a ground station and back (via a reply). In DME, the aircraft avionics or interrogator initiates the process by transmitting interrogation signals. When the DME ground station receives an interrogation, it sends a reply (on a different frequency) after a fixed delay known as the reply delay. The aircraft, upon reception of the reply, determines the time elapsed between the interrogation transmission and reception of the reply. This is the time it takes for the signal to get to the DME station and back (round trip time) plus the reply delay. The range is the half distance traveled by the signal over the round trip time. The process is illustrated in Figure 5.

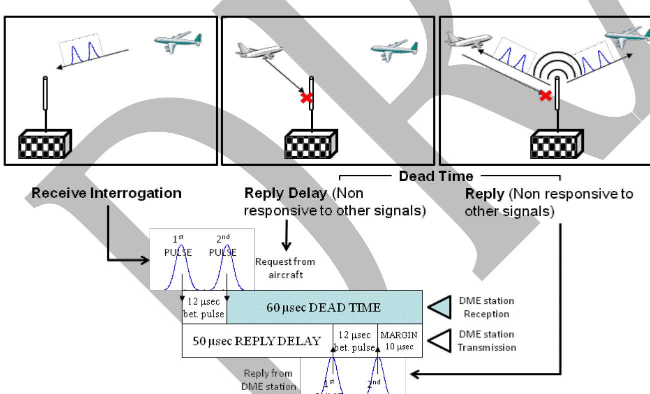


Figure 5. DME Transponder Response to Interrogations

An ideal DME signal is a Gaussian pulse pair with a fixed time interval between the two pulses. The first pulse is used for timing while second pulse provides for the positive identification of the pulses as a DME signal rather than spurious interference or noise. The time interval may differ depending on whether the transmission is an interrogation or reply as well the code used. As a result, all replies from a given station appear the same and are on the same frequency. DME avionics just starting to use a DME ground station without any knowledge of its range to the station cannot tell if a reply to its interrogation apart from a reply to another aircraft. The avionics conducts a search by making multiple interrogations and trying to find a series of replies which would result in a consistent round trip time. Search mode establishes the approximate range and can require up to 150 interrogation pulse pairs per second (ppps) may be used. Avionics today can conduct search using far fewer interrogations than earlier generations – closer to 30 ppps. After establishing the rough round trip time, the search space is narrowed and the avionics can enter track mode which typically uses 5-15 interrogation ppps to make its roundtrip time and hence range measurements.

DME/TACAN operates between 963-1213 MHz with adjacent transmission frequencies separated by 1 MHz. Geographically proximate DME stations operate on different and reasonably well separated frequencies to reduce interference and help with station identification. This is true for both interrogation and reply as the interrogation and reply frequencies are separated by 63 MHz. DME specifies several codes for transmission: X, Y, Z, and W. For each code, there are up to 126 interrogation reply frequency pairs or channels. Each frequency pair is unique and corresponds to a VOR channel/frequency. The primary DME codes are the X and Y. W and Z codes were developed for precision DME (DME/P) which was a more precise, approach DME standard to be used microwave landing system (MLS). DME/P is not commonly used in the United States. The code is encoded by specific delays between the first and second pulse in the interrogation and reply pulse pair. For an X code channel, the interrogation and reply pulse pairs are both separated by 12 μsec. For the Y code, the interrogation and reply pulse pairs are 36 and 30 μsec apart, respectively. The codes also have different reply delays. Table 2 summarizes these values for the channels when operating as DME/N or the initial approach (IA) mode of DME/P. For interoperability, DME/N and DME/P IA code is essentially the same. More details are given in [11]. Figure 7 shows the use and pairing of the interrogation and reply frequencies for each code.

Table 2. DME/N & DME/P IA Code characteristics

Code	Interrogation (μs)	Reply (μs)	Reply delay (μs)
X	12	12	50
Y	36	30	56
W	24	24	50
Z	21	15	56

DME beacons currently generate up to 2700 reply ppps and should be capable of supporting over 100 aircraft. Its transmissions are at a constant power level typically 1 kW for an en route DME. A TACAN beacon transmits an additional 900 ppps to provide azimuth information. The azimuth information is provided by comparing a 15 Hz North burst and a 135 Hz auxiliary burst to the TACAN amplitude envelope. These bursts are identified by its unique pattern. On an X code channel, the North burst consisting of 12 pulse pairs each and the auxiliary burst consisting of 6 pulse pairs. The amplitude of the transmitted signals are modulated generated by a cardioid rotating at 15 Hz and further modulated by a 135 Hz ripple. This is shown in Figure 6. A user compares the received amplitude of the 15 Hz burst relative to the overall envelope. If an aircraft is directly east of the TACAN, the North burst is at its maximum. At due west, the North burst would be minimum. Use of the 135 Hz auxiliary bursts allows for a more accurate azimuth measurement. The peak transmission power of a US en route TACAN is 3.5 kW [12].

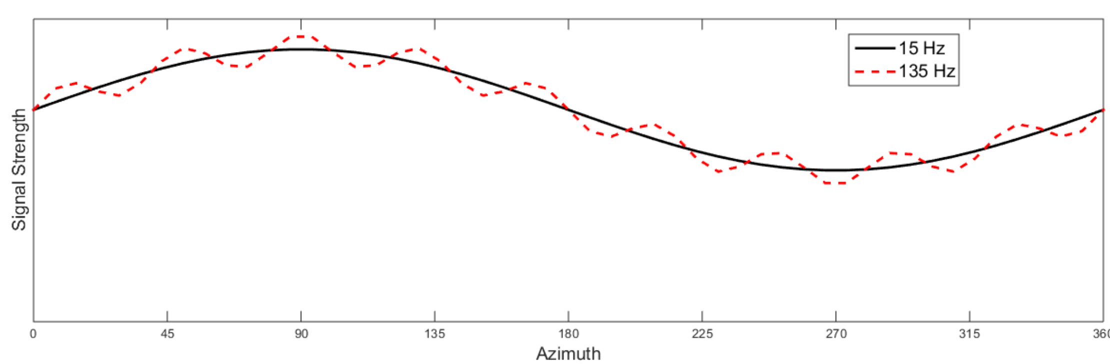


Figure 6. TACAN Amplitude Modulation Relative to Azimuth

In addition to replies (to interrogation for determining distance) and azimuth bursts (in the case of TACAN), both TACAN and DME have two more transmissions. Roughly every 30 seconds, a Morse code identification of the transmitter is transmitted. This comes in the form of 2 pulse pair set, with the pulse pairs separated by 100 ms, transmitted at 1350 Hz rate. Dots and dashes are indicated by having this 1350 Hz pulse pair set transmitted for 0.1 and 0.3 seconds, respectively. A gap of 0.1 and 0.3 seconds is used between dots and dashes within and between Morse code symbols, respectively. The other transmission is the squitter. The squitter or spontaneously transmitted pulse pairs are transmitted if the station does not receive enough interrogations to meet its minimum level of transmissions. For TACAN, this level is 3600 ppps and for DME, this can be as low as 900 ppps. The order precedence from highest priority to least is easily remembered using the acronym AIDS (Azimuth, Identification, Distance, Squitter).

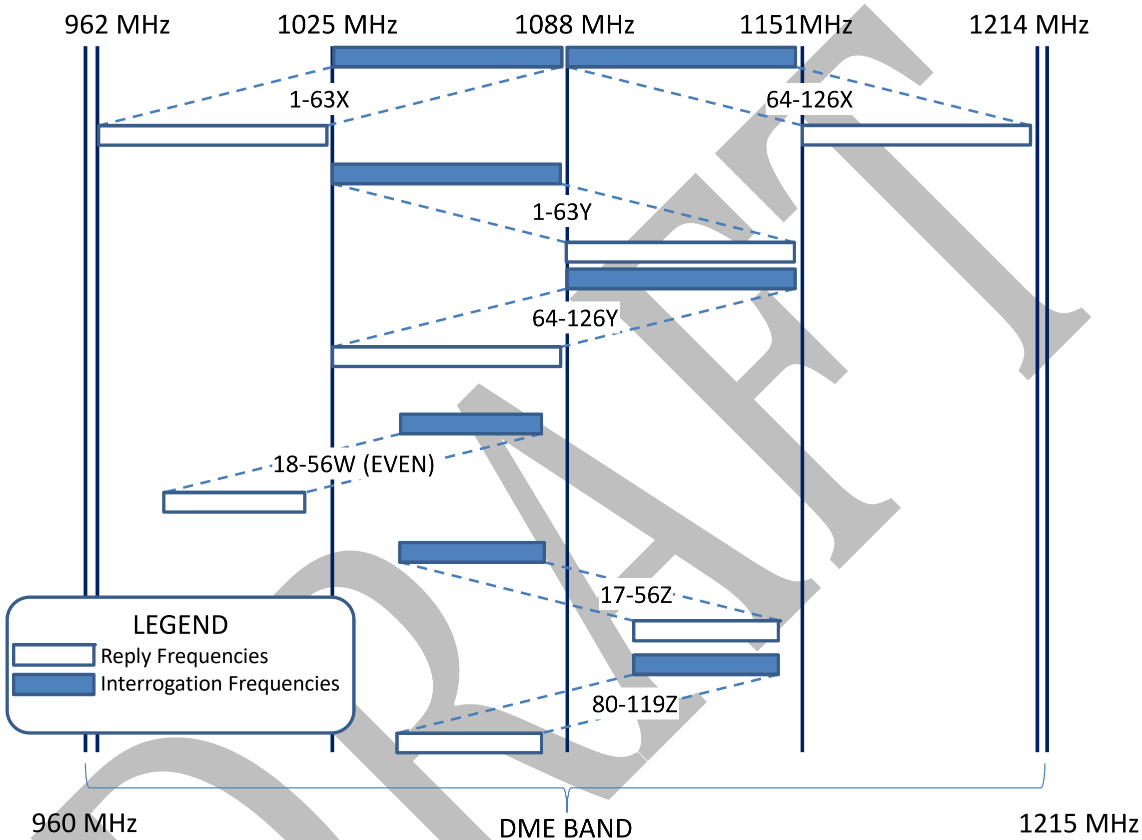


Figure 7 DME Interrogation-Reply Frequency Pairings for Different Codes Based on [11]

3.2.4 Formation of the FAA

The inefficient and disjointed adoption of the CAA DME (NSME) and TACAN highlighted a structural weakness of the CAA. It lacked adequate authority to oversee the national airspace (NAS) and its many stakeholders. The weakness of authority was fatally evident in a series of collisions in the early 1950s. The most dramatic was a June 1956 collision in Arizona between a TWA Super Constellation and DC-7 under VFR conditions. This accident resulted in 128 fatalities. One contributing cause was the lack of ability by air traffic control to separate IFR and VFR as well as fast and slow moving traffic. This led the US Congress to create an agency that could manage the full spectrum of airspace needs. Congress passed the Airways Modernization Act (1957) and the Federal Aviation Act (1958) which created the Federal Aviation Administration (FAA). The FAA was entrusted with the ultimate responsibility over developing, regulating and controlling the national airspace with responsibility over safety regulation as well as air navigation and air traffic control. One immediate task was to organize and the various fielded and developed systems such as DME, ILS, PAR and surveillance radars into an integrated modern airways system [4]. This action also had the foresight of recognizing that the airspace decisions affect both civil and military communities and that a unified organization is required to ensure that these needs are met harmoniously and effectively.

This development coincided with the growing use of commercial jet aircraft and the coming of the jumbo jet era. These would place even higher demands on the NAS. The NAS would have to support faster aircraft, flying at higher altitudes and on new routes. Late 1958 saw the first scheduled transatlantic jet flights. Supporting this capability required a high level of autonomy and reliability due to the gaps in navigation and surveillance coverage over the oceans. The development of inertial navigation for aviation helped provide this capability.

3.2.5 Inertial Navigation Systems (INS)

An inertial navigation system (INS) uses a suite of gyroscopes ("gyros") and accelerometers to measure rotation and acceleration of the vehicle and integrates the information from these inertial sensors to provide a position [SEE ASIDE]. The inertial sensors provide a relative measurement such as position displacement. The INS computer then calculates absolute position by tabulating the displacements from a known position. As such, an INS is self-contained and does not require external man-made signals. It is useful in areas with poor and no terrestrial radio navigation coverage. However, as INS position error grows in time unless calibrated by an absolute reference, it must have error characteristics that do not grow too quickly. For example, extended missions such as transoceanic flight require errors to stay below 20 nautical miles (nm) over several hours.

These INS capabilities started being available in the 1950s with the development of inertial technologies for attitude and navigation particularly for ship and ballistic missiles [14] [15]. The technology migrated to other applications such as military aircraft and spaceflight and by the late 1960s this technology (inertial measurement and computational technology) became viable for commercial aviation. The heritage of the earliest commercial aviation INSs, such as the Delco Carousel on the Boeing 747 (B747) Classic (100 to 300 series), can be traced directly to in the Titan II ballistic missile and the Apollo program [15]

Unlike the terrestrial systems discussed, the development of inertial navigation systems for civil aviation was not driven by the FAA or its predecessor. The advances came as a result of industry developing inertial sensors and platforms for various applications. Delco developed many of the early gimbaled INS while Honeywell lead the development of the strapdown INS in the 1970s. Additionally, as the system is contained within the aircraft, the FAA was not responsible for its operations. Instead, its role focused more on determining when and how INS can be safely used rather than defining the technology. Generally, the underlying technology may change as long as it meets FAA performance standards.

The earliest commercial aviation inertial systems, such as the Delco Carousel, were gimbaled systems. In a gimbaled INS, the gyros and accelerometer are attached to pivoted structures or gimbals that rotate these sensors to maintain the same orientation in an inertial reference frame. The inertial sensors were typically arranged orthogonally as seen in Figure 8. The amount of rotation of each gimbal indicate attitude. As the accelerometer are maintained in the same inertial frame, double integration of each accelerometer yields displacement along its axis [SEE ASIDE]. As such, gimbaled systems do not require significant computations to calculate attitude and position. Another benefit of gimbaled systems is that they can be easily calibrated on the ground by pivoting the gimbal mechanism through a range motion adequate for calibration. The drawback is that mechanical gimbals breakdown. Even with reliability improvements, the gimbaled INS typically had a mean time between failures (MTBF) of 2000 hours [15]. Two or three independent gimbaled INSs were commonly installed for redundancy. The 747 Classic had three INS which improved operations and allowed for transoceanic operations even after losing one INS.

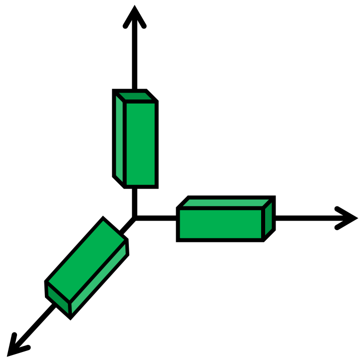


Figure 8. Classic Orthogonal Configuration of Inertial Sensors (Accelerometers & Gyroscopes) for IMU

With the introduction of these gimbaled INS, the FAA, in 1965 issued advisory circular (AC) 25-4 [16] to support use of INS in transport aircraft which allowed for its use as a means of navigation. Allowing the use of INS as a means of navigation meant that an aircraft equipped with two INSs could meet FAA rules for transoceanic flight which rules require two independent sources of navigation. To support these flights, the AC specified that the INS needed to have accuracy (95%) of 20 nm cross track and 25 nm along track in the horizontal direction. This AC was only recently (2012) superseded by AC 20-138C [17].

While inertial performance has improved, this has not resulted in equivalent gains in aviation INS operations or specifications. Indeed, while AC 25-4 performance specifications are easily met by modern inertial systems, performance assumptions remain essentially unchanged and aircraft only receives inertial coasting credit based on these assumptions. One reason for the lack of performance change is that inertial technologies are US export restricted and more accurate sensors would fall under these restrictions. Export limitations would prevent the use of more precise inertial technologies for many commercial airlines and vital routes. Instead, the focus has been on developing lower cost and more reliable inertial devices.

In the 1970s, advancements in the computational power of integrated circuits and gyro technology such as fiber optic gyros (FOG) and ring laser gyros (RLG), enabled the development and commercialization of strapdown INS, the dominant form of INS used today. With strapdown systems, the inertial sensors are fixed with respect to the aircraft, eliminating the mechanical linkages needed by the gimbals. The elimination of the mechanical gimbals greatly improved reliability and allowed for different configurations of the inertial sensors. Reliability with strapdown INS increased roughly an order of magnitude or more. MTBF range from 20000 hours [15] to 60000 hrs [18] with 100000 hours within the realm of possibility [18]. Strapdown inertial systems were introduced to commercial aviation in the Boeing 757/767 in the late 1970s. These strapdown INSs were significantly cheaper, by a factor of 2.5, than the gimbal based system on the B747 Classic [15].

Different implementations and configurations of strapdown inertial sensors were also possible. Three common implementations are as: 1) inertial reference units (IRU) which provides position output, 2) inertial navigation systems (INS) which combines the IRU with a navigation computer, and 3) attitude heading reference system (AHRS) which provides attitude information but not position information. An inertial reference system (IRS) is essentially an INS with lower navigation performance – 4 nm/hour [18]. INS is typically 2 nm/hour or better. The Boeing 777 (B777) air data inertial reference unit (ADIRU) sensor configuration demonstrates the flexibility of using strapdown. It has a set of six gyros and accelerometers in a hexad configuration, shown in Figure 9, to check in the measurement domain. This "skewed redundant" configuration provided the same level of redundancy as the B747 Carousel system while using fewer sensors.

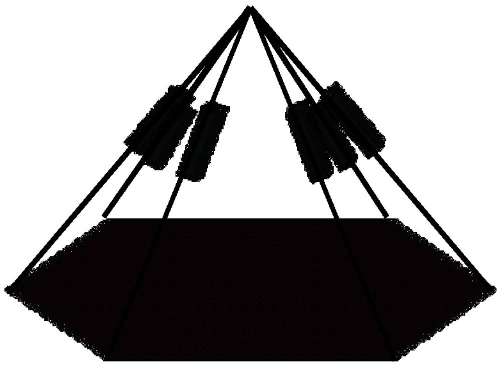


Figure 9. Hexad Configuration of Inertial Sensors in Boeing 777

The Boeing 787 ("Dreamliner") uses the same gyro sensors as a 757/767/777 but carries two fully functional IRUs capable of meeting 2 nm/hr accuracy (95%) and two IRUs that provide everything except position and velocity. Factoring inflation, the average cost of the IRU was 7 times less than the original goal set for 757/767 or about 20 times less than a gimbaled system [15]. The cost and performance benefits of strapdown INS has resulted in the rapid adoption and domination of this form of INS in aviation. By 1990, strapdown was essentially the only form of INS being produced [15].

The prevalence and reduced cost of INS allowed them to become a complement to the previously discussed systems, mitigating some of the shortcomings of these systems. INS is used to aid ILS to provide autoland – finally achieving the ultimate goal of blind landings. Inertial smoothing is used by autoland systems to handle the ILS errors that exceed those specified for Category III (CAT III) autoland. A DME/DME/Inertial (DDI)-equipped aircraft uses its INS to coast through gaps in DME coverage. With adoption of GPS by civil aviation, integrated GPS/GNSS INS became another common set up. For example, the 787 navigation set up also includes GPS and so it has 3 independent navigation sources (2 IRU and 1 GPS) allowing for transoceanic flights even with the failure of one source. Integration with other sensors is spelled out in Title 14 Code of Federal Regulations (14 CFR) Part 121 rules, Appendix G [20]. 14 CFR are also referred to as the Federal Aviation Regulation (FAR).

The misuse of inertial navigation also expedited the use of GPS in commercial aviation and other civil applications. In 1983, Korean Airlines (KAL) flight 007 unwittingly crossing in Soviet Kamchatka. The pilots were unaware and mistakenly thought they were on course navigating with their INS. In fact, they were over 200 nm off course and navigating using the magnetic heading while in INS armed mode (which would trigger INS based navigation if within 7 nm of the true course). The erroneous flight into Soviet airspace and cold war tensions resulted in KAL 007 being shot down by a Soviet interceptor. In reacting to the shoot down, US President Ronald Reagan announced that GPS would be available for international civil use [19]. While it is likely this decision to make GPS available would eventually have been made, the blood spilled in KAL 007 expedited this process.

3.2.5.1: ASIDE/INSET Inertial Navigation Technical Operations

Inertial navigation develops position, velocity and attitude based on measurements of rotation and acceleration. Gyroscopes provide a means of determining rotation through by measuring rotation rate. Accelerometers measure specific force which translates to acceleration, the contribution of gravity. We can readily see how the calculation is accomplished by examining a gimbaled INS. In a gimbaled INS, the gyroscope outputs drive torque motors that maintain the orientation of the sensors essentially fixing them in inertial space. A feedback control is employed on the gimbal torque motors such that the gyroscopes experience no rotation rate. With the sensors configured orthogonally, the resulting accelerometers output represent the acceleration in each of the principal axes in that fixed inertial space. Hence, to get velocity and displacement in each axis, a single or double integration of accelerometer in that axis is required. As seen in the figure, displacement in the x-axis is simply the double integration of the x-axis accelerometer and likewise for the other axis. Attitude is determined implicitly by the rotation of the gimbals. In a strapdown configuration, the calculation of attitude is more explicit and involves propagating the gyro outputs. As the accelerometers now rotate, the accelerations measured needs to be projected back into inertial space using the calculated rotations. Hence strapdown INS requires more computational resources and more accurate gyroscope.

Inertial gyroscopes and accelerometers can be implemented using many different technologies. While it is beyond the scope of this chapter to discuss them individually, we can go over the error types which are common to the sensors, despite the diversity of technologies. Major sensor errors include biases, scale factor and output noise. Biases are composed of null shift bias which are a fixed turn-on to turn-off bias and in-run biases which are non-constant, stochastic variations about the null shift bias. Scale factor errors are mapping deviations from sensor input to output. The perfect scale factor (sf) is one where a given change in input results in the same amount of change in output. A sf of .05 would indicate that with even the best straight-line fit between input and output, there is still 5% of deviation. Other errors commonly indicated are noise and bias instability. In addition to sensor error, there are errors due to implementation and installation. Assembling and installing the INS can result in non-orthogonality and misalignment errors, respectively. These two errors have very similar effects. There are second order errors include non-linearity and gravity sensitivity. Acceleration due to gravity and motion have the same effect, errors in the measuring the vertical results in displacement errors. This is known as vertical instability and without assistance from other sensors, such as an altimeter, the resulting altitude and position error can grow quickly and unstably. All of these errors have temperature dependency. As a result, INS/IMU often undergoes a lengthy calibration at the factory as well as calibration prior to each flight while on the ground (for example to calibrate null shift biases). Continuous calibration with other sensors (GNSS, DME) may also be employed but currently is rarely done.

There are many technologies and architectures for inertial sensors. Technical details of inertial sensors and their integration with other systems in aviation are provided in Chapter CCC.

3.3 Conventional navigation aid in a GNSS primary era

GNSS based navigation represents a new era in aviation and the transition to GNSS brings new challenges to air navigation service providers (ANSP) and civil aviation authorities (CAA). There are several important differences between GNSS and past systems that affect how GNSS is developed for aviation. Key amongst these are: 1) sovereign control of signal in space and 2) vulnerabilities and its effects.

In the terrestrial radio navigation systems previously discussed, control of the navigation source is held by the ANSP while the CAA is responsible for developing their safety regulation [8]. Terrestrial systems are typically owned and operated by the ANSP. The CAA set standards on ground equipment and avionics performance. For GNSS, the ANSP and CAA generally will have to rely on satellites and signals beyond their control. This is even true in the US where the US DoD operates and sets specifications on GPS while the US FAA is both the ANSP and CAA. So one purpose of GNSS aviation systems is to check the performance of the systems through monitoring or redundancy. The amount of trust to place in GNSS satellites and constellations is still a source of debate, as evident in the discussion on advanced receiver autonomous integrity monitoring (ARAIM) – see Chapter CCC. This is an important point as it determines what and how much monitoring and checking must be placed on the GNSS-based navigation system.

The vulnerability of the navigation source and the effects of these vulnerabilities are also different and handled differently. In an INS, the main vulnerability is sensor failure (loss or error) and redundancy is generally the primary mitigation. While system breakdown is also a vulnerability for radio navigation, GNSS also has the issue of susceptibility of the signal to jamming and spoofing. Terrestrial signals are typically received at high power – well above the noise floor. This makes them difficult to jam and hence the traditional safety analysis has examined equipment failure rates. For GNSS, signals are received at significantly lower power than terrestrial navigation signals as GNSS signals has generally lower transmit power and much longer propagation distance. Hence, GNSS has greater vulnerability to interference threats. Similarly, GNSS signals need to traverse greater distances and experience greater delays (ionosphere, troposphere) than terrestrial signals. Another consideration is the effect of such failures.

Failure of INS only affects one aircraft. Loss of a terrestrial DME or ILS signal due to jamming or to equipment failure is a local event. Generally, the affected level of air traffic that can be handled by air traffic via re-routing. In the case of GNSS, a moderately powered jammer (~10-100 W) can cause GNSS outages over a large area (100-200 nm) [21]. Widespread outage event in a high density airspace would be much more difficult to handle by air traffic.

An exacerbating factor with these vulnerabilities for GNSS is that it is a multimodal system whereas the conventional aids discussed only serve aviation. Jamming or spoofing of GNSS for aviation may just be collateral damage from attacks on GNSS for other uses such as vehicle tracking. Also, loss of GNSS may affect other systems that rely on GNSS for timing and synchronization. If the affected systems includes aviation communication and surveillance systems, it would be more difficult to handle outage.

In creating standards, these differences are important considerations. With traditional aviation systems, demonstrating safety primarily was focused on equipment reliability analyses. With these systems, the equipment or at least their specifications was under the control of the CAA. Hence, as the performance of the navigation system is specified by the CAA, equipment failure becomes a more tantamount concern. For the fielded DME or ILS, occasional checks of signals in space is conducted ensure safe use. In contrast, GNSS signals are not provided by the CAA. Hence, GNSS augmentation systems such as SBAS and GBAS, exists to provide continuous checks of the signal in space and ensure that these signals perform to desired CAA targets. Significant fault mode and effects analysis (FMEA) is conducted to demonstrate the safe of use of GNSS with the augmentation system.

In part because of these differences, conventional navigation systems will still have a large role in the future airspace. In fact, programs such as the FAA alternative positioning navigation and timing (APNT) seeks to leverage and improve existing terrestrial infrastructure to achieve many of the operational capabilities enabled by GNSS [22]. This capability ensures safety and mitigates economic damage from the loss of GNSS. ILS, DME and inertial are key elements to providing APNT.

3.4 ASIDE/INSET: Aviation organizations & Standards

An alphabet soup of organizations and documents are part and parcel of the development of any aviation standards. While confusing, the involvement of these organizations and production of these documents are necessary for the safe and efficient operations of the airspace. Standards embed safe design and offer guidelines for manufacturers. The international nature of commercial air operations means that the harmonization of standards across different nations is vital.

For this discussion, DME/TACAN is used as an illustrative example to show the relationships more concretely. There are international (ICAO) standards as well as the national standards and rules. These standards and certifications have to deal with all aspects of DME/TACAN use from the ground equipment and its manufacture to avionics and its installation to its use and operations.

ICAO SARPS

International aviation standards are set by ICAO and its member nations, the signatories of the Chicago convention. Member nations are required to implement these standards or inform ICAO of any differences [8]. The highest level principles and standards are the Standards and Recommended Practices (SARPs) of the Annexes to the Chicago Convention with Annex 10, Volume 1 governing radio navigation aids [23]. The SARPs are generated by ICAO subgroups with two main purposes. The SARPs are to enunciate: 1) the minimum performance standards of the system (accuracy coverage, capacity) and 2) the main characteristics of the system (signal in space, signal format, ground station sensitivity, spectrum, and channel plan). The SARPS also provides a basis for developing and procuring equipment (ground and airborne). SARP are updated as technology evolves. For example, the first DME SARPs were developed in 1950. By 1985, several iterations of the DME SARPs had been adopted with the latest version incorporating DME/P. SARPs can potentially affect all nations and their air carriers. Given this far reaching breadth, systems typically need to reach a reasonable level of maturity before the process of generating SARPs is undertaken.

Of course, ICAO does not make laws and regulations in member nations. Nations individually adopt airworthiness regulations to establish national rules governing aviation. For the US FAA and European Union, these are title 14 of Code of Federal Regulations (14 CFR) and Certification Specifications (CSs), respectively. These were previously called the Federal Aviation Regulations (FARs) and Joint Aviation Requirements (JARs). FARs and JARs have different individual parts that are applicable to different categories of aircraft and aviation activities. FARs derive their authority from the US federal government and are part of its administrative laws. JAR harmonizes airworthiness and certification requirements across the multiple nations of Europe. While they have no legal status in and of themselves, individual nations can ratify the JARs making them national law. The foundations of FARs, JARs and ICAO standards should be compatible and the FAR and JAR serve as model regulations.

The SARPs have authority only when they become part of a national standard. These standards typically follow the SARPs but may be more stringent than the SARPs. As the SARPs specifies the characteristics and performance of the system, they have direct bearing on DME ground equipment standards. US Order 9840.1, "U.S. National Aviation Handbook for the VOR/DME/TACAN Systems," from 1982 establishes the DME/N national standards [24]. To ensure compatibility of ground equipment produced by different manufacturers, the FAA produces specifications. FAA E-2678A (1978) "VORTAC Equipment Replacement and Facility Modernization" [25] and the later E-2996 (2008) "Performance Specifications: Distance Measuring Equipment" [24] with the former covering VOR, TACAN, and DME/N and the latter covering DME/N. These specifications, when applicable, reference ICAO Annex 10 [8]. As the military has additional requirements for TACAN beyond its civil aviation use, there is also a military standard for TACAN (MIL-STD-291C) [27].

The primary bodies for developing standards for avionics equipment are the RTCA in the US and the European Organisation for Civil Aviation Equipment (EUROCAE). These bodies produce Minimum Aviation System Performance Standards (MASPS) and minimum operational performance specifications (MOPS). MASPS specify key characteristics needed in a system while the MOPS detail the standards for specific equipment, usually avionics. Special committees are formed to draft and develop these documents. The RTCA MOPS for DME/N is Document 189 (DO-189) [28] while EUROCAE has Eurocae Document (ED) 54 [29]. There is also ED-57 for DME ground equipment [30]. Recall that the RTCA has no governmental authority and so there needs to be an official document that codifies these requirements. This comes in the form of a technical standard order (TSO) which provides standards on equipment, material or part. FAA TSO-C66 series prescribes the minimum performance standards for airborne DME. TSO-C66c [31], the most current version, references DO-189 as the standard that must be met for new models of DME produced after January 1991. It also specifies the environmental standard (DO-160 [32]) and computer software verification standard (DO-178 [33]) that apply. The minimum performance standards for ILS glide slope, localizer receiving equipment are prescribed in the TSO-C34 and TSO-C36 series, respectively [34][35]. European Union agency with regulatory authority over civil aviation, the European Aviation Safety Agency (EASA), issues ETSO (European Technical Standard Order) with the DME standard being ETSO–2C66b [36].

Airlines may have additional requirements beyond those specified in the MOPS or the FAA standards. Additional standards such as the Aeronautical Radio, Incorporated (ARINC) Characteristics allow manufacturers to build to equipment compatible to airline needs. DME/N is the topic of the ARINC Characteristic 709-5 "Mark V Airborne Distance Measurement Equipment [37]."

Finally, there can also be important information of guidance rather than regulatory nature. Advisory circular (AC) provides information of an advisory or non-regulatory nature. ACs can be general in nature or reference specific topic areas such as: 1) aircraft and airworthiness (e.g. equipment and installation), 2) airmen (training for pilots, instructor, crew), 3) airspace, 4) air traffic and general operating rules, 5) air carriers, 6) schools (pilot, maintenance, repairs), 6) airports, 7) navigation facilities and 8) flight information (aeronautical charts and other publications). Relevant to DME is AC 90-100A (the 90 series pertains to airspace) which provides operational and airworthiness guidance on terminal and en route area navigation (RNAV) operations [38]. This AC helps pilots determine if they are eligible, i.e. have the necessary set up and equipment, to perform these procedures. Relevant to DME equipment, it specifies that DME/DME when augmented with GPS or IRU is necessary to support RNAV (DME alone does not have sufficient coverage in the US). Furthermore, the DME would be required to meet performance outlined in TSO-66c However, as this is guidance, operators may choose an alternative method "provided the alternative method is found to be acceptable by the FAA".

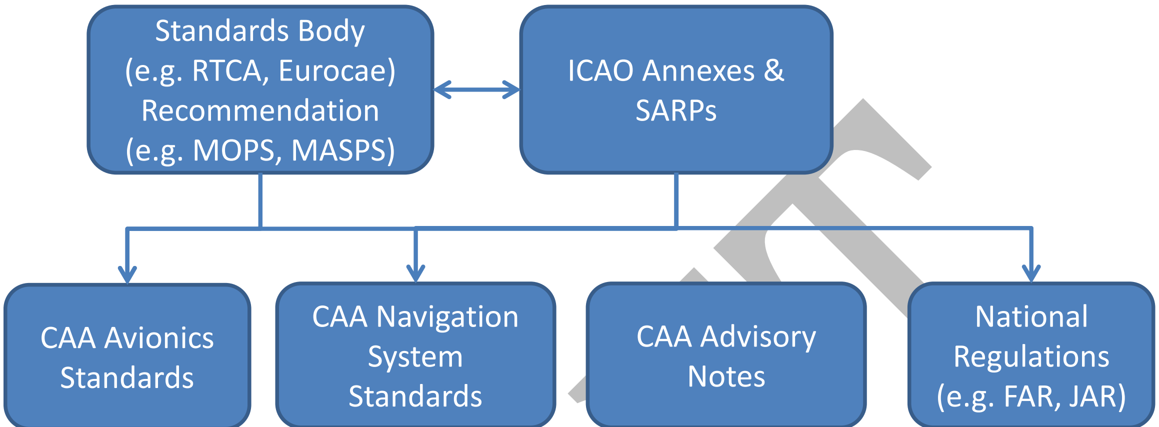


Figure 10. Relationship between Standards Body and Various Standards

3.5 Concluding Observations

The development of ILS, DME/TACAN, and INS were propelled by different forces and factors resulting in very distinct courses. However, they demonstrate a few common lessons and traits use to understanding the development of aviation navigation systems and safety of life systems. First, the course of development is a long one – 10-20 years from concept to first operational installation with many difficult technical and also institutional issues to be solved. Acceptance of the technology and standardization take time both due to the consensus needed nationally and finally internationally but also the number of different specifications and documents needed to specify the system and its equipment.

Second, no course of development of navigation systems is exactly the same. Historically there have been two paths for developing new navigational capabilities. One means, as seen in ILS and DME is airworthiness development within the CAA/ANSP such as the FAA. Another way is operational demonstration. The operator or airline develop and demonstrate that the technology consistently meets requirements (accuracy, safety) to the CAA, such as FAA flight standards. However, even within each path, the process is often very different. A key is making sure all critical stakeholders are involved early and the process is conducted with harmonization in mind.

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