

Navigating into the Future

- What GPS has in Store

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ABSTRACT

Global Navigation Satellite (GPS) system has gradually come of age and has found itself a place as standard Navigation equipment in most aircraft. However, data from a GPS Receiver is not reliable enough for it to be used as a primary or sole source of navigation information. As a result GPS only system is allowed to be used only as a supplemental means of navigation for aircraft in the less critical situations such as en-route, terminal and nonprecision approach stages of flight. All that is about to change with the advent of SBAS and GBAS.

Space Based Augmentation System (SBAS) provides the much needed reliability assurances to the solution from the GPS, in addition to the improvement of accuracy and availability of the solution. The SBAS, gives the all important integrity by bounding the errors from the GPS. It improves the accuracy of the solution by providing differential corrections. It also enhances the availability of solution by providing one additional ranging signal. The addition of SBAS to GPS allows the integrated GPS-WAAS system to be used as the primary means of navigation for en-route, terminal, non-precision approach as well as Cat I precision approach mode of operations.

The paper presents a general overview of the GPS based system and its modernization to cope up with the future navigation with some details of a GPS-WAAS receiver being developed.

INTRODUCTION

In 1993 Department of Defense of United States declared that GPS has achieved Initial Operational Capabilities (IOC), which was later declared to have achieved Fully Operational Capabilities (FOC) in 1995. Studies were made by various research organization such as MITRE (Markin, 2001) to determine the possibility of using GPS for aircraft navigation. Based upon the observations and results, the FAA and the aviation community realized that while GPS provides a lot of useful operational capabilities, it alone is not sufficient for aircraft navigation - especially landing. The need for the augmentation of GPS was established which led to the concept of Satellite Based Augmentation System (SBAS) and Ground Based Augmentation System (GBAS). Even though Selective Availability (SA), an intentional degradation of GPS accuracy feature of GPS, was turned off by presidential declaration on May 1, 2000 - which led to improved accuracy of the position solution from GPS, the receiver integrity and availability of integrity did not improve without bringing into new concept. (DeCleene, 2000).

Figure 1 shows the applicability of satellite systems in aircraft navigation with reference to different phases of flight. This shows which category of service is applicable/required in which phase of flight. In brief, GPS with SBAS can be used for en-route, terminal, nonprecision approach and Cat I precision approach. Where as GPS with GBAS can be used for precision and nonprecision approach phases of flight.

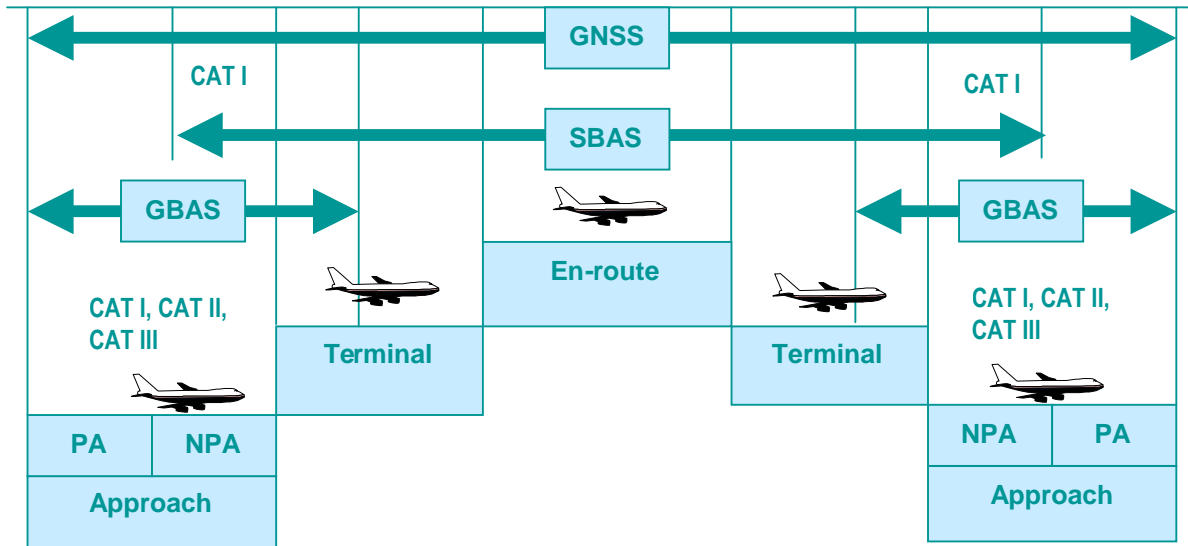


Figure 1: Applicability of satellite based system in aircraft navigation

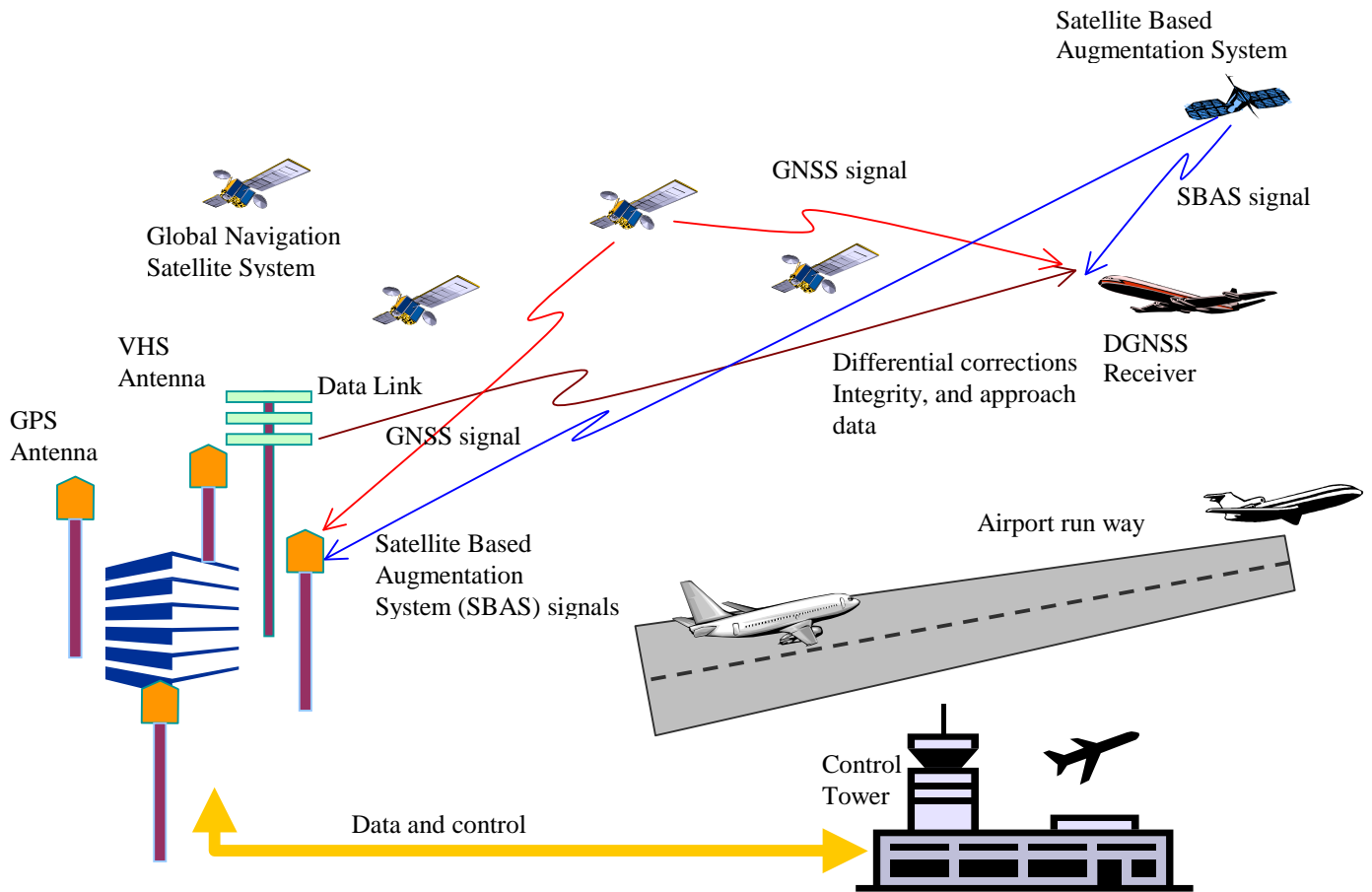


Figure 2: Concept of satellite based aircraft navigation

Figure 2 shows the concept of a satellite based aircraft navigation. In the figure, the aircraft is equipped with a differential Global Navigation Satellite System (GNSS) Receiver. The receiver is capable of using GNSS, SBAS and GBAS signals. It utilizes the GNSS (i.g GPS and/or GLONASS) and SBAS signals during en-route, terminal, nonprecision approach and Cat I precision approach landing. At the airport, a GBAS system is in place which computes differential corrections for each satellite measurements and transmit it to the on-board GNSS receiver. GNSS receiver applies those corrections to the measurements and then estimates a more accurate solution, which it uses for Cat II and III precision landing.

CNS/ATM PERSPECTIVE

Communication, Navigation and Surveillance and Air Traffic Management (CNS/ATM) is defined by International Civil Aviation Organization (ICAO), which states that “Communication Navigation and Surveillance Systems employing digital technologies including satellite systems together with various levels of automation applied in support of a seamless global Air Traffic Management”.

The objective of the CNS/ATM with regard to Navigation is to enhance pilot’s ability to navigate the aircraft more safely and efficiently. The current technologies used for navigation include VHF Omni-directional Radio (VOR), Distance Measuring Equipment (DME), Instrument Landing System (ILS), Microwave Landing System (MLS), Loran C, Automatic Direction Finding (ADF) Radio Beacon, Airborne Compass, Speed Indicator, Inertial Navigation System (INS).

The air navigation is being modernized to take advantage of the advances of technology evolved and being evolved. The future navigation is expected to use satellite navigation in two phases - Global Satellite Navigation System (GNSS) - 1 and Global Navigation Satellite System - 2. In the first phase, which is going to be operational in the year 2003, will include GPS and GLONASS as the navigation backbone. They alone can not provide the required integrity and availability of integrity necessary for aircraft navigation. This will be supported by Space Based Augmentation System (SBAS). SBAS is being implemented on a regional basis but adhering to a common standard, so that they are interoperable for smooth crossover from one region/system to the other. The second phase, which is expected to be operational in the year 2008 include Galileo as an independent navigation solution source in addition to the components of GNSS-1. GAGAN - India’s version of SBAS and other regional SBAS systems are expected to be in place by then. Together they form the second phase or GNSS-2 of satellite navigation using GPS. Figure 3 depicts two stages of GNSS operations.

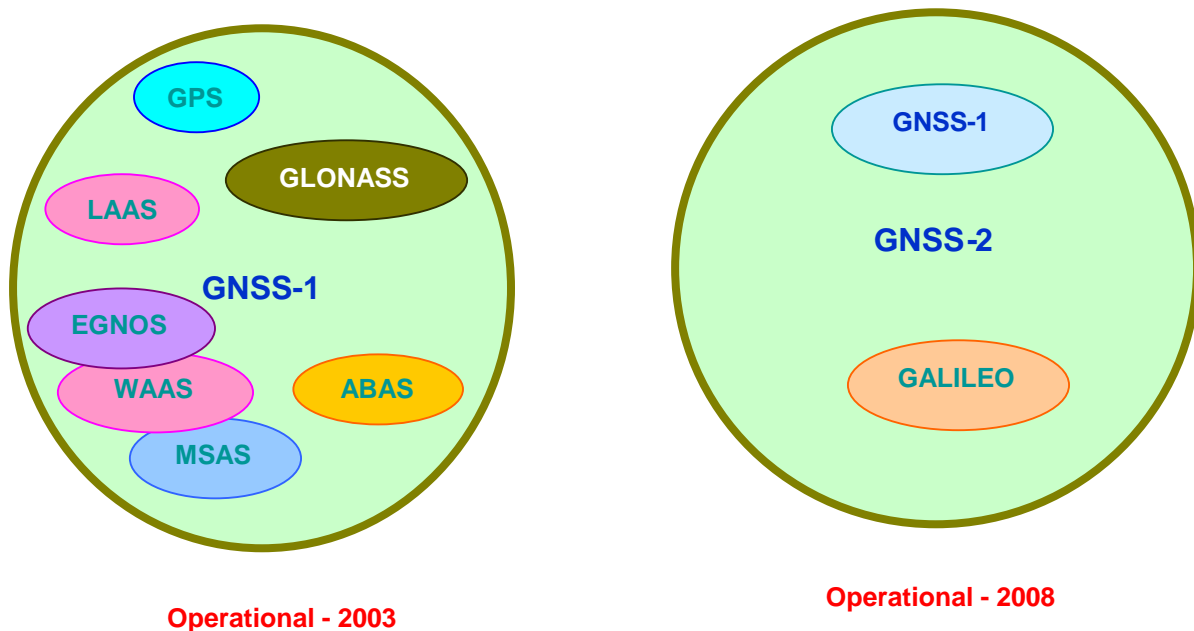


Figure 3: Phases of operations of Global Navigation Satellite Systems

Figure 4 shows the international regions implementing SBAS. The regions that are developing SBAS to take advantage of this form of air navigation are America, Europe, Japan and India. The Wide Area Augmentation System or WAAS in the most advance stage of development and is expected to achieve Initial Operational Capabilities (IOC) in 2003. The European equivalent of WAAS is called the European Geostationary Navigation Overlay Services (EGNOS). Japan is also developing an equivalent system, which is known as Multi-functional Transport Satellite (MTSAT) Satellite Augmentation System (MSAS). India has also embarked on a similar service in the Asian region called GPS and Geo Augmented Navigation (GAGAN).

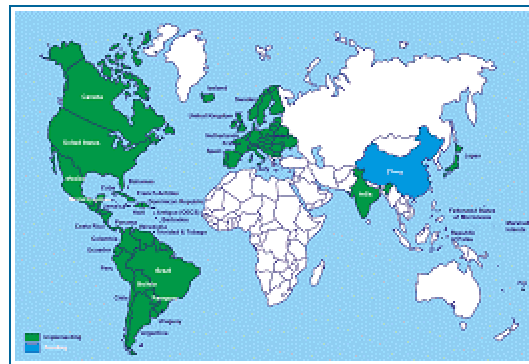


Figure 4: Regions implementing SBAS for aircraft navigation (<http://gps.faa.gov>)

INDIAN INITIATIVE

India's involvement in the satellite based navigation system development has been recently announced in the form of a satellite based augmentation system called GPS and GEO Augmented Navigation (GAGAN). India's endeavour is led by Indian Space Research Organization (ISRO) with the support from the Airport Authorities of India (AAI). GAGAN will be introduced in a phased manner in the next five years. The first phase is slated to be ready by end of 2004, followed by initial experimental phase for another one year and then the final operational phase of another one year (IEEE Spectrum online, March 31, 2002).

As per the preliminary definition, GAGAN will have eight reference stations spread over the country, which will form the backbone for generating the GPS integrity information. They will be networked by dedicated communication links for the transfer of monitoring data to the master control centre. A satellite uplink station planned to be in Bangalore, India, next to the master control center, will transmit the integrity information to a Geosynchronous satellite over the Indian region. Initially tests shall be done using an Inmarsat satellite in the Indian Ocean Region. This will be replaced by a navigation payload to be developed indigenously by ISRO and shall be placed in the orbit with orbital arc 48 and 100 deg east longitude. They will receive the integrity information and transmit it back to the region along with the ranging data.

ISRO is also considering incorporation of L2 and L5 data in the SBAS system. Earlier work on SBAS has helped determine the number of geo reference stations. However, mitigating the multipath effects at the reference station and generating ionospheric Grid Ionospheric Vertical Error (GIVE) estimate are some of the outstanding problems for the Indian initiatives.

WIDE AREA AUGMENTATION SYSTEM (WAAS)

After the SA is turned off the major remaining error in GPS is due to ionospheric delay. This error is significant and depends upon several factors including geographic location, time of day and time with respect to solar cycle. A means to estimate the ionospheric delay error and broadcast it to the GPS based avionics is required to improve the accuracy of the solution. In addition, the GPS satellite failure which may occur from time to time requires to be monitored and disseminated to the GPS based avionics users as and when it happens such that a bad satellite is not used in the solution. This led to the concept and development of satellite based augmentation system, which caters to these two requirements as well as other corrections such

as for clock and ephemeris errors. Inclusion of satellite based augmentation system extended the usage of GPS technology for up to Cat I precision landing. It is found to be inadequate for Cat II and Cat III landing.

The American version of the SBAS is popularly known as Wide Area Augmentation System or WAAS. WAAS is designed to improve the integrity, availability and accuracy of satellite based navigation system. Addition of WAAS helps GPS in the following way for the aviation community (<http://gps.faa.gov>):

- More direct routes not restricted by location of ground based navigation system
- Precision approach capability (up to CAT I) in appropriately equipped airports
- Decommissioning of older and expensive-to-maintain ground based navigation systems
- Reduce and simplify the airborne equipment for navigation and landing
- More efficient air traffic management allowing more traffic without compromising the safety and risk

The key to aircraft navigation using satellite based system is the requirement of Receiver Autonomous Integrity Monitoring or RAIM. RAIM is the ability of the receiver to detect errors and raise timely alarm to indicate that error. RAIM is central to the reliable position from a satellite receiver. Without appropriate RAIM a receiver is unusable for aircraft navigation.

The RAIM requirements for a GPS only receiver is defined by RTCA/DO-208, which are updated in TSO-C129a. A GPS receiver conforming to DO-208 and TSO-C129a requirements is allowed by the FAA to be used as a supplementary means of navigation. Later the WAAS came into being, which led to the redefinition of RAIM for the GPS-WAAS system. The requirements for an airborne GPS-WAAS system including the RAIM are giving in RTCA/DO-229C, which is released in November 2001 (DO-229C, 2001).

Integrity requirements for a GPS based equipment are defined in terms of Horizontal Alert Limit (HAL), Vertical Alert Limit (VAL), Alarm rates, Time to Alert, Probability of Failure Detection and Exclusion. Table 1 gives a brief summary of the RAIM requirements for GPS only and GPS-WAAS system for the en-route, terminal and non-precision mode of operation. The foot note gives a brief definition of the terminologies used in the table.

Please note that in the table, the first three columns are for a GPS only system for airborne application (DO-208/TSO-C129a), whereas the last three columns are for a GPS-WAAS system (DO-229C). In this table for the GPS-WAAS system, the requirement parameters are defined when WAAS provided integrity is not available. However, when the WAAS is available, the integrity parameters are computed as given in Appendix J of DO-229C. In this case, the receiver shall compute a Horizontal Protection Level HPL_{WAAS} , such that the probability that the horizontal error exceeds the HPL_{WAAS} will be less than or equal to 10^{-7} per hour. With these RAIM requirements GPS-WAAS is allowed to be used as a primary means of navigation.

Table 1: Different RAIM related parameter values for En-route, Terminal and Non-Precision Approach

	TSO-C129a/DO-208			TSO-C145/DO-229C (FDE)		
	En-route	Terminal	Non-Precision Approach	En-route	Terminal	Non-Precision Approach
HAL	2 nm	1 nm	0.3 nm	1 nm	1 nm	0.3 nm
Max Alarm Rate/False Alarm Rate	0.002/hr	0.002/hr	0.002/hr	10^{-5} / flight hour	10^{-5} / flight hour	10^{-5} / flight hour
Time to Alert	30 sec	10 sec	10 sec	8 sec	8 sec	8 sec
Min Detection Probability	0.999	0.999	0.999	0.999	0.999	0.999
Min Miss Probability	0.001	0.001	0.001	0.001	0.001	0.001
Failed Exclusion Probability				10^{-3}	10^{-3}	10^{-3}
Availability of				99.80% with SA	99.80% with SA	97.06% with SA

Detection				99.9% without SA	99.9% without SA	99.7% without SA
Availability of Exclusion				94.55% with SA 98.0% without SA	94.55% with SA 98.0% without SA	57.30% with SA 92.0% without SA

Footnote:

Horizontal Alarm Limit (HAL): Maximum horizontal error allowable for a given navigation mode. If the horizontal position error is higher than this value, a failure has occurred.

Maximum Allowable Alarm Rate: Total alarm rate with no satellite malfunction. This is also called the False Alarm Rate. The alarm is expected to be mainly due to Selective Availability (SA). The SA can be assumed to have a nominal time constant of 2 min.

Time to Alarm: Maximum allowable elapsed time from the onset of position failure till the integrity alarm is annunciated. A failure is defined to occur when the GPS horizontal position error is more than the specified alarm limit for the particular phase of flight.

Minimum Detection Probability: Assured probability of detecting a failure provided a failure has occurred. This is also defined as 1 – Miss Probability. Therefore Miss Probability is the conditional probability that the detection algorithm decides that there is no failure when failure does exist.

Horizontal protection Level (HPL): Maximum horizontal error guaranteed by the FDE algorithm used by the system for all possible geometries and assumed error characteristics. This depends on the FDE algorithm that is being used, and Probability of 'missed alert' and 'false alert'.

Failed Exclusion Probability: Probability that satellite failure is detected but it is not excluded within the time to alert.

The more critical application of GPS-WAAS is in the precision approach, where the accuracy and integrity requirements are more stringent. DO-229C defines two types of approaches called

- a) Lateral Navigation (LNAV)/Vertical Navigation (VNAV), which is also called Approach with Vertical Guidance-1 (APV-1) and
- b) Approach with Vertical Guidance-2 (APV-2) and GNSS Landing System (GLS).

This has been recently revised when FAA announced a new type of service called LPV, which is also called APV-1.5 on March 13, 2002 (DeCleene, 2002).

Table 2 gives a summary of DO-229C requirements with regard to approach (DeCleene, 2002)

Table 2: Summary of DO-229C requirements with regard to approach

	Position Update Rate	Alert Limit	Full-Scale Deflection	Hazard Criticality (misleading information)	Annunciation if service lost or not available
Precision approach mode –GLS	5 Hz	Stored in database	ILS look-alike	Severe-Major	Stored in database
Precision approach mode –APV 2	5 Hz	Stored in database	ILS look-alike	Severe-Major	Stored in database
LNAV/VNAV approach mode	1 Hz	Stored in database	Lateral: ILS look-alike	Major	Stored in database
Non-Precision approach mode	1 Hz	HAL = 0.3 NM	Lateral=0.3 NM	Major	N/A

Figure 5 shows a comparison of navigation performance for different approaches. As can be seen in the figure, the requirements are very stringent for GLS i.e. for Precision Approach in comparison with the other two approaches.

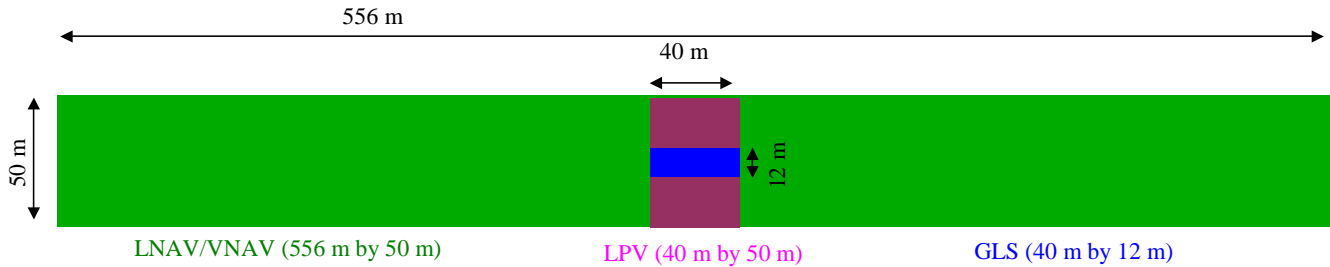


Figure 5: Navigation performance comparison for different approaches

A GPS based system to be used in an aircraft has to meet the above requirements to be qualified by FAA or other competent authority for navigation including approach. This will lead to the certification of TSO-C145, a new version of which (TSO-C145a) is due in mid 2002.

LOCAL AREA AUGMENTATION SYSTEM (LAAS)

To meet the demand of accuracy and reliability for precision approach landing, ground based augmentation systems have been conceptualized and are being developed. The ground based augmentation system provides accurate information about the local errors such as tropospheric delay error in addition to more accurate error estimates of other parameters. Standards and requirements are evolving to establish the requirement specifications for using ground based augmentation system for precision landing. The American version of ground based augmentation system is called the Local Area Augmentation System (LAAS).

LAAS will augment the GPS to provide an all weather approach, landing and surface navigation. LAAS plays a very important role in satellite based aircraft navigation providing very high accuracy, integrity and availability allowing Cat I, II and III approaches, which are not possible with GPS and WAAS.

LAAS will be effective in a limited space of about 20-30 miles around an airport. Its reference station generates corrections and broadcasts it using VHF data link, which is intercepted by the approaching aircraft and makes use of the information and corrects the onboard GNSS receiver for higher accuracy and integrity enabling it to land in the airstrip. With the aid of LAAS, an aircraft will be able to land with a curved approach path with obstructed views and restricted airspace which is currently not possible using the instrument landing systems. LAAS will provide multiple precision approach capabilities to runways within the LAAS coverage area (<http://gps.faa.gov>).

LAAS is expected to reach initial operational capabilities for Category I approach in September 2003. It will be followed by meeting the requirements for Category II and III which is expected to happen by 2006. LAAS will reach the fully operational capabilities status in 2011.

GPS MODERNIZATION

The mission of GPS modernization is to provide precise and continuous position, velocity and time information to the GPS users. In addition, Anti-jam/spoof protection, Safety of Life signal for civilian users, upgraded and redundant control. (Paul Novak, 2001). In summary the following are the objectives for modernization

- a) Improved accuracy
- b) Better availability
- c) Greater coverage
- d) Improved integrity
- e) Redundancy
- f) Higher signal strength

Since S/A is turned off, the achievable accuracy from GPS has been improved. In parallel efforts are being made to modernize the GPS services. Figure 5 shows evolution of GPS modernization

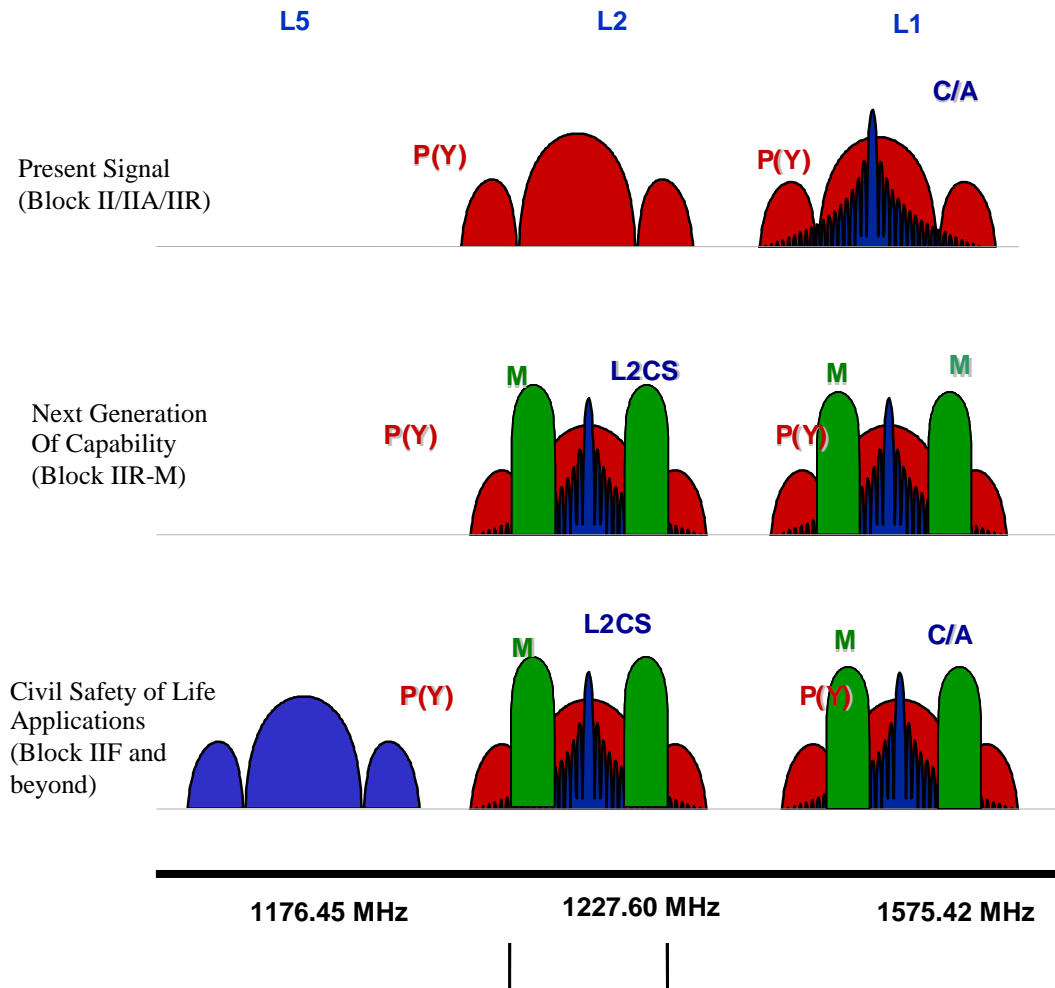


Figure 6: GPS civil signals: L2 and L5

As shown in the figure, a new civil signal shall be added at the GPS L2 frequency, which is at 1227.60 MHz. Receiver technology has advanced tremendously compared to 1970s when CA code was developed. The outdated CA code will be replaced by a better code. This signal can be used for ionospheric delay correction. Currently the ionospheric delay correction is done using L2 codeless or semi-codeless technique, which is a complex and generally more expensive solution. This will allow redundancy of channels thereby giving a more robust solution. The code is designed in such a way that it gives maximum protection against cross-correlation allowing tracking of very weak signal in presence of another strong GPS signal. Correlation protection available for the current CA code is >21 dB and for the new L2 CS (L2 Civil Signal) is >45 dB. The signal will be available at about 2.3 dB lower signal strength from the existing CA code (Stansell, 2001).

GPS L2 civil frequency will be available beginning with initial GPS Block IIF satellite schedule for launch in 2003 (FAA fact sheet). This is expected to have IOC in 2008 and FOC in 2010 (Paul Novak).

Another new civil signal shall be added at a new GPS L5 frequency at 1176.45 MHz. This falls in the band that is protected worldwide for aeronautical radio navigation and therefore to be protected for safety-of-life applications. Additionally this band will not cause any interference to the existing signals. This signal will have improved power (3.7 dB higher than the currently available CA code resulting in better signal quality), higher chipping rate (10.23 MHz compared to 1.023 MHz of the current CA code thereby reducing multipath effects), longer codes and a data less channel (1023 chips compared to 1023 chips resulting in higher correlation gain). L5 will provide significant benefit above and beyond the capabilities of the current

GPS constellation, even after the planned L2 frequency. Benefits include precision approach capability worldwide with little or no infrastructure support from ground, as well as interference mitigation.

This will be available on GPS block IIF satellite scheduled for launch beginning in 2005 (FAA fact sheet). It is expected to reach IOC status in 2012 and FOC status in 2014 (Novak, 2001).

ACCORD'S ROADMAP FOR GNSS RECEIVER

Accord is actively involved in adapting its software intensive GPS receiver technology for CNS/ATM applications. Accord has taken up the development of a GPS/WAAS receiver to address the en-route, terminal and Non-precision phases of flight. Accord's roadmap in aerospace GPS is to further pursue the research and development activities to build a GPS-SBAS and later a GPS-SBAS-GBAS receiver capable of precision approach. This receiver will have a much higher accuracy, integrity and RAIM availability compared to Accord's currently available receiver. This high performance receiver is expected to be used for aircraft navigation including precision approach as well as in the core of GBAS reference station in airports.

CONCLUSIONS

The satellite based navigation is taking shape and the world is gearing up to adapt itself to the new technologies for a safer and more efficient flight. The satellite based augmentation system is being developed to cater to the en-route, terminal, nonprecision approach, LNAV/VNAV and Cat I landing. Together with the GPS, it will give the required accuracy, integrity and availability of integrity during those phases of flight. A ground based augmentation system gives the required information for Category II and III landing. The United States is spearheading the efforts of satellite based navigation which is being followed by various other nations including India. GPS modernization in the form of newer signals as well as similar technologies such as Galileo/GLONASS will only help in making the satellite based navigation a reality.

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