Global Navigation Satellite System (GNSS)

Course Notes

A.ROUGÉ

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GNSS

FANS (Future Air Navigation Systems), a committee of experts of the International Civil Aviation Organization (ICAO), proposed technical solutions for future navigational aids in 1983. The FANS committee demonstrated that navigation, communication and surveillance would be linked in the years ahead and thus introduced the theoretical concept of **CNS/ATM** (Communication Navigation Surveillance / Air Traffic Management).

The **CNS/ATM** concept, adopted by ICAO in 1991, is a response to the lack of consistency in ATM and the limitations of conventional radio. It concerns deploying new resources to handle the growth of air traffic.

The **CNS/ATM** concept includes a worldwide positioning and time measurement system known as the Global Navigation Satellite System (**GNSS**).

GNSS is based on one or more existing satellite constellations augmented with related systems to achieve levels of precision, integrity, availability and continuity that respond to the requirements of the civil aviation community.

> A navigation system's <u>precision</u> is a statistical expression of the level of conformity between the measured position and the actual position (for example, 100 m on the horizontal plane in 95% of cases).
>
> A navigation system's <u>integrity</u> is its ability to detect a degradation in precision beyond a threshold and to warn the user of this degradation without exceeding a warning period. Threshold and warning period are specified depending on flight phase.
>
> A navigation system's <u>availability</u> is its ability to provide positioning and nominal integrity services <u>at</u> <u>the</u> <u>start</u> of the flight phase considered.
>
> A navigation system's service <u>continuity</u> is its ability to provide positioning and nominal integrity services <u>during</u> the flight phase considered.

A navigation resource that satisfies these four criteria for a flight phase constitutes a <u>unique</u> <u>resource</u> for this flight phase.

A navigation resouce that satisfies the criteria for precision and integrity but does not satisfy the availability/continuity criteria is termed a supplementary resource for this flight phase. The lack of availability/continuity requires installation of a unique resource. Since the supplementary resource is integral, the unique resource may be inactive as long as the supplementary resource is available.

It is possible to define restrictive operational procedures with prediction for availability before the flight phase. In this case installation of a unique resource is not required and the navigation resource is qualified as primary resource for navigation.

In 2011 two global positioning systems (GPS) are operational, the American **NAVSTAR-GPS** and the Russian **GLONASS** (GLObal Navigation Satellite System).

The European **GALILEO** system is in development and will be operational in 2014.

1.1 GPS Introduction

GPS is a system for navigation using satellites developed by the United States Department of Defense (**DOD**) for military purposes.

The system provides two services:

1. Precision Positioning Service (**PPS**) for authorized users (American military, NATO, etc),
2. Standard Positioning Service (**SPS**) for civilian users and thus can be used as part of **GNSS.**

The precision of **SPS** (at the equator and in 95% of cases) is 100 meters on the horizontal plane and 150 meters on the vertical plane.

SPS precision has noticeably improved since the voluntary degradation of precision called Selective Availability (**SA**) was deactivated.

Augmentations or additions to GPS are necessary for GNSS because limitations remain, including

- variable precision,
- variable availability,
- low integrity.

GPS uses trilateration to perform position calculations. From a geometry standpoint, trilateration requires 3 distances at 3 reference points (known positions) to calculate a position in a three-dimensional (3-D) space. In reality GPS requires four distance measurements to find a 3-D position. This additional measurement is necessary to estimate the bias relating to the time reference of the GPS receiver when calculating a 3-D point.

The four distances are obtained by measuring four propagation times on a simple trajectory (satellites / GPS receiver) using a <u>globally synchronised</u> infrastructure. The propagation time measurements on a simple trajectory require close synchronisation between the satellite time reference and the receiver time reference.

1.2 GPS space segment

The space segment is composed of 24 satellites (SATs) or space vehicles (SVs) in near-circular orbits at an average altitude of 20,180 km. The orbital period is 12 hours. SATs are located on six planes inclined by 55° with respect to the equatorial plane and spaced apart by 60° in longitude. There are four SATs per plane.

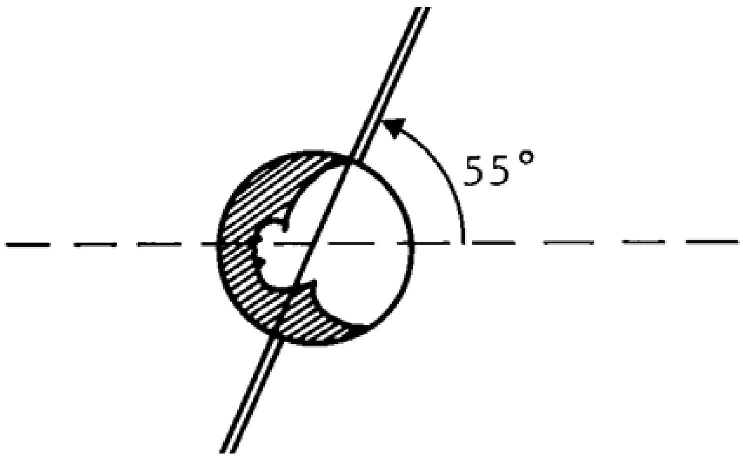

Figure 1.1: Space segment

The choice of this geometry is necessary for global coverage. The principle for calculating the solution to 3-D navigation requires that, *at any point on the globe and any moment*, any receiver can be viewed by at least four SATs. In reality, specific constraints on the visible SATs/receiver group, service continuity and the level of integrity require that this number be increased.

The SATs are equipped with four clocks (two caesium, two rubidium) whose reliability over a week is on the order of 10 to the power of -13 (class 10 power -13). They are reset daily by the control segment. The quality of the clocks, a critical point in the programme, defines GPS time.

The GPS receiver cannot include a clock of such quality. It thus uses a pseudo-synchronised reference (simple electronic quartz) whose bias in relation to GPS time will be considered as a fourth variable in addition to the three localisation variables.

1.3 GPS Principle

The position of the GPS receiver is obtained by measuring the distances to the satellites. The GPS receiver is located at the intersection of a certain number of lines of position (LOP). The LOPs (geometric position of points such that the measurement aboard is constant) are spheres centred on the position of each satellite.

The measured distances are called pseudo-distances; they contain an error because the SAT and user clocks are not perfectly synchronised.

The receiver measures pseudo-distances by estimating the delay between two identical codes, one sent by the satellite, the other generated locally.

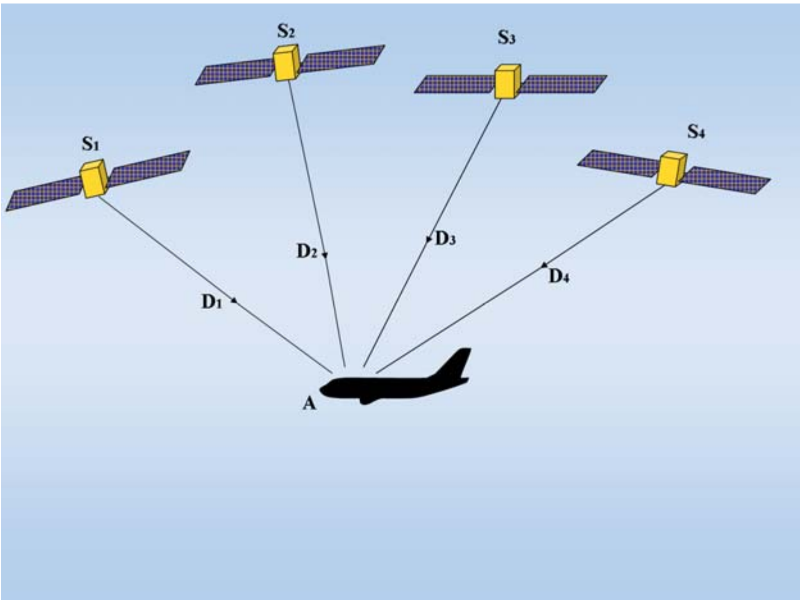

Figure 1.2: Principle

In summary, to calculate a GPS position, four propagation times are measured on a simple trajectory using a globally synchronised infrastructure.

1.4 GPS Signals

Each satellite in the GPS constellation sends two carrier frequencies called L2 (1227.60 Mhz) and L1 (1575.42 Mhz). L2 is a military frequency and L1 a civilian frequency. The two carrier frequencies are modulated by pseudo-random **codes** and a navigation **message**.

A pseudo-random code or pseudo random noise (**PRN**) is a sequence of binary code (0 or 1) that appears random. In actuality, the sequence repeats itself after every N pieces of data. Each element of code is also called a chip. A PRN code does not contain data but is used to recognise the satellite and perform the calculation for SAT/receiver distance.

Each SAT emits its own unique coarse acquisition (C/A) code and precision code (P-code). The C/A or civilian code is short (1,023 elements, duration of code chip of 1 microsecond, and 1 ms in length). The P- or military code is long (duration of code chip is 0.1 microsecond with a length of 7 days).

A navigational message is a binary sequence (data) that gives the satellite's position and other parameters.

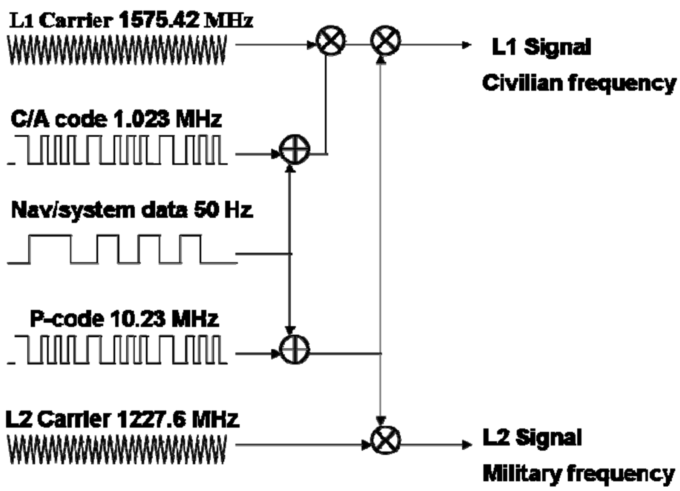

Figure 1.3: GPS Signals

The civilian **L1** carrier is triply modulated (**C/A** code, P-code, navigation message) but the P-code will not be used for **SPS** (“civilian” receiver).

The **L2** carrier is modulated by the P-code and navigation message. **PPS** (military receiver) uses P-code on two frequencies to evaluate propagation conditions.

The navigation message is superimposed on PRN codes with modulo addition of code and data. Modulation of the carrier is Binary Phase Shift Keying (**BPSK**) modulation at two phase states (0° and 180°).

1.5 GPS Navigation Message

This is a data message sent at a speed of 50 bits/second. It contains data specific to the satellite that emits it (ephemeris and clock correction), data on the entire constellation (almanac) and parameters relating to ionospheric propagation.

GPS ephemeris is the table for predicting the position of the satellite being considered. GPS almanac includes the set of 24 ephemeris.

The navigation message is composed of frames that are 1500 bits long and last 30 seconds. Each frame is divided into five subframes that are 300 bits long and last 6 seconds.

Transmission time for the entire navigation message requires 25 frames, or 12 minutes and 30 seconds.

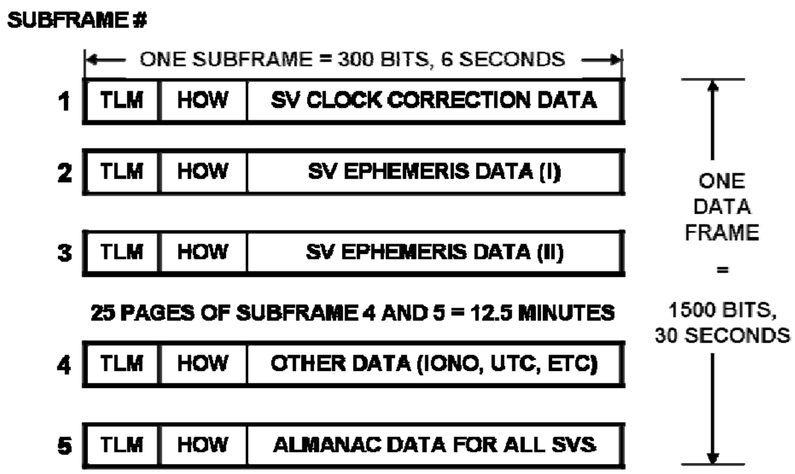

Figure 1.4: GPS Navigation Message

The SAT stores the data, which is updated by the control segment.

During the first measurement, if the receiver is not initialised with an approximate time and position, the receiver operates in full search mode: this is called Search the Sky. In this case, it will require nearly ten minutes to locate its position.

1.6 GPS Code correlation

The GPS uses Code Division Multiple Access (CDMA). All 24 SATS simultaneously emit on the same frequencies (L2 and L1). A GPS receiver receives all signals from the visible constellation. Potential interference is resolved because the receiver recognises the double signature (C/A and P-codes) of each satellite.

Codes must have the following properties:

- possibility of filtering some in relation to others, or null intercorrelation,
- possible identification using a delayed version of itself, auto correlation presenting a marked peak.

The measurement principle consists of correlating two identical sequences; the code received and the same code generated locally.

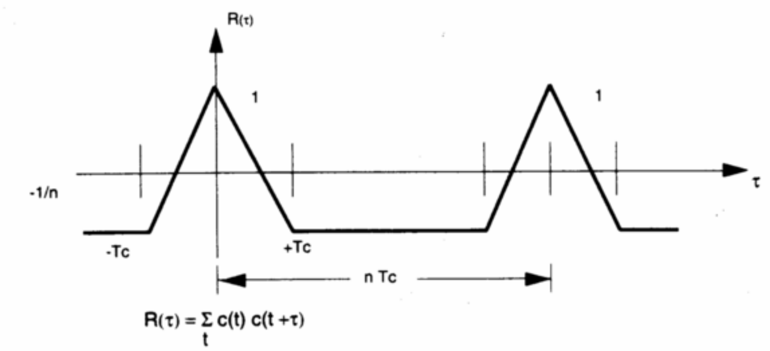

Figure 1.5: Correlation function

For this, local code is switched with received code to calculate the autocorrelation function.

The autocorrelation function (bit by bit sum of products) is periodic and causes well-defined maximums to appear.

1.7 GPS Control Segment

The American military is responsible for the control segment and maintaining the entire space segment. It is composed of **5 stations** on the ground at the following sites:

- Colorado Springs master control station and monitor station
- Hawaii monitor station
- Ascension Island monitor station and ground antenna
- Diego Garcia monitor station and ground antenna
- Kwajalein monitor station and ground antenna

The monitor stations verify satellite status, reporting to the master station which determines the corrections to be made to the orbital parameters, time data, etc. Corrections are sent to the satellite concerned.

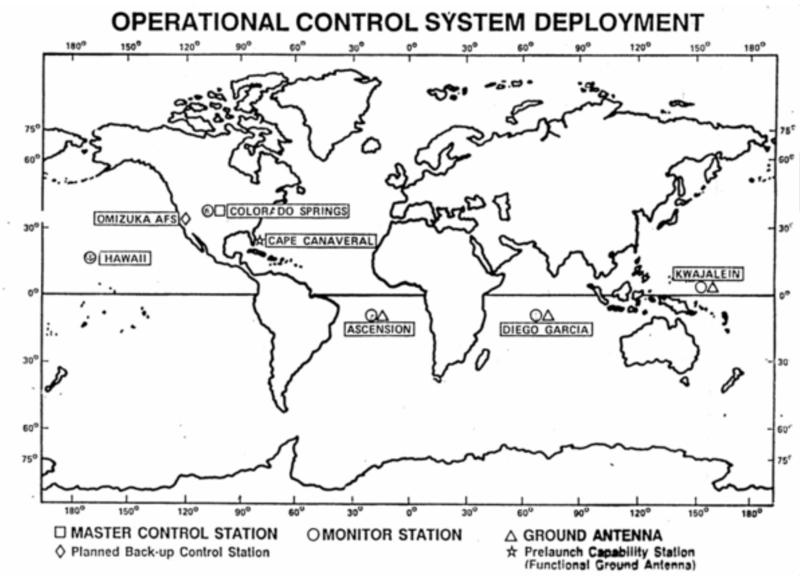

Figure 1.6: Control segment

This segment is also responsible for intentionally degrading the precision of the navigation solution for SPS by introducing errors in the position (erroneous data introduced in the ephemeris section of the data message, known as ephemeris overcoding) and time data (time dither) of each satellite. This voluntary degradation is called selective availability (SA) and has not been used since 2000.

1.8 GPS User Segment

It is composed of all receivers able to receive GPS signals. Civilian receivers are distinct from military receivers. High dynamic users (civil aviation) can be distinguished from low dynamic users (geodesy). Lastly, the receivers are single (L1) or dual frequency (L1 and L2), single or multi-channel and may include such special features as autonomous integrity monitoring or augmentation access.

1.9 GPS Precision

By principe (measurement of four pseudo-distances), precision of the solution of navigation depends on the geometry with which the receiver sees the constellation. Precision varies in time and space. Navigation service can thus be greatly degraded and even unavailable in certain cases. The degradation (or dilution) of the precision in position is inversely proportional to the volume of the tetrahedron created by the receiver and the four SATs used. At each moment, the receiver must choose from all SATs received at an elevation angle of at least 5°, the group of four SATS resulting in minimal dilution of precision (DOP).

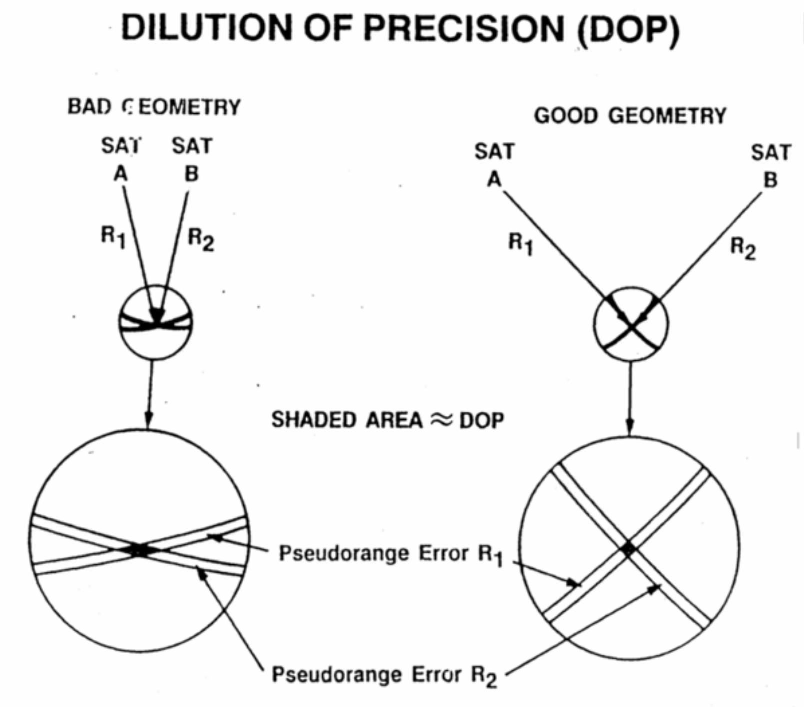

Figure 1.7: Dilution Of Precision

The concept of DOP can be illustrated by reasoning in two dimensions. If the angle at which the LOPs cross is small, precision is greatly diluted. If the LOPs cross at 90°, the position error is proportional to the distance error. In three dimensions dilution will be minimal if three SATs are observed 120° apart just above the horizon and a SAT is directly overhead.

The measurement of the propagation time for the descendant SAT/receiver signal is affected by several factors:

- ionospheric propagation delay (IPD) (most significant factor)
- satellite position (ephemeris)
- synchronisation (satellite clock)
- receiver noise
- multi-trajectory.

These factors introduce an equivalent error on the SAT/receiver distance measurement, known as User Equivalent Ranging Error (UERE).

Final localisation precision may be expressed as the product of UERE and a degradation factor from the Geometric Dilution Of Precision (GDOP). POSITION ERROR = UERE x GDOP.

In three dimensions this degradation or dilution factor is called Position Dilution Of Position (PDOP).

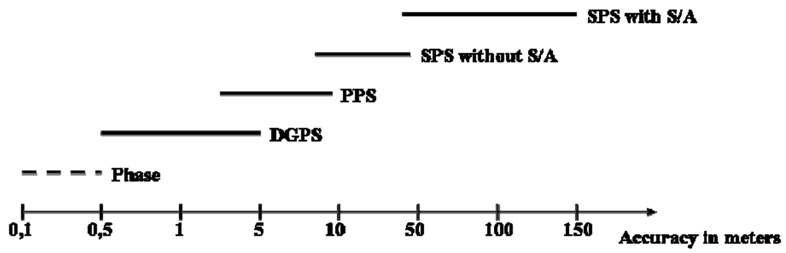

Figure 1.8: Errors

The precision of non-augmented GPS, i.e. without additions, is variable. It depends on the service used (PPS or SPS), presence of SA, differential correction data and lastly receiver dynamics ("static" receivers in civil engineering used a phase tracking technique to improve precision). The requirements of the civil aviation community are quite high: highly dynamic receivers, integrity and availability.

1.10 Ground Based Augmentation System (GBAS)

The **GBAS** is a local augmentation of GPS and GLONASS based on the concept of local differential.

The technique of local differential assumes a spatial correlation in the errors. Two receivers located fairly closely together (< 30 km) take the same measurements that have the same errors. A ground or differential receiver, whose exact position is known, helps provide corrective terms for an embedded GPS receiver nearby.

The ICAO **GBAS** uses a data connection on VHF band ILS-VOR (108–118 Mhz) to send corrections. The data connection is known as VHF Data Broadcast (VDB).

The range of a GBAS station is on the order of 30 km. Coverage is from 35° Azimuth up to 15 nautical miles of the threshold and 10° Azimuth between 15 nautical miles and 20 nautical miles from the threshold.

The ICAO GBAS can interconnect the GBAS stations to create a large-scale differential correction network, which is called a Ground Regional Augmentation System (**GRAS**).

The GBAS is sometimes referred to as the Local Area Augmentation System (LAAS).

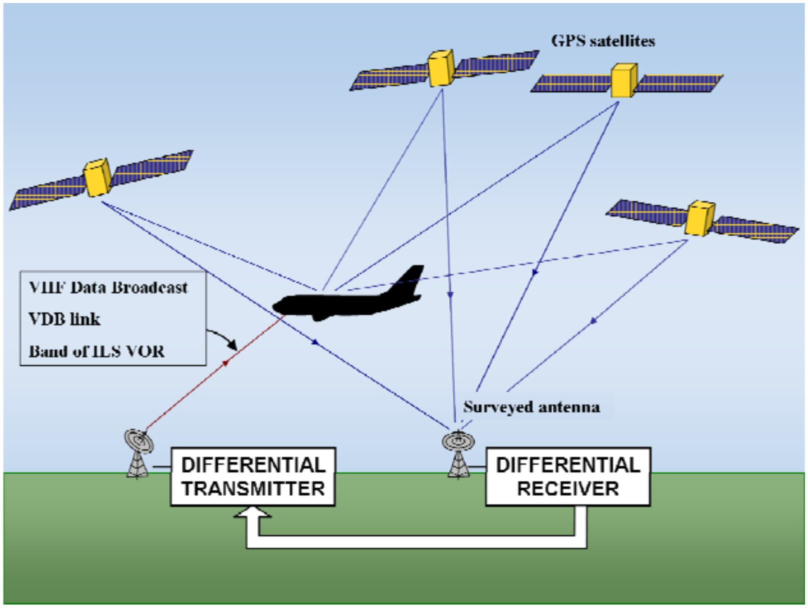

Figure 1.9: GPS Differential

1.11 Satellite Based Augmentation System (SBAS) – European Geostationary Navigation Overlay Service (EGNOS)

An **SBAS** is a regional augmentation (at the continental level) of **GPS/GLONASS**. An **SBAS** has three sub-sections:

- a ground infrastructure of **GPS/GLONASS** signal control stations
- one or more geostationary **SBAS satellites**
- **SBAS** receivers (augmented GPS/GLONASS receivers).

The station network monitors the GPS/GLONASS signals and emits a correction signal to the geostationary **SBAS satellites.** Correction data is then emitted over a large area to the **SBAS** receivers.

Various SBAS have been developed, including Wide Area Augmentation System (**WAAS**) for the USA, European Geostationary Navigation Overlay Service (**EGNOS**) for Europe, **MSAS** for Japan and **GAGAN** in India.

EGNOS, the European augmentation to **GPS,** has been operational and available for air navigation since March 2011. It relies on a network of 40 ground stations and three geostationary INMARSAT satellites emitting corrections and GPS pseudo-signals.

EGNOS monitors, corrects and assures signals provided by **GPS** and gives Europe a positioning precision on the order of 1 to 2 metres on the horizontal plane and 3 to 5 metres on the vertical plane.

It significantly augments integrity and reduces the warning delay to only six seconds (compared with two to three hours for GPS alone).

1.12 Airborne Based Augmentation System (ABAS)

ABAS is an augmentation to GPS that uses airborne data to improve integrity.

Unlike **GBAS** and **SBAS**, **ABAS** does not improve precision.

A GPS receiver equipped with Receiver Autonomous Integrity Monitoring (**RAIM**) includes technology that improves GPS integrity. To locate a position, a user must access four satellites with good geometry (i.e., PDOP<6 and elevation angle greater than 5°). RAIM requires redundant data and thus additional satellites. Five satellites are required to detect a faulty satellite. Six satellites are required to detect and isolate the faulty satellite. RAIM is an ABAS technology that uses only GNSS data.

Aircraft Autonomous Integrity Monitoring (**AAIM**) uses data from onboard sensors (inertia and pressure-altitude).

1.13 GLONASS

GLONASS is the satellite navigation system of the Russian Federation. It has been in operation since January 1996.

GLONASS specifications:

- 24 satellites, 3 orbital planes, 8 SATs per plane
- Quasi-circular orbits at 19,100 km inclined at 64.8° relative to the equator
- Period of 11 hours and 15 minutes

- Each satellite emits two signals on Band L, an L1 carrier at 1.6 Ghz and an L2 carrier at 1.2 Ghz
- L1 for standard navigation service and L2 for precise navigation service (authorised users only)

1.14 GALILEO

GALILEO is the future European satellite navigation system, which will become operational in 2014.

GALILEO specifications:

- 30 satellites, 3 orbital planes inclined at 56° relative to the equator. Nine SATs +1 spare per plane.
- Quasi-circular orbits at an altitude of 23,222 km.
- Period of 14 hours
- Each satellite emits two signals (two frequency bands 1164–1215 Mhz and 1559–1591Mhz)

1.15 GPS Acronyms

GNSS

Global Navigation Satellite System

GPS

Global Positioning System

GLONASS

GLOBal Navigation Satellite System

DOD

Dept Of Defense

SPS

Standard Positioning Service

PPS

Precision Positioning Service

PRN

Pseudo Random Noise

C/A code

Coarse acquisition code

P-code

Precision code

GDOP

Geometric Dilution of precision

SA

Selective Availability

SBAS

Space Based Augmentation System

GBAS

Ground Based Augmentation System

ABAS

Airborne Based Augmentation System

RAIM

Receiver Autonomous Integrity Monitoring

IPD

Ionospheric Propagation Delay