

Future Satellite Navigation Services and Augmentations

Jay W. Spalding
U.S. Coast Guard Research and Development Center
March 2006

Introduction

This report is intended to provide a high level view of the evolving changes in satellite navigation services. Satellite navigation dates back as one of the first space applications. To fully understand the current state and how it is changing, we need to review how we got here and the influences causing change into the future. A chronological approach is taken in this paper giving Global Positioning System (GPS) and associated systems background, significant studies and efforts causing change affecting the transition to the future state, and some speculation on what that future state may bring. A more detailed discussion of satellite navigation accuracy, integrity and availability provides more perspective on the issues and understanding of the seemingly relentless pursuit of better performance. A short discussion of GPS governance and budgeting reveals the system's greatest challenges. Specific Department of Homeland Security (DHS) responsibilities are quoted. Conclusions and recommendations for specific efforts are given. There are opportunities for research today to proactively affect the future state with investment in a modest program. After 10 years of studies and planning we are seeing new technologies in orbit. The first "modernized" GPS satellite with two frequencies for civil use was set to operational status on December 16, 2005. The first European Union Galileo test satellite was launched December 28, 2005.

Background

The GPS that is used today was designed in the late 1970's as a military system during the Cold War. The system was designed to be independent of ground control for weeks and even months at a time to minimize reliance on the ground control segment. In normal operations, the GPS control segment uploads new data to a GPS satellite once a day. Each upload contains sufficient data to support the satellite's broadcast for weeks. As a military system this makes GPS very robust. The satellites are placed high enough in orbit to be virtually untouchable and an interruption from the several ground stations can be tolerated for an extended time. This strategy was driven by the military "doomsday" requirements of the time. When the system was designed, there were no requirements to support safety of life applications such as maritime or air transportation. GPS relies entirely on predicted data based on performance from past days and weeks. When a fault occurs in a GPS broadcast there is no infrastructure for immediate intervention to prevent misleading navigation information. The technology and decisions made lead directly to the development of "Augmentations" as they came to be known. Differential GPS (DGPS), as implemented by the U.S. Coast Guard (CG) (Maritime DGPS - 1996) and Federal Aviation Administration (FAA) (Wide Area Augmentation System (WAAS) – 2003), address shortfalls in the original design with regard to safety of life applications. For the last two decades, the basic signal in space has not significantly changed. The system has been formally shared with the civil sector since President Reagan's directive that guaranteed that C/A code GPS signals would be available at no charge to the world after the downing of Korean Flight 007 in 1983. This tragedy might have been prevented if its crew had access to better navigational tools. That directive helped open up the commercial market. In fact, it was soon realized that this signal, available for civil use, was so accurate it threatened national security and errors were intentionally added (Selective Availability). This degraded performance helped build a thriving DGPS industry that effectively corrected the intentional errors that were in place from starting in 1989 through May 2000. When Selective Availability was turned to zero, users suddenly realized consistent sub 10-meter accuracy from non-differential civil equipment. Ten years of gradual improvements in receiver technology and in the operation and control of the GPS satellites pushed stand alone performance levels close to DGPS accuracy.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE MAR 2006		2. REPORT TYPE		3. DATES COVERED 00-00-2006 to 00-00-2006	
4. TITLE AND SUBTITLE Future Satellite Navigation Services and Augmentations				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Coast Guard Research and Development Center,1082 Shennecossett Road,Groton,CT,06340				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 9	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Current state

Satellite navigation, as implemented by the Global Positioning System, is regarded as a modern marvel. It has enabled myriads of applications that never occurred to the developers of GPS. The economic impact of GPS has been huge. GPS has spawned a multi-billion dollar industry driven by location technology that is still immature. Tremendous productivity gains in many industries have been realized. The use of GPS for surveying is a great example of the industry taking advantage of such a capability. Surveying with GPS has had the biggest economic impact of any GPS application. The tremendous advantage over traditional methods has led to GPS being a part of every major construction project. The country's basic geodetic infrastructure now consists of a network of GPS reference stations versus traditional monuments or markers in bedrock. This application of GPS has always been the most profitable for the GPS industry and the surveying community. Real-time GPS surveying now guides the blades of construction equipment ensuring incredible accuracy and speed in many applications. GPS has become a ubiquitous technology in cars, boats, and phones. The communications industry relies heavily on GPS for timing of its networks. Transportation has completely embraced GPS to support navigation and tracking applications in all modes. For maritime use, GPS is the enabling technology for electronic charting and automatic identification systems. Today GPS consists of a constellation of at least 28 operating GPS satellites.

Current Augmentations for Maritime Navigation

Maritime DGPS

Established in 1996 as a formal service, the CG has been supplying DGPS corrections to mariners continuously since 1990. Developed by the R&D Center and partners, DGPS is an international standard method of augmenting GPS to improve the accuracy and integrity in over 40 countries around the world. Maritime DGPS currently can deliver accuracy within a few meters and notify users of integrity problems in a few seconds. Maritime DGPS is the approved system to meet the well-documented requirements for maritime navigation outlined in the Federal Radionavigation Plan. The CG operates over 60 remote broadcast sites as part of its entire network from two control centers. In the late 1990's the market for Maritime DGPS was vibrant and growing. When Selective Availability was turned to zero in 2000, sales of the maritime beacon receivers for DGPS plummeted. For the maritime navigation user, the value added by a separate DGPS correction receiver evolved from being an accuracy and integrity enhancement to being mostly an integrity enhancement. For most recreational users the enhanced accuracy from about 7 meters average stand-alone performance to 1-2 meters differential performance is not worth the extra cost. The integrity issue remains, but is not a high concern for recreational users. The desire for Maritime DGPS has further decreased with the availability of the FAA Wide Area Augmentation System (WAAS). Most new receivers come equipped with integrated WAAS capability so users achieve improved accuracy and integrity through the WAAS service at little additional cost and with no extra equipment. However, there is no prescribed method for applying the WAAS integrity features to maritime navigation, and there are no provisions in maritime equipment requirements for WAAS to satisfy CG navigation regulations. Today, GPS stand-alone accuracy and WAAS meets recreational user needs. There is still a professional maritime and terrestrial user market that benefits from the official standing of international Maritime DGPS for harbor navigation and its 1-2 meter accuracy for many precise applications. There are IMO/IEC standards in place for Maritime DGPS equipment. Due to the extra cost and complexity, Maritime DGPS is generally not marketed to recreational users.

NDGPS

Nationwide DGPS is essentially the same technology as the Maritime DGPS. NDGPS has been funded by the Federal Railroad Administration and managed by an interagency committee with the intention of providing DGPS service across the entire country for all terrestrial use. Maritime and Nationwide DGPS appear to users as one system. From a technical point of view, the two systems are combined and operated by the CG as a single system. NDGPS broadcast sites are generally more powerful with a greater range of

coverage than the original Maritime DGPS sites. In several places along the U.S. coastline Maritime DGPS coverage areas have been replaced by NDGPS sites.

WAAS

The FAA Wide Area Augmentation System (WAAS) provides precise navigation for aviation applications over North America. Integrity features and methods of WAAS are designed to support aviation with a very low probability of misleading information. The integrity and correction signals are near the basic GPS spectrum, making WAAS reception very inexpensive to add to GPS receiver designs. The potential for maritime use of the WAAS is understood, and the accuracy of WAAS appears to be suitable for many maritime requirements. However, WAAS-based integrity methods have not been developed to support maritime applications. The WAAS methods for the horizontal protection limit produce very conservative numbers that may not be suited for maritime navigation. The use of WAAS for maritime navigation is being studied by Volpe National Transportation System Center at this time. The FAA is broadcasting WAAS on two geostationary Inmarsat 3 satellites. However, WAAS is very popular in recreational maritime and land markets due to the low added cost to the GPS receiver and no added complexity due a separate correction receiver.

Transitions

In 1995 two key studies by the National Research Council set the course for technical and governance improvements to GPS. These marked the official beginning of sharing the system with the civil sector in terms of design and control. The recommendations of these studies have taken years to implement and the system thinking has transitioned to consider all users versus the focus on military use in the past. The civil sector has had significant input to address system shortfalls for civil use. GPS is now going through a modernization program with new signals and capabilities being added to new satellites. GPS III, the next generation of satellites and control system, has been studied and planned for the last three years. Major contracts for satellite and control development should be let this year. The first of these satellites will not be launched until at least 2012.

CG Maritime DGPS is recapitalizing. The CG's goal is to maintain the same service with reduced cost and improved flexibility. Although there is no planned effort to improve performance, the new system would be easier to improve. The NDGPS interagency effort has been researching and demonstrating a high accuracy capability that can achieve sub-meter accuracy with new broadcasts from the NDGPS sites. In Europe, several promising efforts are distributing similar high accuracy performance over the Internet. The role of GPS augmentations will evolve or will be eliminated depending on the final outcome of GPS modernization. GPS and CG DGPS are part of the critical infrastructure for marine transportation, communications, all types of construction and are increasing for land transportation. Maritime DGPS also provides critical input to several systems to support Maritime Domain Awareness.

Future State

Radionavigation is a technology area tremendously influenced by computing power. Advances in processing have led to new algorithms for navigation and communications. The desire and need for improved performance is growing faster than the ability of space systems to deliver. Innovative use along with long system lead times will always yield the situation where the fielded space system lags behind the current applications on the ground. Innovative developments continue to wrest more capability from the radionavigation system as time goes on. Accuracy requirements are closely related to the rate of technology development. Once a new capability exists, applications are quickly developed to take advantage of the capability for both improved performance and reduced cost. Additional satellite signals at other frequencies will create new opportunities to exploit the system. Receiver development that leverages improved processing will yield new capabilities with the same signals.

2010: Satellite navigation in 5 years

By 2010 navigation accuracy and integrity may have been improved to a level that allows most maritime navigation operations without augmentation. New GPS signals will be available and improve accuracy while multiple frequencies will provide alternatives to counter interference. Galileo will be in an initial phase of rapid implementation. New satellite signals will expand the availability of service to urban areas and difficult geography and environments such as dense forests and indoors. Car navigation systems will be common.

2020: Satellite navigation in 15 years

By 2020 Satellite navigation will be a mature routine utility. Users will not be able to conceive of a time without this capability. The capability itself will consist of personal devices with hundreds of gigabytes of location-oriented information available in real-time. The whole concept of getting lost will be a thing of the past. Anything of interest from your shipments to your dog to your children will be tracked. Everything will be geo-referenced and accessible in proximity searches. The whole concept of addresses, street names and turn-by-turn directions could be considered quaint. A significant generation of adults will have lived their whole lives with GPS. Personal navigation/communication devices will link people to their world with a wealth of geo and time-coded information. Personal navigation will be multimodal with no transition from walking to transport by car, boat or plane. Navigation buoys and street signs will seem superfluous as colossal wastes of money to satisfy an older generation. Users will put their trust in an extremely robust reliable constellation of over 50 satellites with the power to navigate inside buildings and in difficult urban settings.

Future Augmentations

Given the design of GPS, real-time system integrity had to be accomplished by separate systems. Well known requirements for this integrity “channel” now exist and perhaps the capability would be most appropriately included within new system designs. There is no free lunch however; a more robust monitoring and earth-to-satellite communication system would be required. Both Galileo and GPS III have plans for these services.

Galileo Safety of life service

The Galileo safety of life service will be the first satellite navigation signal with real-time integrity built into the basic service. This real-time integrity monitoring is envisioned as a regional system, essentially a ground-based augmentation. The degree of U.S. participation in such a regional approach remains to be determined. The Galileo documentation suggests that these regional enhancements will be funded by partnerships in the region. It is a regional augmentation approach basically like WAAS that uses the Galileo satellites as the communications mechanism to notify users instead of a dedicated geostationary channel like WAAS.

GPS III

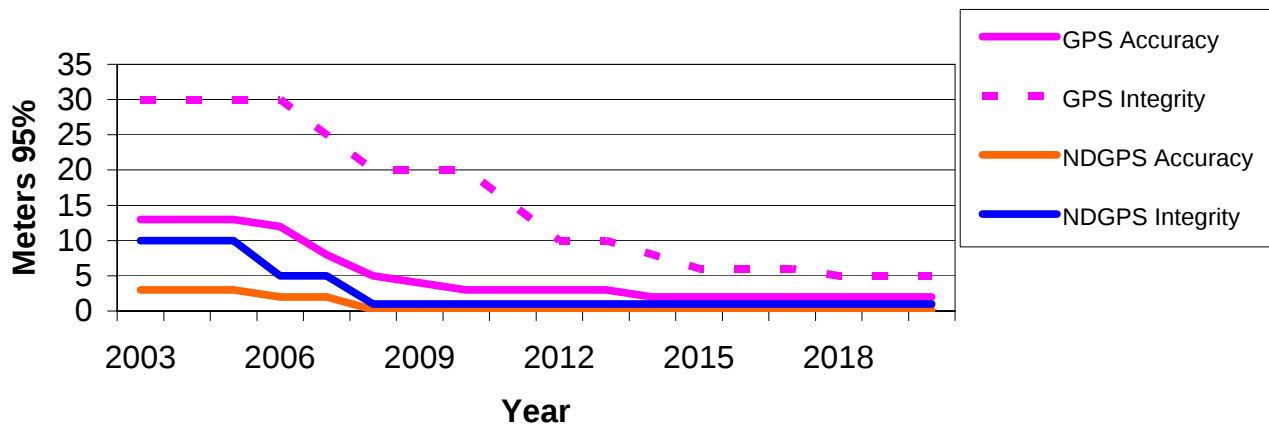
Plans and proposals for GPS III include real-time integrity. Contracts will be let this year for the space segment and control segment. This potential capability is certainly more than 10 years away.

Notional Performance into the Future

The following chart shows the relationship between service accuracy and integrity as we move into the future. GNSS accuracy will continue to improve. Additional GPS signals and the implementation of Galileo will push accuracy down to a meter in about 10 years. While these improvements are discrete features, the nature of their implementation over a period of time distributed through an existing constellation makes them a somewhat gradual improvement. Integrity or the level of accuracy that can be guaranteed is much more difficult to drive down. Integrity depends on error statistics and must always be somewhat higher than the realized accuracy. Integrity represented by the curve on this graph is notional and considers both the

system's built-in integrity functions and measures and possible integrity techniques employed by the user such as Receiver Autonomous Integrity Monitoring (RAIM). For example, in today's case for GPS Integrity, the GPS system has no real-time notification or action to handle problems. A maritime user could autonomously (RAIM) compute integrity with a 30-meter threshold with reasonable false alarm and probability of missed detection rates. As more satellites and signals are added this threshold could be lowered. Galileo will have built-in integrity monitoring, as will GPS III. Integrity thresholds are necessarily conservative in order to provide sufficient time to alarm so it is very difficult to achieve integrity on par with the accuracy obtained. This integrity figure is why the navigation user ends up with a system that may exceed requirements for accuracy in order to meet requirements for integrity.

Notional Performance



Accuracy, Integrity and Availability

Accuracy has traditionally been considered the primary measure of a navigation system. Today, GPS provides outstanding accuracy for most maritime operations. Officially at 13 Meters 95 percent, standalone performance is usually within 10 meters. Public DGPS services using NDGPS or WAAS yield accuracies on the order of 2 meters.

However, once a system has established accuracy that meets users' needs, other attributes come under scrutiny to judge a system's performance. Availability and integrity are measures that become paramount in executing operations with the accuracy the system provides. Relying on the signal and trusting its performance are critical for navigation applications where a vessel is committed to a course of action for a period of time. These types of applications are generally referred to as safety of life applications. In maritime use, the severity of consequence has led to the development of systems that moderate risks to a reasonable level while preserving capability. However, as shipboard systems become more integrated, the potential to mislead the user increases as manual steps are eliminated. It becomes critically important that the entire system, including shipboard components, be able to indicate when there are problems. Stand-alone GPS as a component in integrated navigation is particularly weak in this regard. GPS satellites can fail, mislead users and it can take hours for the problem to be addressed. This integrity issue is the primary justification for the various augmentations of GPS. Detecting and acting on detected errors is a very challenging aspect to building navigation systems. The statistical algorithms and methods are meant to catch all errors and eliminate the possibility that the user is misled. Absolute certainty is not possible but very low levels of uncertainty can be achieved. The appropriate level is largely determined by the application e.g. aviation one in a thousand. Much depends on the consequence of an error, e.g "controlled flight into terrain" or vessel grounding on a sandbar. In the engineering of these systems, accuracy, integrity and availability form a triangle that is somewhat mutually exclusive. For a given application, a balance must be struck

between accuracy, integrity (protection limits, probabilities and time to alarm) and time available (percentage). The CG achieved the appropriate balance for precise maritime navigation with Maritime DGPS in the 1990's at a very reasonable budget. Given a much higher budget, the FAA has achieved the appropriate service to support aviation in WAAS. Accuracies and availability are similar for Maritime DGPS and WAAS, but the integrity methods are more sophisticated for aviation and the budget was much higher in order to achieve the FAA's goals for WAAS.

One of the consequences of any integrity process is the fact that the accuracy of a system is always significantly better than the protection limit expressed as position error. The CG Maritime DGPS achieves 1-2 meter accuracy with the best user equipment, but advertised accuracy is 10 meters. This margin gives the system the time to detect an error and get a warning out to the user before the 10-meter threshold has been exceeded. The FAA WAAS has similar accuracy but the protection limit is higher, e.g. 40 meters in order to provide a much lower probability of misleading information.

RAIM

Receiver Autonomous Integrity Monitoring (RAIM) is a statistical technique that uses extra information to determine the integrity of the position fix. This extra information is usually additional GPS satellites beyond the four satellites required for a three-dimensional fix. For a maritime user height information can be used as well. With strong satellite geometry, a fifth satellite adds the ability to detect that there is a problem with one of the satellites and a sixth satellite adds the ability to isolate the fault to an individual satellite. Several assumptions have to be made for the RAIM process, such as that all of the variance in the position is due to an error on a single satellite. Another assumption is that this single satellite is the one that will have the most detrimental impact on the position error.

Users in mid latitudes often have over eight satellites. With the current 28 satellite GPS constellation, the RAIM approach is very useful. However, there are times when the user does not have a sufficient number of satellites for the RAIM to be effective. For example, RAIM algorithms may use a 1-meter DGPS system accuracy to protect a 10-meter protection limit threshold at 99 percent probabilities 97 percent of the time. The three percent is a RAIM outage while the navigation receiver is still maintaining what is probably excellent navigation performance. The RAIM simply cannot confirm it. RAIM is a valuable tool for the standalone user. For positioning applications where work can be scheduled or postponed for a short while such as overseas AtoN positioning operations, RAIM can provide the integrity needed to confirm the quality of a buoy setting operation using stand-alone GPS. For navigation operations that require a high availability, RAIM needs an incredibly robust and accurate satellite constellation in order to ensure adequate coverage and a low enough threshold for stand-alone applications. As given in the notional chart, a stand-alone GPS user could probably use RAIM today to provide adequate integrity at about the 30-meter level for maritime operations.

GPS Governance

Over the last 10 years the technical improvements to GPS have been fairly well developed. Industry groups have formed committees, the government has let study contracts and the best technical choices have been determined. Unfortunately, this has been the easy part. The management and funding of GPS has been a recurring problem. The President issued new policy in 2004 to address some of the issues with the formation of the National Space-Based Positioning, Navigation, and Timing (PNT) Executive Committee. The National Space-Based PNT Executive Committee replaced the Interagency GPS Executive Board (IGEB), which oversaw GPS and its augmentations from 1996 to 2004. In either case, GPS has had difficulty in being properly funded. Several satellites in the existing GPS constellations are well beyond their design life and have used up the redundancies in their systems to stay on the air. A single fault in these satellites will take them out of service. Replenishment of satellites has been continually delayed. Getting new services in orbit is tied to this replenishment. The GPS control segment has been long overdue for upgrades and improvements. On paper the situation is dire, the satellites are on their last legs and resources for control and operations are barely adequate. The system continues to perform admirably, a testament to its design and the

operators who keep it “flying.” GPS has evolved into an important utility that should be adequately funded. Despite the continuing budget battle, progress is being made and new capabilities will be in orbit as more satellites are launched. Timelines are uncertain and always move to the right.

Specific language from U.S. SPACE-BASED POSITIONING, NAVIGATION, AND TIMING POLICY December 15, 2004 regarding DHS responsibilities:

The Secretary of Homeland Security shall:

Identify space-based positioning, navigation, and timing requirements for homeland security purposes to the Secretary of Transportation, and coordinate the use of positioning, navigation, and timing capabilities and backup systems for homeland security purposes by Federal, State, and local governments and authorities;

In coordination with the Secretary of Transportation, and with other Departments and Agencies, promote the use of the Global Positioning System positioning and timing standards for use by Federal agencies, and by State and local authorities responsible for public safety and emergency response;

In coordination with the Secretary of Defense, and in cooperation with the Secretaries of Transportation and Commerce, ensure:

Mechanisms are in place to identify, understand, and disseminate timely information regarding threats associated with the potential hostile use of space-based positioning, navigation, and timing services within the United States; and

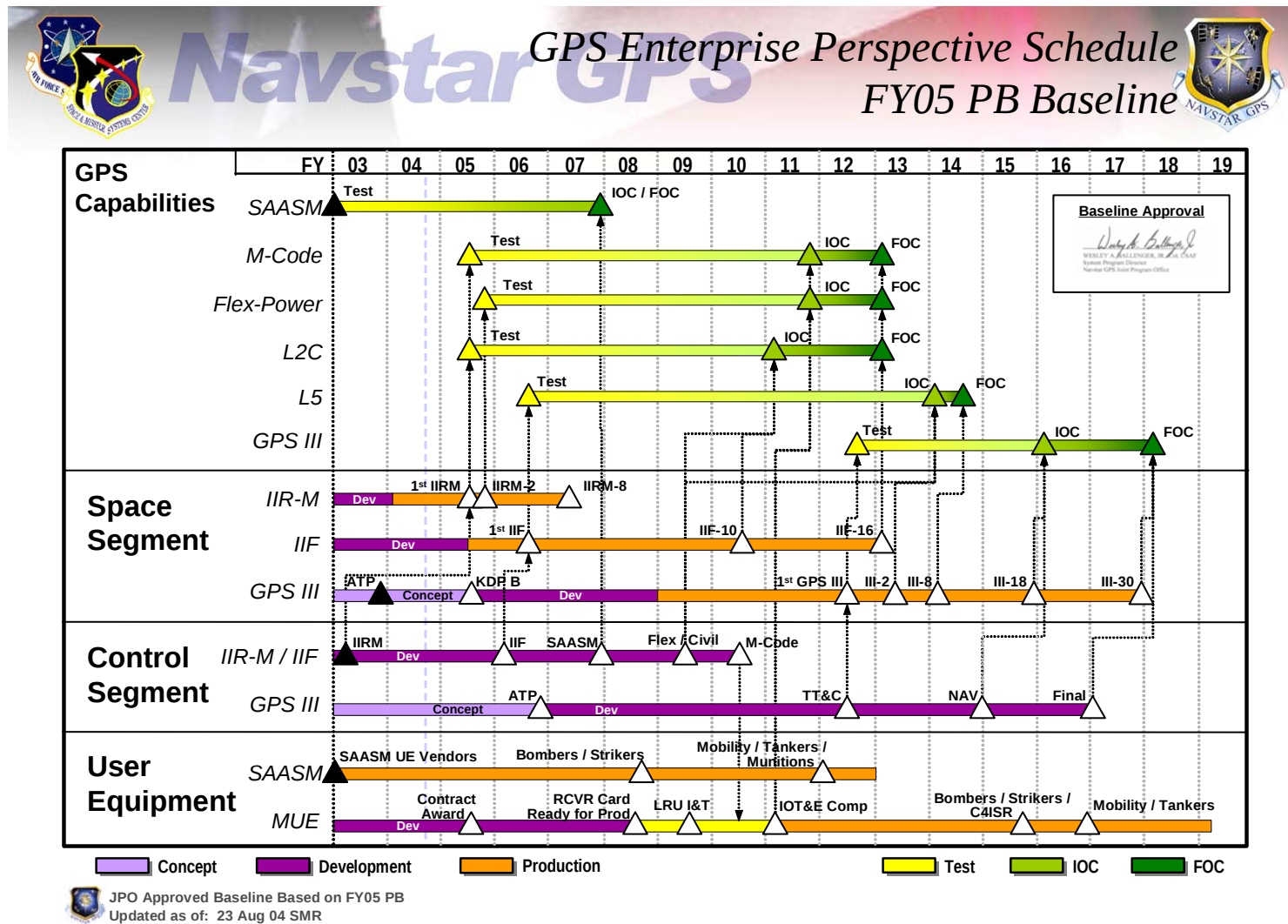
Procedures are developed, implemented, and routinely exercised to request assistance from the Secretary of Defense should it become necessary to deny hostile use of space-based position, navigation and timing services within the United States;

In coordination with the Secretaries of Defense, Transportation, and Commerce, develop and maintain capabilities, procedures, and techniques, and routinely exercise civil contingency responses to ensure continuity of operations in the event that access to the Global Positioning System is disrupted or denied;

In coordination with the Secretaries of Transportation and Defense, and in cooperation with other Departments and Agencies, coordinate the use of existing and planned Federal capabilities to identify, locate, and attribute any interference within the United States that adversely affects use of the Global Positioning System and its augmentations for homeland security, civil, commercial, and scientific purposes; and

In coordination with the Secretaries of Transportation and Defense, and the Director of Central Intelligence, and in cooperation with other Departments and Agencies: (1) develop a central repository and database for reports of domestic and international interference to the civil services of the Global Positioning System and its augmentations for homeland security, civil, commercial, and scientific purposes; and (2) notify promptly the Administrator, National Telecommunications and Information Administration, the Chairman of the Federal Communications Commission, the Secretary of Defense, the Director of Central Intelligence, and other Departments and Agencies in cases of domestic or international interference with space-based positioning, navigation, and timing services to enable appropriate investigation, notification, and/or enforcement action.

Timeline of future GPS services



Conclusions

Satellite navigation is a basic enabling technology that can be exploited in many ways to benefit DHS, the CG and maritime operations. DHS has a significant role to play in protecting domestic use of GPS. The CG benefited greatly from the first generation of applications developed in the 1990's. The next generation of applications shows great promise to contribute to CG and DHS productivity and results. As satellite navigation becomes more robust, and users rely more on electronic navigation versus Short Range Aids (SRA), the CG can begin to plan for gradual SRA service reductions. Basic understanding of satellite navigation technologies is a key element in exploiting location-based systems for operational advantage throughout the Department. Land and maritime applications have similar accuracy, integrity and availability requirements. There are significant gaps in knowledge in properly applying satellite navigation to land and maritime use.