AVIATION THEORY CENTRE

Addendum to:

Aircraft General Knowledge

for the
CASA PPL/CPL
Day VFR Syllabus

RNAV/GNSS Systems

Aviation Theory Centre

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Introduction

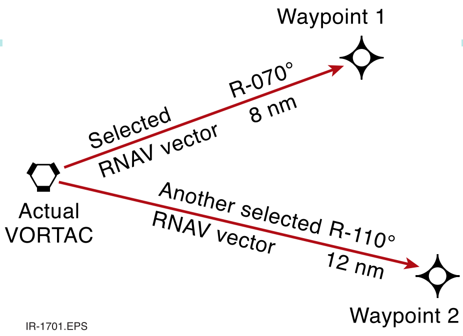

Figure 1-1 Tracking between waypoints.

1.1 CASR Part 61 of 01SEP2014 introduces in the Manual of Standards (MOS), a potential change to the knowledge syllabus for the subject 'Aircraft General Knowledge' now titled, 'General Aircraft Knowledge'. This change suggests that GNSS may be a required element of these studies.We have therefore prepared this addendum for our AGK book to cover the introductory knowledge for RNAV systems including GNSS and GPS.

Primary types of RNAV

1.2 An increasing number of aircraft are being fitted with area navigation (RNAV) systems. These systems, which have to meet specified accuracy requirements for approval, allow pilots to operate on routes independent of the normal route structure, which is based on short-range radio navigation aids. RNAV systems provide accurate track guidance along routes that do not have to be aligned with radials or bearings from VORs and NDBs. This capability results in more efficient use of airspace and, potentially, very significant savings in flight time and fuel, especially for long-distance flights.

1.3 RNAV enables you to fly along the following routes:

- dedicated RNAV routes which are published on special airways charts; and
- random routes, which are either planned by the pilot or cleared by ATC for track shortening, allowing direct point-to-point tracking between any series of en route positions.

1.4 Area navigation (RNAV) is achieved by tracking between waypoints, which are positions defined either by latitude and longitude coordinates, or by a bearing and distance from a previously defined position. You can usually enter the series of waypoints that make up the route into the RNAV system, either prior to departure (which is normally the case) or in flight.

1.5 We will discuss two systems which are approved for use in Australia:

- inertial navigation system (INS); and
- global positioning system (GPS).

Inertial Navigation Systems

1.6 Inertial navigation systems are self-contained RNAV systems which, because of their expense and relative complexity, are normally only found in larger, more sophisticated aircraft. INS does not require the reception of signals from ground-based transmitters. Very accurate position information and other useful navigational data is derived from the effects of inertia on the internal components of the system.

Basic Components & Operating Principles

1.7 A conventional INS is composed of the following basic components:

- accelerometers (usually of the pendulum type or solid-state oscillators);
- gyroscopes (either conventional mechanical rate gyros or solid-state ring laser gyros);
- a reference platform (a gyro-stabilised mounting for the accelerometers and gyroscopes); and
- a navigation computer unit, which is primarily concerned with converting the output of the accelerometers into a velocity, thus determining the speed and direction of the aircraft.

1.8 The gyroscopes stabilise the platform on which the accelerometers are mounted, maintaining them level with the earth's surface. The accelerometers measure the north–south and east–west accelerations of the aircraft, which are then converted into velocities by the INS computer. These velocities are then processed in relation to the initial position entered by the pilot prior to departure while the aircraft is stationary, to produce a continuous indication of the aircraft's present position, as well as a wide range of other navigational data, such as current wind velocity, time and distance to next waypoint.

> **Note:** The term *inertial reference systems* (IRS) is sometimes used in conjunction with INS. In IRS systems, the gyroscopes used for platform stabilisation are also a source of pitch, roll and yaw attitude inputs for other aircraft systems, such as attitude and heading reference for flight instruments (AI and DG), autopilots and weather radar stabilisation.

1.9 Normally, an aircraft equipped with INS will track between a series of RNAV waypoints programmed into the system by the pilot, either manually or automatically from a database. The system is extremely accurate, although the accuracy does degrade progressively at a slow and variable rate after initial alignment before flight. Some systems allow automatic in-flight position updates to be accomplished by using signals from VOR and/or DME stations within range, thereby ensuring an accurate navigation performance over an extended period.

Global Navigation Satellite Systems

1.10 *Global navigation satellite system* (GNSS) is the generic term used to describe a global position and time determination system. The system includes one or more satellite constellations, aircraft receivers, system integrity monitoring, and augmentation as necessary to achieve the *required navigation performance* (RNP) for the particular phase of operation. GNSS is the term now used in discussions and policy development forums related to satellite navigation by ICAO and leading aviation authorities.

1.11 The satellites and other components of the system broadcast signals that aircraft receivers can interrogate to establish accurate position and time reference. Since GNSS primarily broadcasts signals from space, direct rather than reflected transmissions can be used, allowing the use of higher frequencies. This in turn provides very high quality signals and thus high levels of accuracy. By the use of multiple satellites, GNSS has the potential of generating very precise position information.

1.12 In this section, we focus on the United States military system known as the Navstar *global positioning system* (GPS). It should be regarded as just one element of the ultimate global architecture that we call GNSS. However, it is a system that has reached a mature stage of development and is in widespread civilian use.

Other Systems

1.13 There are other systems evolving or being planned which use similar technology. The Russian military system known as the *global orbiting navigation satellite system* (GLONASS) is operational and has been offered for civilian use, and the communication satellite council of INMARSAT (International Maritime Satellite) is proposing to launch INMARSAT 3 satellites equipped with navigation transponders. The Japanese also have a system on the drawing board which will use geostationary satellites. It is likely that receiver technology will develop rapidly to the stage where signals from more than one satellite system can be processed for navigation purposes.

RNAV Developments

1.14 In June 1999, the United States Department of Transportation's FAA issued a Technical Standard Order to supplement and update the requirements of TSO-C129. That TSO had laid down the standards required for GPS when C/A (discussed later, on Pages 7/8), was the standard of data available for civilian use. With the removal of that standard in June 2000, a much higher degree of accuracy became available to all users of the equipment, so TSO-C146 was produced to satisfy it.

1.15 Under TSO-C146, the aim is to enhance accuracy, integrity and availability of the navigation system by using satellite based wide area augmentation systems. These are based on a series of geostationary satellites being developed in the USA (WAAS), Europe (EGNOS) and Japan.

Galileo

1.16 Soon, a new GNSS system will become available through the European Commission and named "Galileo". This system will comprise a constellation of 30 medium-earth orbit satellites (27 active plus three spares on standby) together with necessary earth stations.

1.17 It is envisioned that receivers will have the capability (through dual frequencies) to use both the current US Navstar GPS as well as Galileo, thus greatly adding to continuity of service.

1.18 Commercial users and those who pay a fee for access to optimal Galileo service will be able to enjoy a positioning service which will be extremely accurate to within a metre in both lateral and vertical senses. For general use, Galileo will be available, free of charge in the same way as the Navstar system is currently available.

Useful Definitions

1.19 Before moving on, it is useful to list some of the more important definitions related to GNSS/GPS. The definitions can be referred to as the various terms arise later in this chapter.

Sole Means Navigation System

1.20 A sole means navigation system is a navigation system which, for a given phase of flight, must satisfy the required accuracy, integrity, availability and continuity performance requirements.

Primary Means Navigation System

1.21 This is a navigation system which, for a given operation or phase of flight, must satisfy accuracy and integrity performance requirements but not necessarily the availability and continuity of service requirements. With respect to the latter, safety is achieved by either limiting flights to a specific time or by imposing operational requirements and restrictions.

Supplemental Means Navigation System

1.22 This navigation system must be used in conjunction with a sole means navigation system.

Availability

1.23 Availability is an indication in percentage terms of the ability of the system to provide useful and acceptable service within a specified area of coverage.

Required Navigation Performance (RNP)

1.24 RNP is a statement of the navigation performance accuracy necessary for operation within defined airspace. It prescribes the required track containment standard, which is the maximum allowable track deviation in nautical miles left or right of track, within which an aircraft must be contained with a 95% probability for the route. For example, RNP 4 means that the aircraft's RNAV system must be capable of navigating the aircraft within 4 nm of track.

Integrity

1.25 Integrity refers to the probability that the system will provide accurate navigation as specified, or the ability to provide timely warnings to the user that the system should not be used for navigation.

Pseudo-range

1.26 Pseudo-range is the determination of position, or the obtaining of information relating to position, for the purposes of navigation by means of the propagation properties of radio waves, i.e. the distance from the receiver/processor to a satellite plus an unknown clock offset distance. With four satellites in view, it is possible to compute position and clock offset distance.

Receiver Autonomous Integrity Monitoring (RAIM)

1.27 RAIM is a technique whereby a civil GPS receiver/processor determines the integrity of the GPS navigation signals using only GPS signals or GPS signals augmented with altitude. At least one satellite in addition to those required for navigation must be in view for RAIM to operate.

Almanac

1.28 Almanac is a set of parameters providing orbital data for the entire GPS constellation. It is used by the GPS receiver to predict the satellites in view and their estimated pseudo-ranges.

Ephemeris

1.29 Ephemeris is the data that defines the current position of each satellite in the constellation. Empheris data is transmitted as part of each satellite's unique navigation data message.

World Geodetic Standard (WGS)

1.30 WGS is a constant set of parameters describing the size and shape of the earth, i.e. an earth model.

Navstar Global Positioning System (GPS)

1.31 The Navstar GPS has three functional elements:

- a space segment;
- a control segment; and
- a user segment (the airborne receivers).

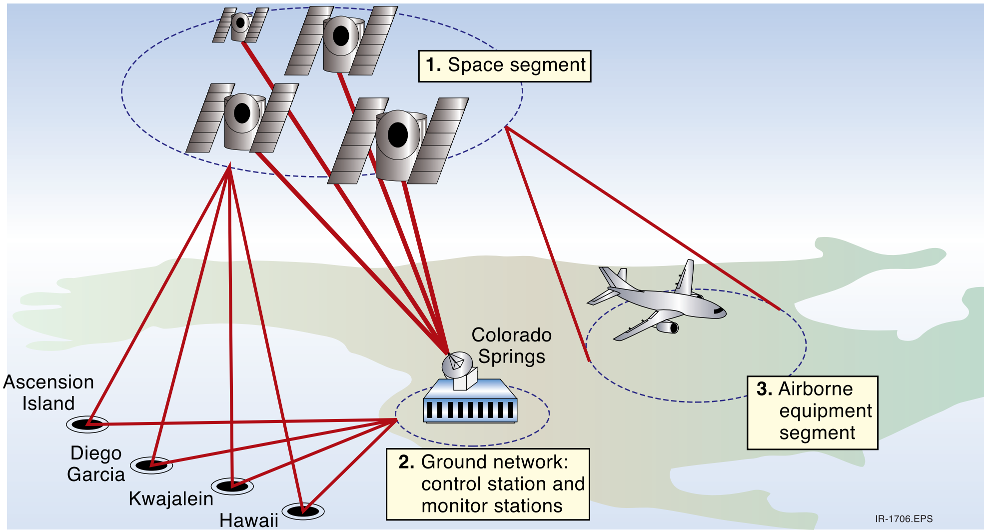

Figure 1-2 The GPS consists of three basic segments.

Space Segment

1.32 The space segment consists of a constellation of 24 satellites orbiting the earth at an altitude of just over 20,200 km (10,900 nm) in six strategically defined orbital planes. Three of the satellites are operating as spares with the remaining 21 in the constellation sufficient to provide global navigation coverage. The objective of the GPS satellite configuration is to provide a window of at least five satellites in view from any point on earth.

1.33 The satellites orbit at an inclination angle of 55°, taking approximately 12 hr to complete an orbit, and the orbital position of each satellite is known precisely at all times.

Note: As a point of interest, the GPS space segment consists of so-called Block II and IIA satellites and upgraded versions known as Block IIR satellites. The service they provide is identical as far as a user is concerned. They will be the basis of the system for at least the next decade.

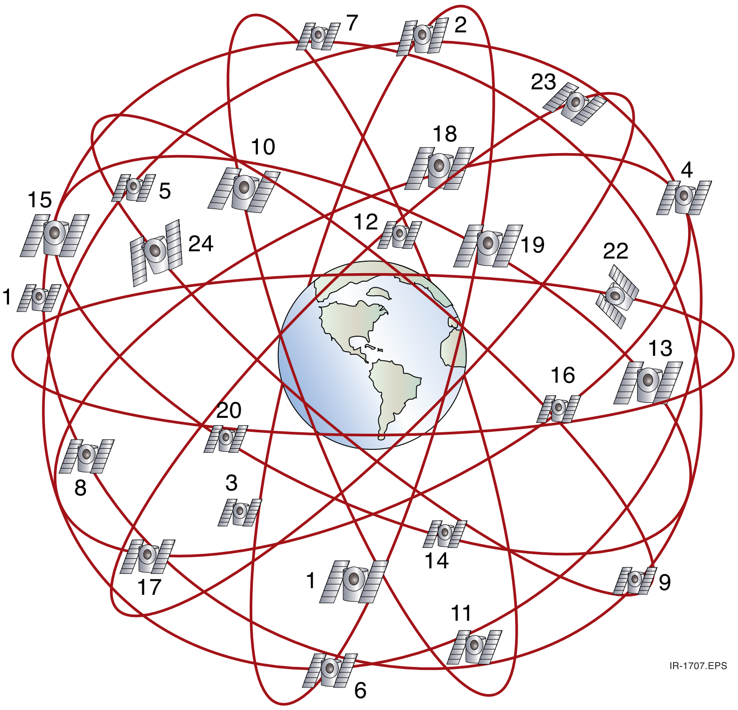

Figure 1-3 The orbital configuration of the 21 GPS satellites.

Pseudo-Random Code

1.34 Each satellite transmits its position and precise time of transmission, and a separate signal is used by the receiver to establish range from the satellite. This is achieved by the satellite RF carrier transmissions being modulated with a 50 bit/second navigation message and a unique encoded signal known as a pseudo-random code. It repeats itself every millisecond and is used by the GPS receivers to recognise and track individual satellites for ranging purposes. There are two types of pseudo-random code:

- a coarse acquisition (C/A) code (sometimes referred to as the *standard positioning service* (SPS)) available for general civilian use, which provides accuracy in the order of 100 m in position and 140 m in altitude with a 95% probability given a quality receiver; and
- a precision (P) code (also known as the *precise positioning service* (PPS)), which permits extremely precise position resolution (formerly available for authorised military users only, this is now available to all users).

1.35 As will be discussed later, a minimum of three satellites is required to determine a two-dimensional fix if altitude is known. For a three-dimensional fix, four are required. The navigation message contains information on satellite ephemeris, GPS time reference, clock corrections, almanac data and information on system maintenance status.

Control Segment

1.36 The controlling authority is the United States Department of Defence. By letter of agreement between the United States Government and ICAO, civilian access via the

C/A code only is permitted on a no-cost basis for the foreseeable future. The deliberate degrading of the accuracy of the system for civilian users, i.e. the standard positioning service (SPS) accessed via the C/A code, is known as *selective availability* (SA).

Note: In early 2000, the U.S. Department of Defence turned off SA.

1.37 The control segment includes monitoring stations at various locations around the world, ground antennas and up-links, and a master station. The stations track all satellites in view, passing information to a master control station which controls the satellites clock and orbit states, and the currency of the navigation messages.

1.38 Satellites are frequently updated with new data for the compilation of the navigation messages transmitted to system users. Assuming the current level of space vehicle technology, the planned life span of a GPS satellite is around seven to eight years.

User Segment (The Receiver)

1.39 As previously mentioned, the receiver identifies each satellite being received by its unique pseudo-random code, i.e. the C/A code for civilian operations. It then starts to receive and process navigation information. Ephemeris data takes about 6 seconds to transmit, but almanac data takes about 13 seconds. For this reason, almanac data is stored in the receiver's memory. During operation, almanac data in the receiver is changed on a continuous basis. On start-up, the receiver recalls the data that was last in memory on the preceding shutdown. From this information and the stored almanac data, the receiver determines which satellites should be in view and then searches for their respective C/A codes. It then establishes ranges to the satellites, and by knowing their position, computes aircraft position, velocity and time. This process is known as *pseudoranging.*

1.40 Range determination is a simple matter of measuring the period between the time of transmission and the time of reception of each satellite C/A code and multiplying that time interval by the speed of light in free space. The GPS receiver in fact does this by emitting its own code at the same time as the satellite's, and uses it and the time the signal from the satellite is received to establish the time interval. Timing is critical. This is the reason why the time reference is provided by synchronised high-precision atomic clocks in the satellites.

Fixing Position

1.41 A three-dimensional position in space (position and altitude) is accomplished by the receiver determining where it must be located to satisfy the ranges to four or more appropriately positioned satellites. A two-dimensional fix requires only three satellites in view if altitude is known. The synchronisation of the receiver's time reference with that of the satellite is important in this process.

1.42 Timing errors are detected and eliminated by the receiver's computer. Figure 1-4 shows a two-dimensional position established, assuming the respective clocks are synchronised perfectly. However, if the receiver's clock is, say, one second fast, as is the case in Figure 1-5, then the period between transmission and reception with respect to each of the three satellites interrogated will be sensed initially as taking one second longer. This will be represented as a gross error in all three ranges and thus, rather than producing a precise fix, will create a very large area anywhere in which the receiving aircraft could be positioned. The receiver's computer senses this and immediately begins a trimming process until it arrives at an answer which allows all ranges to arrive at the one and only position possible. This process automatically eliminates the effect of receiver clock error for subsequent tracking and position fixing.

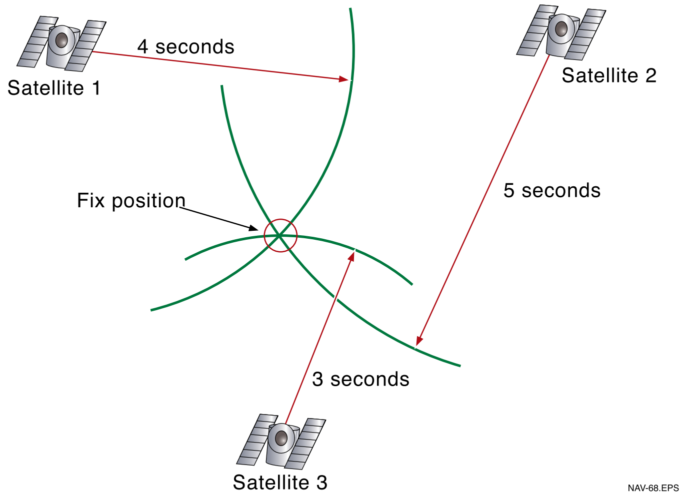

Figure 1-4 Two-dimensional fix established with perfect timing.

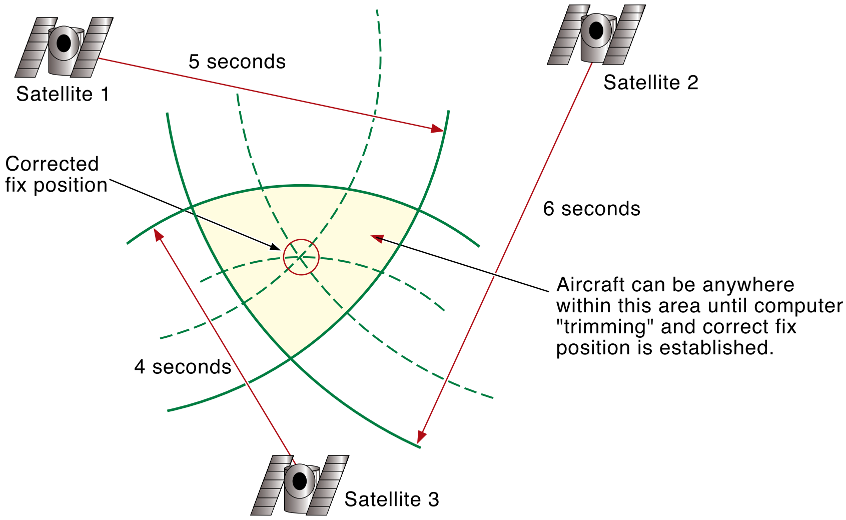

Figure 1-5 Effect of receiver clock error of 1 second on two-dimensional fix.

Receiver Design

1.43 The capability of making range calculations to three, four or more satellites has an impact on the design, cost and accuracy of GPS receivers, namely, whether they are single-channel receivers operating sequentially or the more expensive and accurate receivers providing multiple channels operating simultaneously. GPS receivers approved as a supplemental or primary means navigation aid have multiple channels and come under the provisions of an FAA Technical Service Order (TSO C129). IFR/primary navigation certification specifications for GPS equipment include a requirement for multiple receiver channels and a navigation integrity monitoring system known as *receiver autonomous integrity monitoring* (RAIM).

RAIM

1.44 RAIM is a special receiver function which analyses the signal integrity and relative positions of all satellites which are in view, so as to select only the best four or more, isolating and discarding any anomalous satellites. At least five satellites must be in view to have RAIM find an anomalous situation, and six to actually isolate the unacceptable satellite. In controlled airspace ATC must be advised if RAIM is lost for more that 5 minutes. (*AIP ENR 1.1 para 19.11.2*)

1.45 When operating, it ensures that the minimum acceptable level of navigation accuracy is provided for the particular phase of flight. In the process, it ensures that a potential error, known as the *position dilution of precision* (PDOP) or *geometric dilution of precision* (GDOP), is minimised. The PDOP depends on the position of the satellites relative to the fix. The value of the PDOP determines the extent of range and position errors.

1.46 When the satellites are close together, the tetrahedron formed covers a large area and results in a high PDOP value (see Figure 1-6).

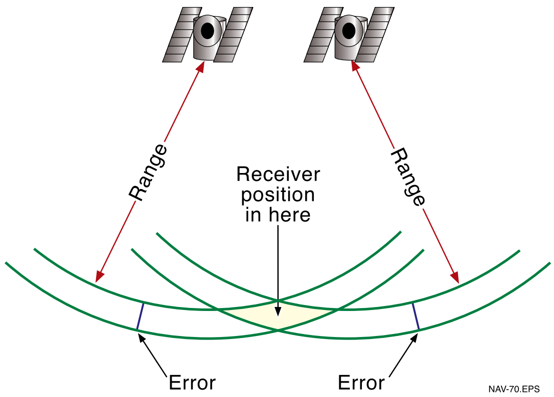

Figure 1-6 Poor satellite geometry resulting in high PDOP.

1.47 However, when the selected satellites are far apart, the area covered by the tetrahedron is much more compact, resulting in a lower PDOP value and therefore greater accuracy. A PDOP value of less than six is acceptable for en route operations. A value of less than three will be required for non-precision approaches.

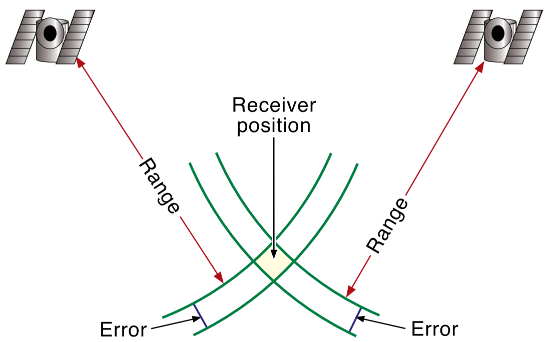

Figure 1-7 Good satellite geometry resulting in low PDOP.

Barometric Aiding

1.48 Barometric aiding is the process whereby the digital data of the pressure altimeter is used by the GPS receiver as, in effect, the range readout of a (simulated) additional satellite. It is only applicable when there are less than five satellites in view and

RAIM alone cannot be effective. Barometric aiding provides additional redundancy and RAIM capability and therefore increases the navigation coverage of GPS.

Masking Function

1.49 The masking function in the GPS receiver software ensures that any satellites in view which lie below a fixed angle of elevation relative to the receiver are ignored. This is due to the range errors that will be generated because of the greater distances that their signals will have to travel through the ionosphere and troposphere to reach the receiver. The fixed angle stored in the receiver is known as the *mask angle.* In some receivers, it is selected automatically by the receiver, depending on the strength of the transmitted signals at low angles of elevation, receiver sensitivity and acceptable low-elevation errors. When fixed, it is typically set at around 7.5° (Figure 1-8).

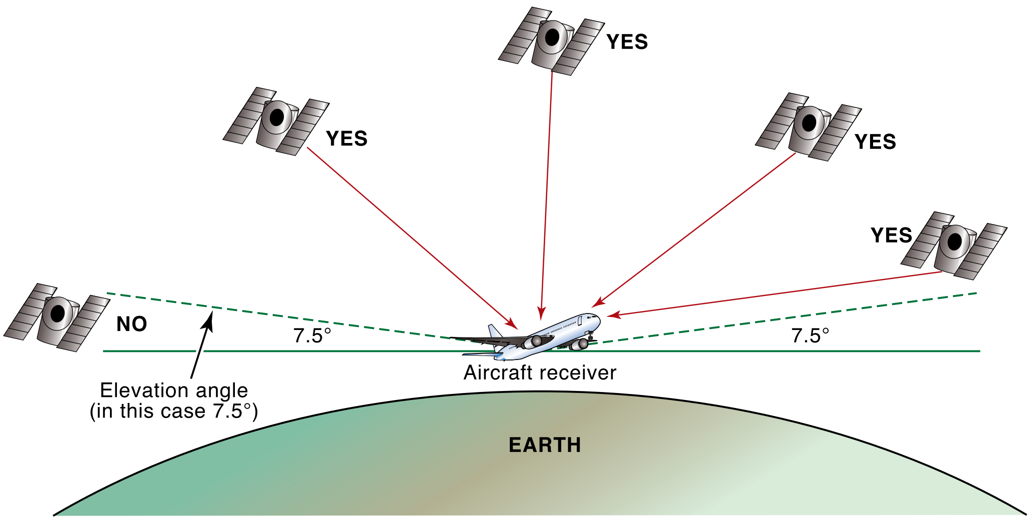

Figure 1-8 Mask angle.

Receiver Displays

1.50 Displays for the pilot vary from one GPS unit to another. Flight planning data is usually entered via an appropriate keypad on a control display unit (CDU) or control panel. The usual navigation information (i.e. position, track, groundspeed, EET and, with a TAS input, TAS and wind) is displayed. The unit must also be capable of showing satellite status, satellites in view and being tracked, the value of PDOP, RAIM status and signal quality etc.

Operating Modes

1.51 GPS receivers normally provide three modes of operation:

- navigation with RAIM;
- navigation (two or three dimensional) without RAIM; and
- loss of navigation (annunciated as DR in some receivers).

Differential GPS

1.52 The accuracy standards available for 95% of the time have already been mentioned. However, for the GPS to be of any value as a primary navigation source for precision approach/departure operations, a much higher order of accuracy is required. Furthermore, the higher accuracy standard should be available 99.99% of the time. We know that GPS is capable of providing unprecedented levels of accuracy with P-code access, i.e. the PPS. This standard of accuracy is now available to civilian users, assuming direct interrogation of GPS.

1.53 One ingenious way of improving the accuracy available for civilian users is by using an enhancement known as *differential GPS* (DGPS). A GPS receiver is installed at a ground station located in the terminal area. The station compares the GPS computed position with the actual (surveyed) position of the station and determines the difference, if any, which of course would be common to other airborne GPS receivers operating in the area. The station transmits the appropriate error correction signal by data links to the aircraft with the result that an accuracy in the order of +1 to -10 m is achievable. Figure 1-9 shows the simplicity of the concept.

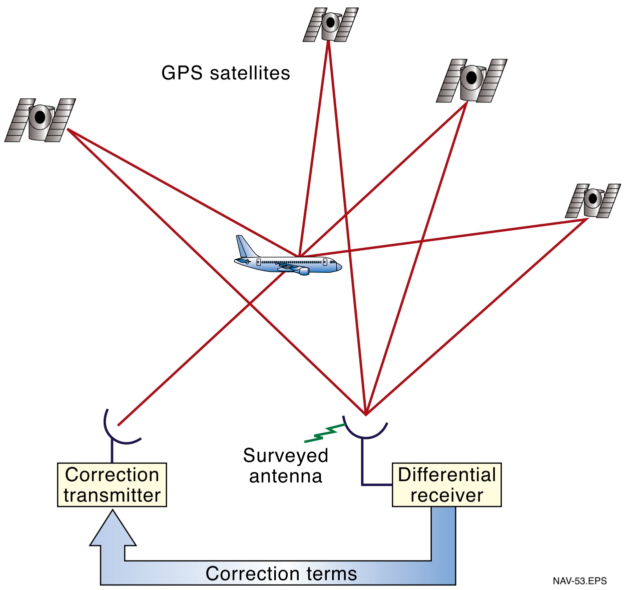

Figure 1-9 Differential GPS.

1.54 This enhanced standard of accuracy is acceptable for non-precision instrument procedures but not for precision approaches. However, a lot of research and development work is being undertaken, particularly in the United States by the FAA, to improve the accuracy even further. In fact, the FAA have confidently predicted that Category II and III precision approach navigation capability using GPS will be possible in future.

1.55 As well as developing differential GPS for precision operations, a much wider network of ground receivers, with geostationary navigation receiver and communication satellites and relays, is being developed for en route operations. The enhanced network is known as a *wide area differential GPS* (WADGPS).

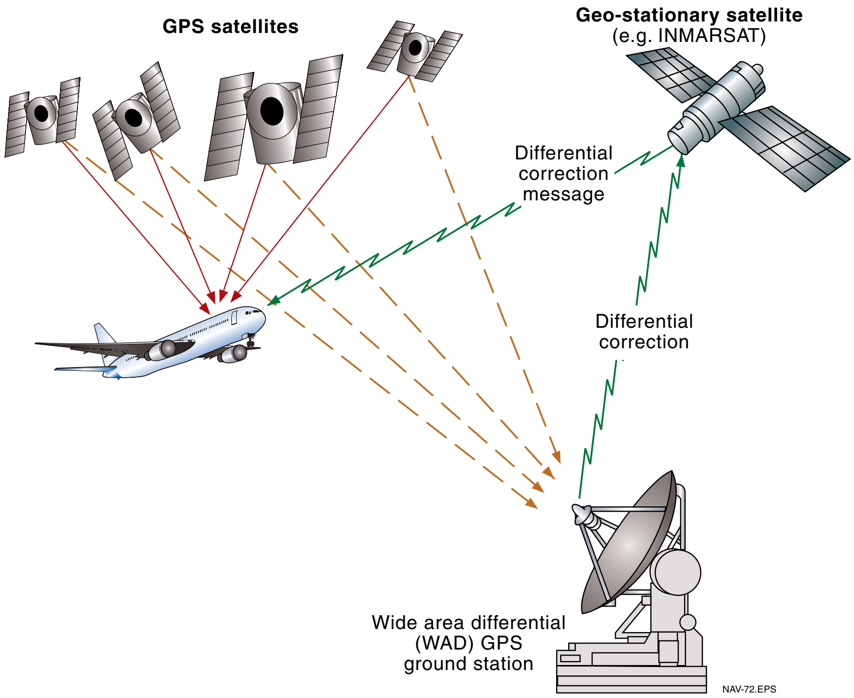

Figure 1-10 Concept of wide area differential GPS.

Note: GPS (GNSS) is still a developing technology as far as civil air operations are concerned. GPS equipment meeting system integrity standards and operated in accordance with specified limitations and procedures is approved as a primary means navigation aid for IFR en-route operations and specified IFR arrival procedures. Two significant developments are ADS-B and *Performance Based Navigation* (PBN).

Automatic Dependent Surveillance - Broadcast

1.56 Along with the advancements in GNSS has been the development of automatic dependent surveillance. *Automatic Dependent Surveillance - Broadcast* (ADS-B) is a system whereby an aircraft's current en-route GPS position is transmitted automatically and on a continuous basis, from the aircraft directly, via communication satellites and via ground stations, to the relevant air traffic service centres. Suitably equipped aircraft can also transmit directly and see each other's position.

1.57 ADS-B is an air traffic surveillance technology that enables aircraft to be accurately tracked without the need for conventional radar. Airservices has deployed ADS-B ground stations across Australia which, when combined with radar, provide ATC surveillance capability over the entire continent, above FL300 (30,000 feet).

1.58 Substantial coverage also exists at lower levels extending to approximately 25 km radius around the station at sea level. It is like an ice cream cone with a flat base - 25km radius at ground level up to 250 km radius at 30,000 feet.

1.59 ADS-B services are being implemented in stages during which time surveillance coverage will progressively increase. Currently (2013), the system is supported by 29 duplicated ADS-B ground stations nationwide plus 14 ADS-B capable multi-lateration sites in Tasmania and 16 sites in the Sydney basin. These are now delivering continuous surveillance of aircraft operations high level airspace across western, central and northern Australia where radar coverage does not currently exist.

1.60 A further 14 ground stations are being considered to support the needs of airlines, regional and general aviation.

1.61 While the initial application of ADS-B is to provide high quality surveillance for air traffic control, it also facilitates a number of advanced air-to-air applications that will in future significantly improve safety and performance of aircraft operations.

1.62 The technology delivers both environmental and economic benefits through:

- improved aircraft access to preferred routes and levels,
- more efficient diversions around restricted areas and weather and,
- increased accuracy of navigation.

1.63 In addition to delivering radar-like surveillance at a fraction of the cost of radar, it also offers considerable safety improvements through:

- rapid and targeted search and rescue response,
- reduced collision risks around regional aerodromes, and
- improved ATC and pilot situational awareness.

1.64 Other ADS-B safety and operational benefits, include:

- positive ATC identification while within ADS-B coverage;
- no requirement for position reporting while identified;
- identified aircraft receive priority over non-identified aircraft;
- route and altitude conformance monitoring; and
- ATC safety net alerting functions (e.g. short term conflict alert and dangerous area infringement warning).

1.65 ADS-B is a system in which electronic equipment on board an aircraft automatically broadcasts the precise location of the aircraft via a digital data link.

1.66 The data can be used by other aircraft and air traffic control to show the aircraft's position and altitude on display screens without the need for radar.

1.67 The system involves an aircraft with ADS-B determining its position using GPS. A suitable transmitter then broadcasts that position at rapid intervals, along with identity, altitude, velocity and other data. Dedicated ADS-B grounds stations receive the broadcasts and relay the information to air traffic control for precise tracking of the aircraft. The pseudonym is derived from:

- Automatic - it requires no pilot input or external interrogation.
- Dependant - it depends on accurate position and velocity data from the aircraft's navigation system (e.g. GPS).
- Surveillance - it provides aircraft position, altitude, velocity, and other surveillance data to facilities that require the information.
- Broadcast - information is continually broadcast for monitoring by appropriately-equipped, ground stations or aircraft

1.68 ADS-B data is broadcast every half-second on a 1090MHz, digital data link. Broadcasts may include:

- Flight Identification (flight number callsign or call sign)
- ICAO 24-bit Aircraft Address (globally unique airframe code)
- Position (latitude/longitude)
- Position integrity/accuracy (GPS horizontal protection limit)
- Barometric and Geometric Altitudes

- Vertical Rate (rate of climb/descent)
- Track Angle and Ground Speed (velocity)
- Emergency indication (when emergency code selected)
- Special position identification (when IDENT selected)

1.69 The ability of a ground station to receive a signal depends on altitude, distance from the site and obscuring terrain. The maximum range of each ground station can exceed 250 nautical miles.

GPS Errors & Limitations

1.70 So far, the errors we have covered are receiver clock error and how it is resolved, the effect of PDOP on position accuracy, the accuracy (or errors) associated with receiver design, and selective availability (SA). We have also discussed the errors of the standard positioning service (SPS) as compared to the precision positioning service (PPS). However, there are other errors which can affect GPS performance that we must examine briefly.

Ephemeris Error

1.71 Ephemeris error is the error inherent in the data that defines the satellites current position, which in turn is transmitted to the receiver.

Multi-Path Error

1.72 In a similar manner to the behaviour of signals used by other radio navigation systems, it is possible for some of the satellite signals, i.e. the pseudo-random code signals, to reach the receiver antenna after bouncing off the earth's surface as well as directly from the satellite. Thus the receiver can receive signals from different directions. This can lead to distortion of the C/A- and P-coded pulses, which in turn can induce a ranging error.

Ionospheric Propagation Effects

1.73 The ionosphere, which we know is the band of charged particles that lies between 80 and 120 miles above the earth's surface, affects the propagation speed and thus the travel time of the GPS signals, thereby degrading the accuracy of the position solution. Ionospheric propagation effects can be offset by the receiver with data received from the satellites.

Tropospheric Propagation Effects

1.74 The lower region of the atmosphere, which of course is the troposphere, contains significant amounts of water vapour. The effect of this is to slow down the satellite signals, inducing ranging errors. This tends to degrade position accuracy. However, tropospheric propagation effects are to some extent minimised by appropriate compensation modelling in the receiver.

Receiver Error

1.75 This is simply a small ranging error brought about by the difficulty of matching precisely the receiver's emitted digital pseudo-random code with that of the satellite.

Interference

1.76 Because GPS (GNSS) signals are relatively weak, harmful interference can cause significant degradation in navigation or complete loss of navigation capability under certain conditions. With more and more extensive use of all bands of the electromagnetic spectrum, the potential for interference problems to occur has increased. The trend is likely to continue.

1.77 Interference to GPS operation can occur from electromagnetic influences on board the aircraft, e.g. insufficient shielding from VHF transmitters and other equipment, and from external sources, e.g. high powered radar, TV and FM stations in the vicinity of the receiver.

1.78 Appropriate mitigation techniques and shielding systems are employed to offset these problems. However, occurrences where GPS integrity is suspect, there is a loss of RAIM, or interference is experienced should be reported to the appropriate authority with comprehensive details of the circumstances so that the matter can be properly recorded and investigated. GPS system verification sheets are available for this purpose.

Tracking Accuracy and Collision Avoidance

1.79 Tracking accuracy should not really be classified as an error; rather it is a statement giving testimony to the precision of GPS. However, this very quality of precision track-keeping highlights the increased potential for collision, particularly head-on collision, with other GPS equipped aircraft operating on the same track, or approaching the same turning point. As will be discussed later, this problem is not helped by the propensity of some pilots to have their heads always in the cockpit.

1.80 It is essential to maintain the required separation procedures and, when appropriate, to maintain a thorough lookout; these are obvious airmanship requirements. However, this problem is considered to be so significant that there have been discussions in the US and Europe about the notion of requiring airline operators to flight plan with small track offsets (left or right of track depending on the direction) as a safety measure in addition to ATS separation when navigating by GPS on busy airways.

Summary of GPS Errors

1.81 A table summarising the main sources of GPS errors and their cumulative effect on the SPS, PPS and DGPS is shown in Table 1-1.

	Source of GPS Error	S/A ON	S/A OFF	DGPS	P-CODE
a	clock error	2 m	2 m	0 m	2 m
b	ephemeris error	4 m	4 m	0 m	4 m
c	ionospheric propagation error	8 m	8 m	0 m	1 m
d	tropospheric propagation error	3 m	3 m	0 m	3 m
e	receiver noise error	1 m	1 m	1 m	1 m
f	selective availability (S/A)	32 m	0 m	0 m	0 m
g	total pseudo range error [square root of sum of the squares of (a) to (f)]	33 m	10 m	1 m	6 m
h	maximum position dilution of precision (factor)	3	3	3	3
	total position error [(g) × (h) approximately]	100 m	29 m	3 m	17 m

Table 1-1 Sources of GPS error.

Operations without RAIM

1.82 *AIP ENR 1.1 para 19.10.* If RAIM is lost, the accuracy of the system is considered unacceptable for both navigation and ATC separation purposes. Therefore, the following procedures apply:

- tracking must be closely checked against other navigation systems; and
- if in CTA, ATC must be advised when:
  - RAIM is lost for more than ten minutes, even if GPS is still providing position information; or
  - RAIM is not available when ATC requests GPS distance or if an ATC clearance or requirement based on GPS distance is imposed; or
  - the GPS receiver is in DR mode, if applicable, or loses navigation function for more than one minute; or
  - indicated displacement from track centreline is found to exceed 2 nm.

1.83 ATC may then adjust separation as follows:

- if valid position information is lost (2D and DR Mode), or non-RAIM operation exceeds ten minutes, the GPS information is to be considered unreliable, and other navigation techniques should be used until RAIM is restored; and
- if RAIM is restored, the appropriate ATS unit should be notified prior to using the GPS for primary navigation to allow ATC to reassess the appropriate separation standards.

Human Factor Considerations

1.84 We know that, in its fully operational mode, GPS (GNSS) has the capability of providing precise navigation information and guidance. However, like all forms of advanced computer technology, its capability, and therefore ultimately the safety of the flight, is governed largely by the manner in which the equipment is operated and monitored. This can be especially so when the equipment interfaces with an autopilot, flight director or advanced autoflight system. Regardless of equipment design and ergonomic factors, the pilot in command must ultimately shoulder the responsibility for the safe performance of any aviation system under his or her control.

1.85 Accident and incident history shows, however, that an alarming number of pilots tend to be too trusting when using advanced aviation technology, as with GPS operation. There are some who are quite happy to allow the equipment to 'drive the ship' without questioning its accuracy or applying basic airmanship principles, such as cross-checking the steering data it provides. Put simply, some pilots operating equipment like GPS can and often do lose situational awareness, i.e. they allow themselves to drop out of the loop.

1.86 Generally, the tendency develops as the result of complacency, since GPS seems to perform so admirably for most of the time. However, GPS is subject to a number of errors and limitations which pilots must understand. These have been discussed. However, there are also important human factor related errors and procedures applicable to GPS (and, for that matter, other RNAV systems) that need to be addressed. It is therefore necessary to appreciate what they are so that the errors can be avoided.

Mode Error

1.87 Incorrect mode selection is a very significant problem, and one which has come more into prominence now that fully integrated autoflight systems and flight management systems are commonplace, e.g. a tracking error occurs because the autopilot controller has been left in HDG instead of NAV mode.

1.88 In the context of a GPS, it is not possible to discuss specific modes because of the differences in the designs of the various receiver CDUs and control panels. However, suffice to say that when a GPS mode or function switch is operated, a positive check should always be made to ensure that the action or function desired has actually been selected.

Data Entry Error

1.89 As the term implies, this is the error caused by inserting incorrect information, usually via the CDU or panel keyboard, into the GPS receiver computer. It applies to all RNAV systems and can have catastrophic consequences. In the overwhelming majority of cases, incorrect waypoint position coordinates are inserted, i.e. a human error is caused by either inattention, unfamiliarity or a simple typographical error when transferring data from a navigation chart to the GPS.

1.90 However, ergonomic factors can contribute to the problem, e.g. some GPS receivers have complicated CDU keyboards or control panels, or alpha-numeric displays which are difficult to read. Also, it is not unknown for databases to carry mistakes, either through transcription errors by the provider or incorrect navigation data being supplied by the relevant aeronautical information service – all the more reason for using only current databases, checking NOTAMs and adopting rigid data validation procedures.

Data Validation and Cross-Checking

1.91 Validation and cross-checking procedures are designed to detect data entry errors and, in the broader sense, confirm GPS reliability and accuracy by comparing the navigation output with other navigation sources. The following procedures are recommended:

- all data entered, either manually or from a database, should be checked carefully by the pilot against the relevant and current navigation chart (this check should include a second crew member in the case of a multi-crew operation);
- to reduce the chance of data entry error, navigation data should be derived from a current database which cannot be modified by the crew;
- only data from a validated and current database should be used for navigation below LSALT;
- all GPS generated tracks and distances of the flight plan (waypoint string) should be checked against the current chart and flight plan for accuracy before flight, and at any time in flight prior to embarking on an amended route, e.g. prior to 'direct-to' tracking or a diversion to an alternate, i.e. a check for reasonableness should be carried out;
- if the navigation data is derived from a database, the database should be checked to ensure that it remains current for the duration of the flight;

- radio navigation aids, other RNAV systems if fitted, and where appropriate DR and visual navigation techniques should be used to cross-check and backup the GPS navigation data; and
- when within coverage of conventional radio navigation aids, the navigation performance of the GPS should be checked to ensure that track is maintained within the tolerances as defined for the most accurate aid being received, and if there is any discrepancy, the navigation information provided by the radio navigation aids must take precedence.

Keep in the loop. Stay in command.

Non-Standardisation of GPS/Pilot Interface

1.92 Non-standardisation in the design of GPS keyboards or control panels, functions and displays is a factor which increases significantly the potential for pilots to make errors. The proliferation of GPS receiver types contributes to the problem, making it difficult for pilots to transfer from one type of receiver to another. Hence there is a mandated requirement for GPS type training for IFR pilots. Clearly, some form of standard design code for controls and displays of advanced avionics would be desirable, but this is unlikely to be realised. With some GPS receivers, it would appear that marketing and engineering considerations in the design have taken precedence over the operating needs of the user. What looks nice in the glossy brochures can end up having many shortcomings when situated in an aircraft cockpit, i.e. ergonomic (man-machine interface) considerations have not been properly addressed. In short, some GPS receivers are not user friendly.

1.93 A further important factor is the placement of the equipment in the cockpit. Poor design combined with poor placement can make it extremely difficult for pilots to interface with the equipment with confidence. Following are a few of the considerations that are causing concern.

Control Knobs and Switches

1.94 This is a significant area of non-standardisation. There is considerable variation in the types of knobs and switches fitted, their size, the direction in which they work and the functions that they operate. To aggravate the problem, there is a growing trend towards providing multi-functional controls in the interests of neatness and compactness, e.g. providing knobs which control more than one function, depending on the mode selected. The trade-off for this is usually added complexity. Therefore, the potential for mistakes increases correspondingly, especially when workload is high. A GPS receiver with simple unambiguous controls and switches is clearly the best choice, all else being equal.

Data Display

1.95 Screen size can be critical, particularly having regard to the placement of the unit in the cockpit. However, the size and definition of characters and symbols displayed are also important issues. The data must be clearly discernible and within the general cockpit scan, but not too prominent so as to be a distraction, commanding the pilot's attention away from the primary task of flying the aircraft. Generally, with monochrome displays, CRTs are superior to liquid crystal, especially under varying cockpit light conditions. However, the technology in this area is improving rapidly, and colour displays are becoming more common, highlighting a need for standard colour codes as well as standard symbology.

Position in the Cockpit

1.96 This consideration can be influenced by the previous three above. Ideally, the GPS should be located within the NAV/COM group on the main instrument panel or centre pedestal panel, depending on the aircraft type and the information displayed, e.g. some receivers can display a CDI on the data screen. The position must ensure that parallax errors and potential physiological effects, such as spatial disorientation, are avoided.

Authorisation & Documentation

Pilot Training

1.97 Requirements prior to operating GPS equipment for primary navigation:

- An approved GPS may be used as a primary means of en-route navigation above the lowest safe altitude provided the pilot has undertake training with an approved organisation and in accordance with a syllabus listed in the CAOs. Satisfactory completion of the course and competence must be demonstrated and certified in the pilot's logbook by an approved person (FOI, or chief pilot, or CFI of the organisation or their representative). No flight test is required.
- Below the lowest safe altitude you may use an approved GPS for an RNAV (GNSS) or a GPS arrival procedure provided you pass a flight test and your log book is endorsed along with meeting the recency requirements.

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