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CHAPTER 16 – GLOBAL NAVIGATION SATELITE SYSTEM (GNSS)

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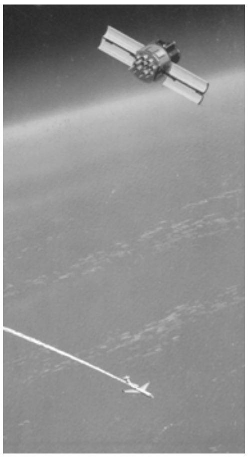
CHAPTER 16: GLOBAL NAVIGATION SATELLITE SYSTEMS

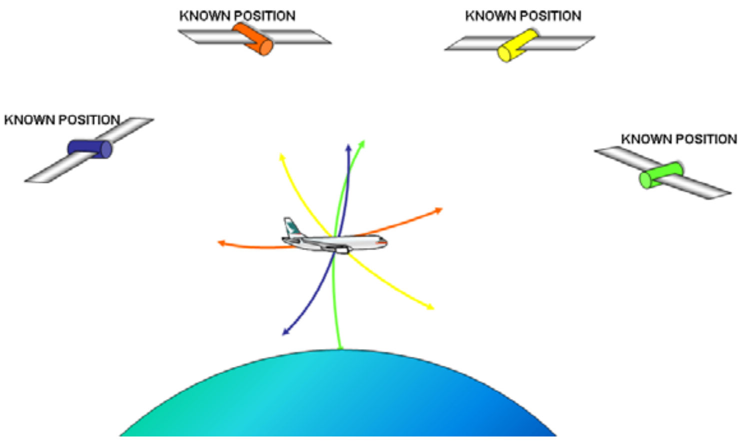
SATELLITE NAVIGATION SYSTEMS



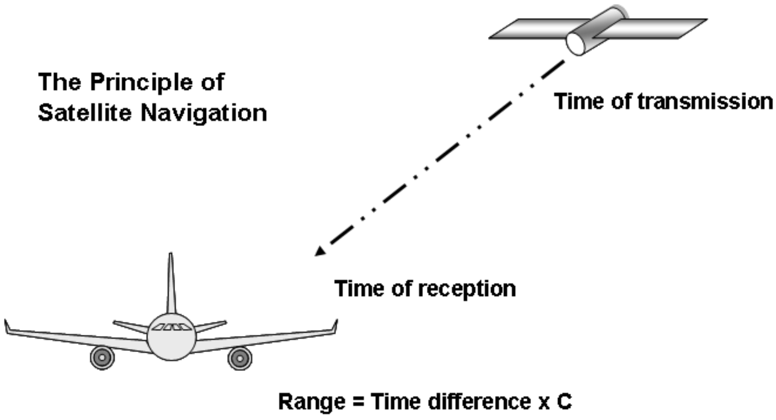
Satellite navigation systems that have been developed in recent years offer global, all-weather, continuous and highly accurate navigation information. Satellite navigation has the potential to supersede all other navigation aids for approach as well as en-route phases of flight. This section explains the principles of satellite navigation and describes the American GPS and Russian GLONASS systems. It also describes the development of the European GALILEO satellite navigation system.

THE PRINCIPLE OF SATELLITE RANGING

Satellite navigation receivers fix the position of the aircraft by obtaining a number of range position lines. The intersection of the position lines is the three dimensional position of the aircraft. The receiver is required to simultaneously (or sequentially) measure range from several satellites, the positions of which are known from data broadcast by the satellites. At least 4 satellites with good geometry are required to obtain a 3D fix. If only 3 satellites are in view, a 2D fix can be obtained if the system is provided with altitude.



Satellite ranging is similar to the principle of DME in that time and the known speed of radio waves are used to measure distance. However unlike DME, GNSS receivers are passive and measure time for the one way journey of the satellite's transmission to the aircraft. To do so accurately, the receiver must know the time of transmission on the basis of a clock exactly synchronised with that of the satellite. The satellite's transmissions are precisely timed by means of an atomic clock but the receiver's quartz clock is less accurate. There is therefore an unknown time difference between receiver and satellite clocks that GNSS resolves mathematically provided sufficient satellites are in view. Further explanation on the process to minimise receiver clock error is given on the following page.



THE GLOBAL POSITIONING SYSTEM

The American satellite navigation system, referred to as GPS (Global Positioning System), consists of three major segments:
The **Space** segment – which is the constellation of satellites described below.
The **Control** segment – which consists of the master control station in Colorado, USA and a number of monitor stations located around the world.
The **User** segment – which consists of the user's equipment that receives, decodes and processes the satellite signals.

The GPS constellation consists of 24 satellites (which includes 3 operational, in-orbit spares) orbiting the Earth in just under 12 hours. The satellites operate in six planes that cross the equator at an angle of 55° with a maximum of 4 satellites in each plane. The orbital planes are at an altitude of about 10900 nm (20200 km). Most of the time at least 4 satellites are in view from any point on the surface of the Earth.

THE GPS CONSTELLATION CONSISTS OF 24 SATELLITES ORBITING THE EARTH IN JUST UNDER 12 HOURS.

THE OPERATION OF GPS

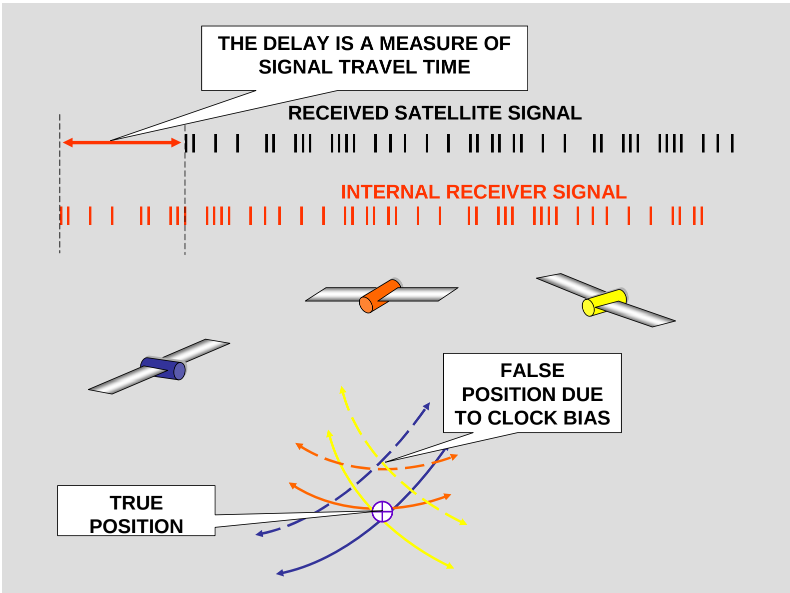
GPS operates on two L-band frequencies:

- L1 1575.42 MHz modulated with two pseudo-random codes, P (Precise) for military use only and C/A (coarse acquisition) for civil use. The position accuracy of the C/A code was deliberately degraded to ±100* metres but from the 1st May 2000 this process, known as selective availability, was discontinued. The accuracy for C/A code users is now potentially ±30* metres. * Assuming a PDOP value of 3 - see 20.9.3

- L2 1227.6 MHz P (precise code only) for military use with an accuracy which is potentially ±6 metres.

For identification purposes each satellite has its own unique C/A and P digital codes and although they appear to be random, they are well defined and predictable and so they are known as pseudo-random codes. They are low power transmissions (lower than the background noise at that frequency) and the weak signals are spread over a wide bandwidth making them less susceptible to jamming. The receiver can detect them by reproducing an exact copy that it matches with the received signal.

Each satellite's unique pulse train (the pseudo random code) contains the identification code, the satellite position in space and the exact time it was transmitted. The receiver generates an identical C/A code pulse train at precisely the same time but due to the signal travel time it is not synchronised with the transmission. The receiver automatically slews the pulse train it is generating in order to match the two signals. When they are matched the receiver 'locks on' and the receiver can measure the signal travel time plus or minus the timing error of the receiver's quartz crystal oscillator. Because of this timing error, the range that is measured is referred to as 'pseudo-range'. As the timing error or clock bias at the receiver is the same for all pseudo-ranges measured at that time, it can be eliminated by using a number of simultaneous equations. These processes are illustrated in the following diagram.



THE POSITIONS OF THE SATELLITES

The measurements of range can only be used to obtain a fix if the positions of the satellites are known. Long-term predictions of the satellite positions are made in the form of almanac data which is valid for many months. The ground monitoring stations also measure accurately the satellite's current position, altitude and speed and relay that information to the satellites. This information is then transmitted by the satellites to the GPS receiver in the form of ephemeris data. Each satellite transmits almanac data for that satellite and for every other satellite in the system as well as its own ephemeris data. Ephemeris data is the most accurate information on any variations in a satellite's orbit and is unique to each satellite. Ephemeris data also includes satellite status, current date and time, as well as orbital location and velocity. All the above information is contained within the NAV message transmitted with both C/A and P codes.

THE CONTENTS OF THE GPS NAVIGATION MESSAGE

The GPS Navigation message contains:

- Clock correction data
- Ephemeris data
- Ionospheric correction index
- UTC time
- Almanac data

Note: It takes 12.5 mins to download all the almanac data.

THE SPEED OF RADIO WAVES

Accurate range calculation from the measured time interval also requires that the speed of the radio signal from the satellite is accurately known. Radio waves travel approximately 299 000 km per second but the signal slows as it passes through the ionosphere and the atmosphere. The ionosphere is a layer of electrically charged particles about 150km above the surface of the Earth. Ionospheric slowing depends on time of day (i.e. diurnal variation), season, solar activity, radio frequency and other factors. It can be partly predicted and so corrections are automatically applied. Because the delay is inversely proportional to the square of the frequency, P code receivers using both L1 and L2 frequencies are able to assess the delay and practically eliminate the error. In the atmosphere further slowing takes place according to the quantities of water vapour that are present.

HOW ACCURATE IS GPS?

The answer to the question depends on who is using the system. For users authorised by the US Department of Defence, Precision Position Service is provided by allowing access to the precision code (P) signals. These are generally military users and the resulting accuracy is ± 6 metres for 95% of the time. For other users, e.g. Civil Aviation, Standard Position Service is provided by means of the Coarse/ Acquisition code (C/A) signals. Accuracy is downgraded to ± 10 metres for 95% of the time. PDOP (see below) can further degrade the quoted accuracy.

SOURCES OF ERRORS

SURVEY DATUM DISCREPANCIES

The figures quoted for accuracy assume that the position given is referenced to the World Geodetic System 1984 (WGS 84) datum. The point of origin of WGS 84 is the Earth's centre of mass. GPS uses WGS-84 for establishing its position in relation to the Earth's surface and conforms to ICAO which adopted WGS-84 as a world standard in 1998. Formerly various local and regional datums were in use giving rise to discrepancies of several hundred metres. By resurveying this source of error has been largely eliminated.

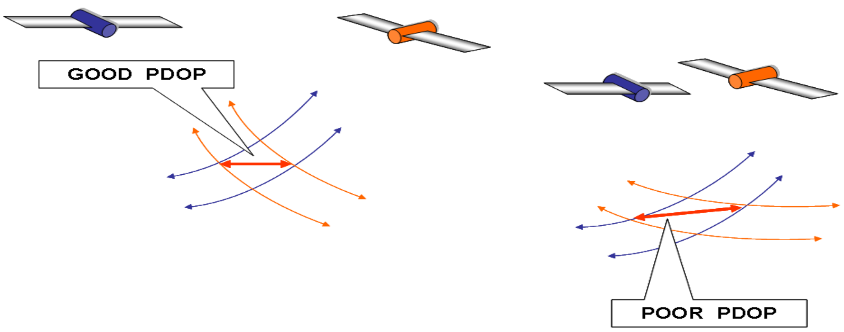
IONOSPHERIC AND TROPOSPHERIC SLOWING OF SIGNALS

As previously stated, one of the most significant causes of error is the slowing of the satellite signals as they pass through the ionosphere and the atmosphere. P code users who have access to two signals on different frequencies can reduce the ionospheric component of this error.

POSITION DILUTION OF PRECISION (PDOP)

If the geometry of the position lines from the available satellites is not ideal, the fixing error due to other causes is magnified. This source of error known as Position Dilution of Position (PDOP) can increase the fixing error from ±10 metres to ±100 metres.

Errors mean the receiver is located in a band of distance from the satellite. Position Dilution of Precision (PDOP) puts the receiver somewhere inside a box formed when the bands overlap. When the satellites used are closer together (see below) the box is elongated and the potential PDOP is greater.



If the available satellites are clustered PDOP reduces the accuracy of the fix

ICAO has specified that for en-route navigation, a PDOP of less than 6 is required, with a PDOP of less than 3 required for non-precision approaches.

PDOP in combination with Time Dilution of Precision (TDOP) may be referred to as Geometric Dilution of Precision (GDOP). The vertical component of PDOP is referred to as VDOP and the horizontal component is HDOP.

MULTIPATH

Multipath is an error in range measurement resulting from the reflection and refraction of the satellite signals by objects and ground near the GPS receiver.

Note: The use of a masking function which excludes satellites below a fixed elevation angle relative to the user's horizon limits both multipath and ionospheric / tropospheric errors. Equipment that meets the TSO C129 specification uses a mask angle of 7.5°.

CLOCK ERRORS

Timing errors due to inaccuracies in both the satellite and receiver clocks, as well as relativity effects, can result in small position errors. Relativity effects arise because of relative motion between the satellite and the receiver.

RECEIVER NOISE

The satellite signals are wide spectrum, low power transmissions and are generally weaker than the background noise when they arrive at the GPS receiver. The weakness of the signal affects the ability of the receiver to match the satellite and receiver generated codes.

EPHEMERIS ERROR

Satellite ephemeris data is updated as the satellites pass over the earth monitor stations. There is however likely to be some remaining small discrepancy between the satellite's true position and the transmitted ephemeris data.

GPS ERROR BUDGET

Sources of error	C/A code users	P code users
Clock errors	2 m	2 m
Ephemeris errors	4 m	4 m
Ionosphere	8 m	1 m
Tropopause	3 m	3 m
Receiver noise	1 m	0 m
Total error	10 m	6 m

NOTES: Total errors found by the root mean square method.

- The accuracy figures quoted above will only apply if there is no dilution of precision (PDOP). A PDOP of 3 is normally assumed.

GPS AND GLONASS

Both the USA and the former USSR developed satellite navigation systems that have common elements but some significant differences. Both their commonality and their unique features reflect their military origin. i.e. the US and USSR attempted to meet military navigation requirements by similar solutions but developed their own systems entirely independently.

The USA launched its first prototype GPS satellite in 1978 and achieved full operational coverage by 1993 with satellites launched from Cape Canaveral at the rate of 5 per year. Full operational coverage consists of 24 satellites, i.e. 21 active plus 3 spares. Their design life is 7 $^{1}/_{2}$ years.

The USSR developed GLONASS (Global Navigation Satellite System) to achieve the same purpose and with a similar design. Satellites were launched from a base near the Aral Sea, the most southerly region of Russia. The first was launched in 1982 and Russia continued deployment at the rate of 2 launches per year, each rocket containing 3 satellites. Full operational coverage of 24 satellites was achieved in 1995 but after the collapse of the Soviet Union GLONASS fell into disrepair. It was recovered and restored in 2011.

There are obvious advantages in designing receivers that use both systems. Potentially users will have six or seven satellites in view at all times where now they have may have only three or four. There are however difficulties in building aircraft receivers that can simultaneously track GPS and GLONASS satellites. It is not just a matter of adding extra channels as there are significant technical differences between the American and Russian systems.

Examples of differences between GPS and GLONASS are as follows:-

1. Satellite Identification GPS uses CDMA (Code Division Multiple Access) to give each satellite a unique code modulation. All GPS satellites operate on the same pair of frequencies. GLONASS on the other hand uses FDMA (Frequency Division Multiple Access) to identify satellites by unique frequencies.
2. Time References. Satellite navigation relies on exact knowledge at the aircraft receiver of the satellite's time reference. Both GPS and GLONASS use UTC but small differences exist between atomic clock standards at the US Naval Observatory and in Russia.
3. Orbit Information. GPS broadcasts information on satellite orbits, updated every hour, in the form of corrections or irregularities to the orbit. GLONASS works quite differently for each satellite broadcasts its 3D position, velocity and acceleration every 30 minutes. The user interpolates for intermediate times.

	GPS	**GLONASS**
Orbital Planes	6 (spaced by 60°)	3 (spaced by 120°)
Satellites (per orbital plane)	4 (unevenly spaced)	8 (evenly spaced)
Orbital inclination	55° to the Equator	64.8° to the Equator
Orbital Radius (from centre of the earth) Orbital Altitude	26560 km 20160 km (10900 nm)	25510 km 19110 km
Orbital Period	½ of a sidereal day	8/17 of a sidereal day
Repeat Ground Track	every sidereal day	every 8 sidereal days
Carrier Signals	L1 1575.42 MHz L2 1227.60 MHz	1602 + (k x 9/16) MHz 1246 + (k x 7/16) MHz (k = Channel number)
Codes	different for each satellite	same for all satellites

BARRIERS TO THE APPROVAL OF GPS BY CIVIL AVIATION AUTHORITIES

Aviation authorities have been reluctant to approve GPS as a sole-means navigation source. Lacking both a record of reliability and a built-in integrity monitoring system, authorities have been cautiously approving GPS as a supplementary or primary means of navigation. To achieve sole-means approval, a navigation system must satisfy five basic performance characteristics: accuracy, availability, reliability, coverage and integrity. A supplementary means must be used in conjunction with a sole means navigation system whereas a primary means must meet accuracy and integrity requirements but need not meet full availability and continuity of service requirements. Availability and integrity are the major issues that have prevented the use of GPS as a sole means of navigation and these can be defined as follows:

AVAILABILITY - the ratio of the total time a facility is operationally available to the total time in a specified period.

NOTE: Current minimum operational standards require there to be a minimum of 5 satellites in view above a mask angle of 7.5°. For short periods of time, in some places, GPS with full operational coverage (21 satellites plus 3 operational spares) does not meet this requirement.

INTEGRITY - the trust that can be placed in the correctness of information from a system. The term includes the ability of a system to provide timely warnings to users when a system should not be used for navigation.

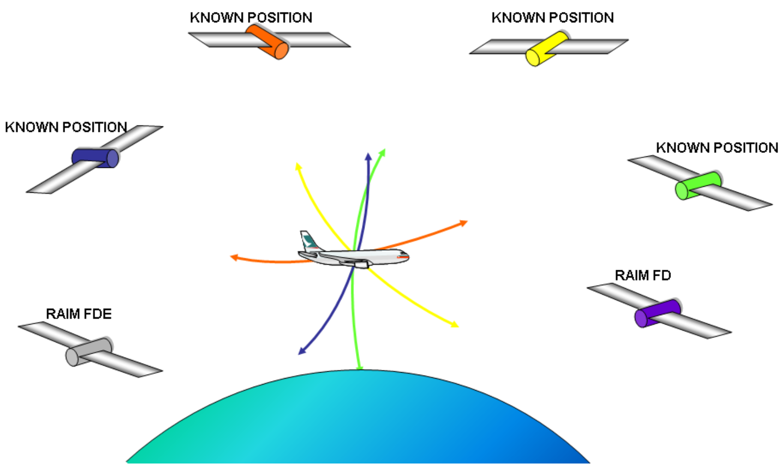
NOTE: Individual GPS satellites are not continuously monitored and considerable time could elapse before a ground station detects and corrects a problem. Meanwhile receivers may continue to use the erroneous signal resulting in navigation errors.

GPS DEVELOPMENTS

There are a number of developments that can overcome the availability and integrity limitations of GPS and these are listed and described below.

RECEIVER AUTONOMOUS INTEGRITY MONITORING (RAIM)

RAIM detects the failure of a GPS satellite by comparing position and time information from various combinations of four satellites in a set of at least five visible satellites. In this way a faulty satellite can be detected and a warning provided to the pilot. A minimum of six satellites must be visible for the RAIM function to continue following the detection of a faulty satellite. GPS even with full operational coverage (FOC) does not meet at all times and at all places the integrity requirements by means of RAIM. RAIM can be assisted by means of Barometric Aiding (see below) which effectively adds a further position line, reducing the requirement for visible satellites by one.



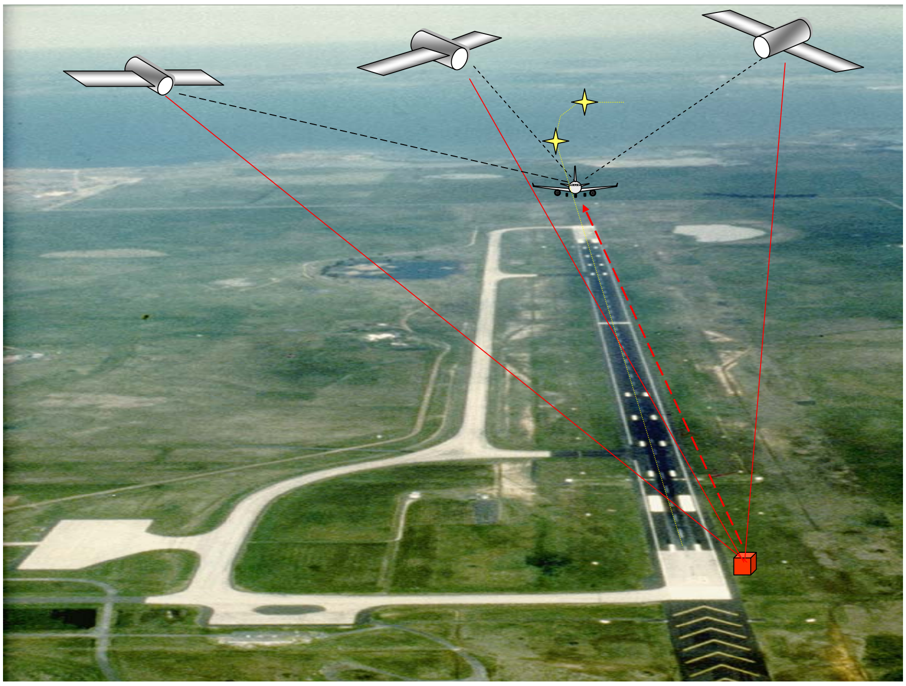
GPS INTEGRITY CHANNEL (GIC)

GIC is a non-Department of Defence system that interfaces with GPS and broadcasts civil GPS integrity information to users in a designated area, based upon measurements made by a ground based monitor or network of monitors

DIFFERENTIAL GPS - APPROACH PHASE AND WIDE AREA (WADGPS)

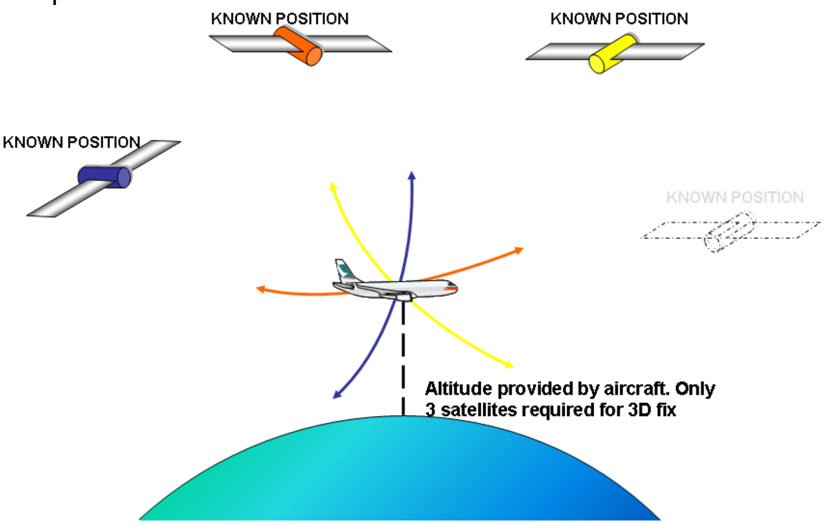
Differential systems use ground based monitoring equipment at accurately surveyed locations to determine the error in the GPS signal. A differential correction can then be computed by comparing the GPS position with the surveyed position of the monitoring station and the correction relayed to the aircraft's navigation system. Differential GPS can be used to achieve the accuracy required for a precision approach by means of a monitor located at the airport (shown next page). It can also be used as Wide Area Differential GPS (WADGPS) to provide a correction service to an entire continent by relaying information to users via a geostationary satellite.

Integrity and differential monitoring can also be described as augmentation systems, either as Ground Based (local area) Augmentation Systems (GBAS) and Space Based (wide area) Augmentation Systems (SBAS). Wide area augmentation is being developed by the US, Europe and Japan.



BAROMETRIC AIDING

With barometric aiding the GPS receiver obtains another measured range by using the output of the pressure altimeter or SSR mode C and so one less satellite is required.



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PSEUDOLITES

It is possible to use ground-based transmitters to broadcast navigation and timing signals similar to those transmitted by the GPS satellites. These pseudo-satellites are low power transmitters that can be used to supplement the GPS constellation allowing navigation and RAIM functions to continue when insufficient satellites with good geometry are in view.

OTHER GLOBAL NAVIGATION SATELLITE SYSTEMS

The coverage of the American GPS satellites alone may not meet in all locations at all times the integrity and availability requirements of civil aviation. At times there have been ‘worm holes’ in the coverage, lasting from a few minutes to a few days, that have caused degradation of accuracy or even total loss of GPS service. GLONASS (previously described) can be used to supplement GPS coverage but other navigation satellite systems are under development. The European Navigation Satellite System, known as GALILEO, was originally scheduled to become operational in 2010 but initial deployment has now slipped to 2014. GALILEO is expected to be fully compatible with GPS so that receivers will be able to combine signals and achieve greatly increased accuracy.
China has indicated that they intend to expand their regional navigation system, called Beidou or Big Dipper, into a global navigation system called COMPASS by 2020. The COMPASS system will utilize 30 medium Earth orbit satellites and five geostationary satellites.

MULTISENSOR SYSTEMS

Availability and integrity problems can be overcome by combining GPS with another system. Various combinations have been proposed including GPS/MLS and GPS/IRS. GPS used in conjunction with an Inertial Reference System provides an optimum solution that makes use of IRS position and velocity data during periods when insufficient satellites are available. It effectively combines the long term accuracy of GPS with the short term accuracy of IRS.

TYPES OF GPS RECEIVER

SEQUENTIAL TRACKING RECEIVERS

Sequential receivers track one satellite at a time and combine the measurements of pseudo-range once all four have been made. They are the cheapest receivers but are unsuitable for use in aircraft.

MULTI-CHANNEL RECEIVERS

The most suitable for aircraft are multi-channel receivers capable of tracking at least four satellites simultaneously. Some receivers are able to track many more satellites and are said to have an ALL IN VIEW CAPABILITY. Such receivers, which must be multi-channel or multiplex (see below), suffer little or no loss of accuracy when one or two satellites are lost from view.

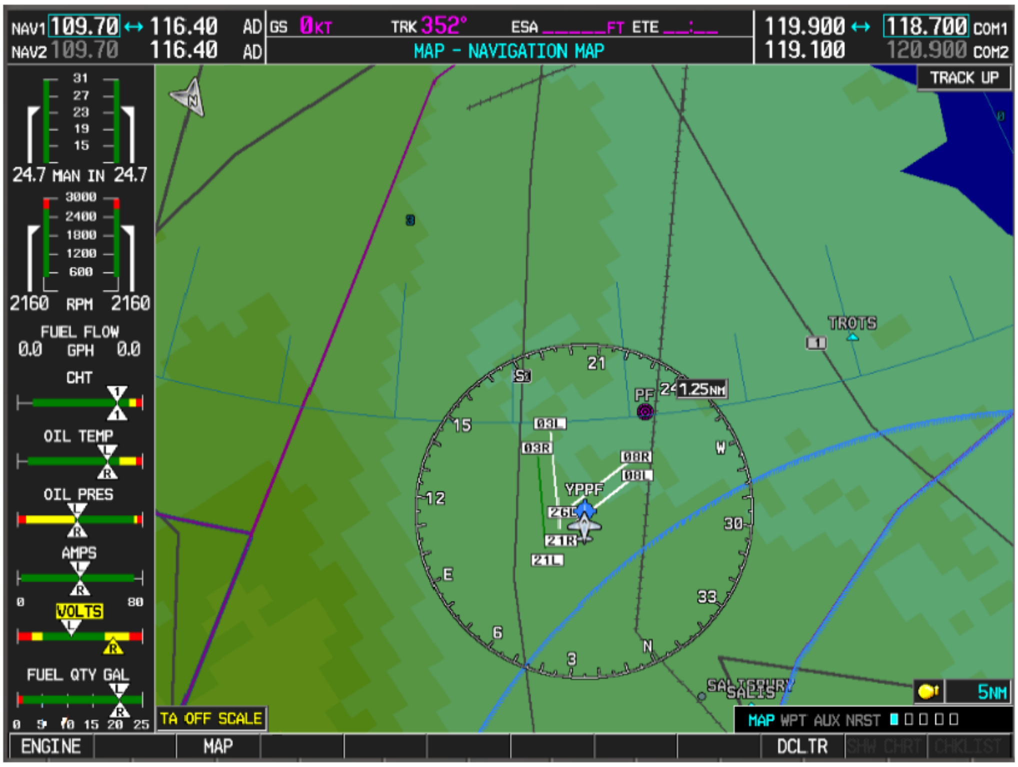
MULTIPLEX

A multiplex receiver switches at a fast rate between the satellites being tracked to obtain an accurate fix position. The NAV message is read continuously from all the satellites.

Note: The term 'SEARCH THE SKY' is used when the receiver must randomly locate and lock on to any satellite in view. This happens if the receiver has only a poor idea of its position and time. Having located a satellite the receiver down-loads the almanac to obtain the positions of the satellites in the entire constellation.

TYPICAL GPS RECEIVER

Illustrated below are two GPS pages from the GARMIN G1000 receiver designed to meet navigation requirements in the air.



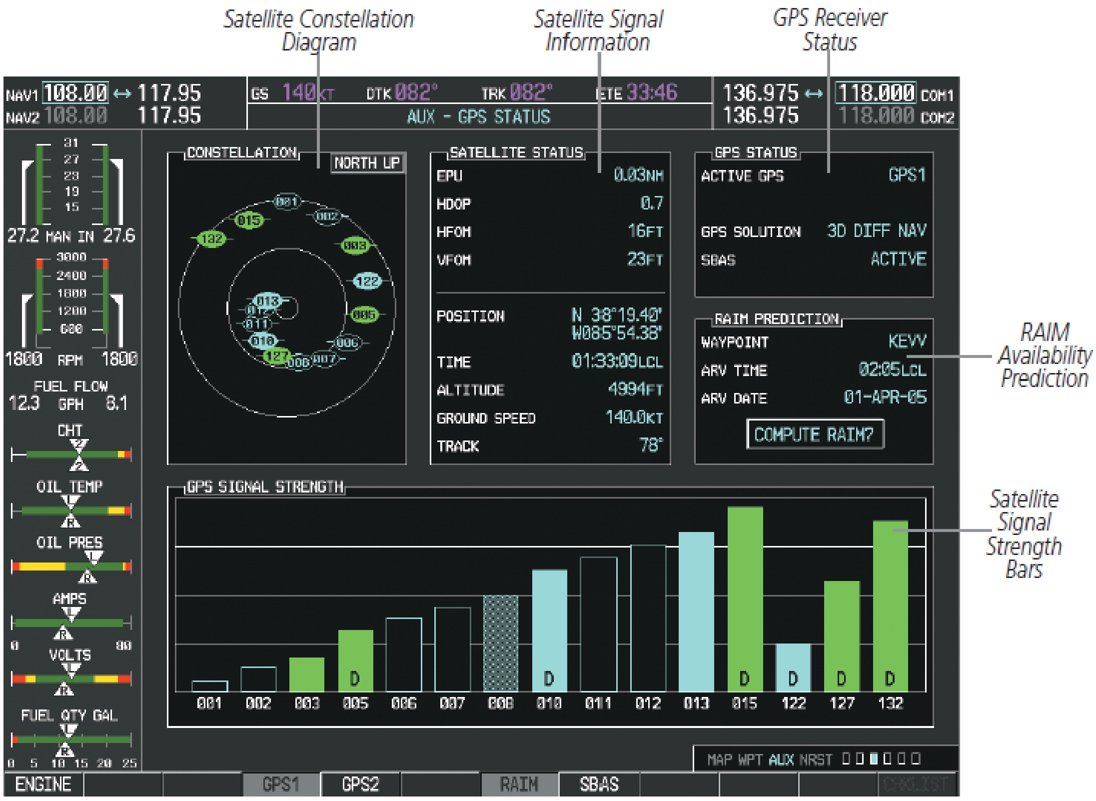


Figure 1-11 GPS Status Page

The receiver provides the following facilities:

- Current position
- Waypoint navigation
- Dilution of precision information
- Current and future satellite coverage
- Evaluation and selection of best satellites
- Dead-reckoning during coverage gaps and other data
- RAIM prediction

THE FUTURE OF SATELLITE NAVIGATION

To quote the ICAO FANS (Future Air Navigation System) committee -"satellite based communication, navigation and surveillance is the centrepiece of the Committee's blueprint for future air navigation systems".

While the long term future of GNSS is assured, there are at present significant obstacles to be overcome:-

- There is concern about the danger of interference with GPS signals and the effectiveness of anti- jamming equipment has yet to be proven.

- Full GLONASS/GPS interoperability has yet to be achieved.

- Aviation authority approval of GPS as a sole-means navigation source is likely to be dependent on the introduction of a ground based integrity monitoring system. This is proving to be very costly and has yet to be deployed.

- There are questions of whom or what will be the controlling authority for GNSS, and who will pay. Opinion in Europe is strongly against reliance on a foreign military system (GPS) but initial deployment of the alternative civilian satellite system GALILEO is not expected until 2014 with the system planned to be fully operational by 2020. The current estimate of the cost of the civilian systems is as much as US$ 5 billion and it has been decided that there will be user fees for some applications. Questions remain on how fees will be levied and of how a user-pays system can operate in conjunction with free-of-charge GPS.

These problems will no doubt be overcome and it would seem likely that satellite navigation will ultimately replace all current radio navigation aids and may render obsolete developing systems such as MLS.

WORKSHEET - GNSS

1. The space segment of GPS consists of:

   (a) 24 satellites plus 3 operational spares
   (b) 18 satellites plus 6 operational spares
   (c) 21 satellites plus 3 operational spares
   (d) 18 satellites plus 3 operational spares

2. GPS satellites operate in ________ orbital planes inclined at an angle of _____ degrees to the equator at an altitude of approximately _____ km.

	No of planes	Angle	Altitude
(a)	4	35	11000
(b)	6	45	20000
(c)	4	45	11000
(d)	6	55	20000

3. Which of the following statements are true?

   (i) Each GPS satellite transmits continuously on the same two frequencies.
   (ii) DME is an active ranging system whereas GPS airborne equipment constitutes a passive system.
   (iii) GPS does not have a ground based control system and so orbital changes are likely to remain undetected.

   (a) All statements are true
   (b) (ii) and (iii) only are true
   (c) (i) and (iii) only are true
   (d) (i) and (ii) only are true

4. Each satellite is assigned its own unique C/A and P codes. What is the availability of these codes to users?

   (a) Both codes are available free of charge to all users.
   (b) The C/A code is only available to the CIA.
   (c) The C/A code is only available to U.S. military users.
   (d) The P code is reserved for high precision authorised users.

5. How many satellites need to be in view to obtain a three-dimensional (lat/long and altitude) fix without barometric aiding?

   (a) 3
   (b) 4
   (c) 5
   (d) 6

6. What is the purpose of barometric aiding?

   (a) The input of height above the ground enables a measured latitude and longitude to be upgraded to a three-dimensional fix.
   (b) The GPS receiver can use pressure altitude to simulate an extra satellite in view thus reducing the reliance of orbiting satellites
   (c) The standard pressure datum used for the measurement of barometric altitude can be used in place of the geodetic datum WGS 84 if this is not available.
   (d) The input of pressure altitude data to the GPS receiver allows a four-dimensional fix to be obtained by civilian users.

7. The measured distance of the receiver from the satellite is referred to as pseudo-range. This term is used because:

   (a) Distance is determined indirectly by measuring the travel time of a radio signal from the satellite to the receiver and the accuracy is affected by errors in the receiver's clock.
   (b) The distance is inaccurate due to errors in the satellite's atomic clock.
   (c) The range was exact at the instant it was measured but is inaccurate by the time the fix is obtained.
   (d) The travel time cannot be accurately measured because of ionospheric and tropospheric slowing.

8. The satellites transmit almanac and ephemeris data. Which of the following statements is true?

   (a) Ephemeris data is less accurate than almanac data.
   (b) The almanac data transmitted by each satellite refers to the orbital paths of the entire constellation.
   (c) Ephemeris data is long-term information relating to the predicted position of the satellite constellation.
   (d) Orbital variations caused by the gravitational pull of the moon and sun are made known to the receiver by means of almanac data.

9. The term integrity when applied to a GNSS refers to :

   (a) the ability of the system to provide useable service within the specified coverage area.
   (b) the percentage of time that the services of the system are available
   (c) the extent to which satellite geometry affects navigation and time accuracy.
   (d) the capacity of the system to provide timely warnings to users when the system should not be used for navigation.

10. The purpose of the RAIM function is to _________ and to do so it is necessary that _______ satellites are in view.

   (a) detect the failure of a satellite/5
   (b) monitor system integrity/6
   (c) reduce inaccuracy due to poor satellite geometry/5
   (d) overcome satellite availability problems/3

11. With ______ satellites visible before detection of a faulty satellite, RAIM can continue to function following its deselection. RAIM ______ assisted by barometric aiding.

   (a) 5 may be
   (b) 6 is not
   (c) 5 is not
   (d) 6 may be

12. PDOP is an abbreviation for_______ and is most significant when using satellites that are located________

   (a) Precise Definition of Position/ close together
   (b) Position Dilution of Precision/ far apart
   (c) Precise Definition of Position/ far apart
   (d) Position Dilution of Precision/ close together

13. Slowing of the satellite signals is one of the most significant errors in the measurement of pseudo-range. Which of the following statements are true?

   (i) Slowing occurs in the atmosphere, as well as the ionosphere.
   (ii) Ionospheric slowing is affected by sunspots, time of year and time of day.
   (iii) Error due to ionospheric delay can be practically eliminated by users with access to both satellite frequencies.

   (a) All are true
   (b) (ii) and (iii) only are true
   (c) (i) and (iii) only are true
   (d) (i) and (ii) only are true