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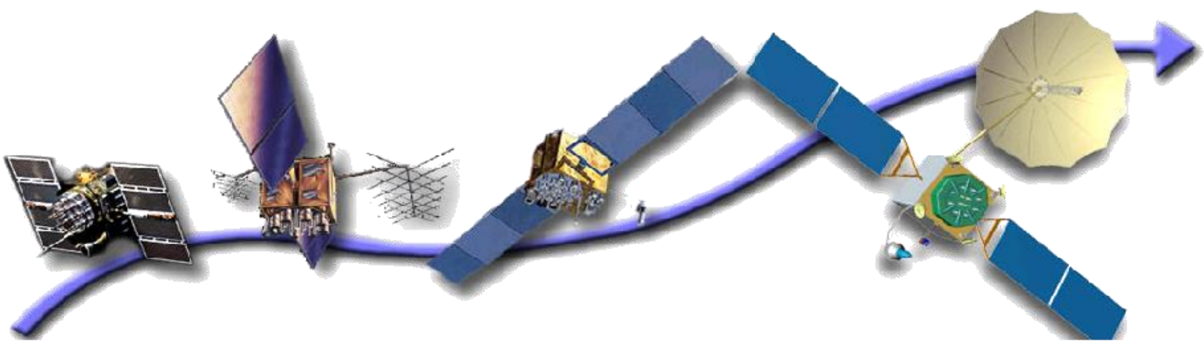


[1]

USDOT

Implementation of Space-Based Position Navigation and Timing Systems

[1] Hessin, Robert. APEC GIT/14 Conference. Space-Based Positioning Navigation & Timing National Executive Committee. Renaissance Hotel, Seattle WA. 21 June 2010. Global Positioning System Policy and Constellation Update.

Introduction

Alan Lakein once said, “Planning is bringing the future into the present so that you can do something about it now.”[2] While The United States has the only fully operational Global Navigation Satellite System (GNSS), known as the Global Positioning System (GPS), several other countries are in the process of developing their own systems. There are also several Regional Navigation Satellite Systems (RNSS), and Satellite-based Augmentation Systems (SBAS) being implemented or are already operational. With the implementation of these space-based position, navigation and timing (PNT) systems we can significantly improve the world’s safety and well being, in an economically efficient manner. For these space-based PNT systems to improve our quality of life they must promote compatibility, interoperability, openness and integrity for all users. We must now plan for these additional systems implementations to improve not just our Nation’s well being, but the world’s.

Report

Space-based PNT system’s purpose is to provide global three-dimensional positioning, navigation, and timing information. All space-based PNT technologies are composed of space, ground, and user segments. The space segment is composed of a satellite constellation ranging between one and 31 satellites. These satellites encrypt information such as three dimensional position, velocity, and timing for the user segment; however the quality usually differs for civil and military use. The user segment is composed of thousands of different types of receivers; however they can be divided into two main categories, military and civilian receivers. Both

[2] Lakein, Alan. "Planning Quotes." Think Exist. Accessed 15 July 2010 < http://thinkexist.com/quotations/planning/>.

receivers however, are able to determine the position and velocity of a specific location. These receivers range in price from just a few dollars to thousands of dollars. [3] The ground segment is composed of a master control station, several monitoring stations, plus several ground antennas. The monitoring stations are used to track and collect information from GNSS satellites that are in range of each station. The antennas are used to upload information to the GPS satellites. While GNSS, RNSS, and SBAS are all composed of the three basic segments, they vary in accuracy and integrity.

GNSS is usually composed of between 24 and 35 satellites, arranged in several orbital planes with at least four satellites in each plane, and is accurate between three and 10 meters.[4] Currently the only fully operational GNSS is the United States Global Positioning System (GPS). Russia is also planning to have their own GNSS called Global Navigation Satellite System (GLONASS) be operational by the end of 2010. In addition to Russia, the European Union (EU) and China are planning to have their own GNSS, Galileo and Compass, respectfully operational sometime in the near future. [5] Below, in table 1 is a comparison of different GNSS.

GNSS	Country	Number of Satellites	Status
GPS	USA	30	Operational[6]
GLONASS	Russia	27	Operational by end of 2010[7]
Galileo	EU	30	Operational by 2015/2016
Compass	China	35	Operational before 2020

(Table 1: Comparison of Different GNSS)

RNSS are composed of fewer satellites, ranging between three and seven satellites, and is planned to be similar to GNSS in accuracy. The main difference between RNSS and GNSS is

[3] Trimble. GPS*: .The First Global Navigation Satellite System* Sunnyvale, California: Trimble Navigation Limited, 2007.

[4] Hessin, Robert. APEC GIT/14 Conference.Space-based Positioning Navigation & Timing: National Executive Committee. Renaissance Hotel, Seattle WA. 21 June 2010. Global Positioning System Policy and Constellation Update.

[5] "Global Navigation Satellite System." Wikipedia: The Free Encyclopedia. Accessed 15 July 2010 < http://en.wikipedia.org/wiki/Global_navigation_satellite_system>

[6] Hessin, Robert. APEC GIT/14 Conference. Space-based Positioning Navigation & Timing: National Executive Committee. Renaissance Hotel, Seattle WA. 21 June 2010. Global Positioning System Policy and Constellation Update.

[7] Shmulevich, Mark. APEC GIT/14 Conference. Russia Space Systems. Renaissance Hotel, Seattle WA. 21 June 2010. GLONASS Status and Policy Update.

that at least one of the satellites in a RNSS orbit is positioned to be always in range of the country it is hosting. While the space-based PNT services are mainly limited to the country of the RNSS, they are more cost efficient than GNSS. Currently Japan and India are in the process of creating RNSS, Quasi-Zenith Satellite System (QZSS) and Indian Regional Navigational Satellite System (IRNSS) respectfully.[8] Below in table 2 is a comparison of different RNSS.

RNSS	Country	Number of Satellites	Status
QZSS	Japan	3	Operational by end of 2013[9]
IRNSS	India	7	Operational by end of 2014[10]

(Table 2: Comparison of Different RNSS)

Differential GPS (DGPS) uses a GPS receiver at a surveyed location to determine atmospheric delays in the GPS signal to increase position accuracy. A differential correction is broadcast for each GPS satellite to increase position accuracy. The most common form of DGPS is SBAS, since it broadcasts differential corrections on the same frequency as a common GNSS broadcast. SBAS generally uses two geostationary satellites and its own network of reference stations to take into account atmospheric delays, and usually has sub-meter accuracy. [11] In addition to the low implementation costs due to the small number of satellites, SBAS provides a more accurate information. [12] Currently the United States, Russia, the EU and Japan have operational SBAS named Wide Area Augmentation System (WAAS), System of Differential Corrections and Monitoring (SDCM), European Geostationary Navigation Overlay Service (EGNOS), and Multi-functional Satellite Augmentation System (MSAS) respectfully to augment GPS. [13] India is also in the process of building a SBAS named Geo Augmented Navigation

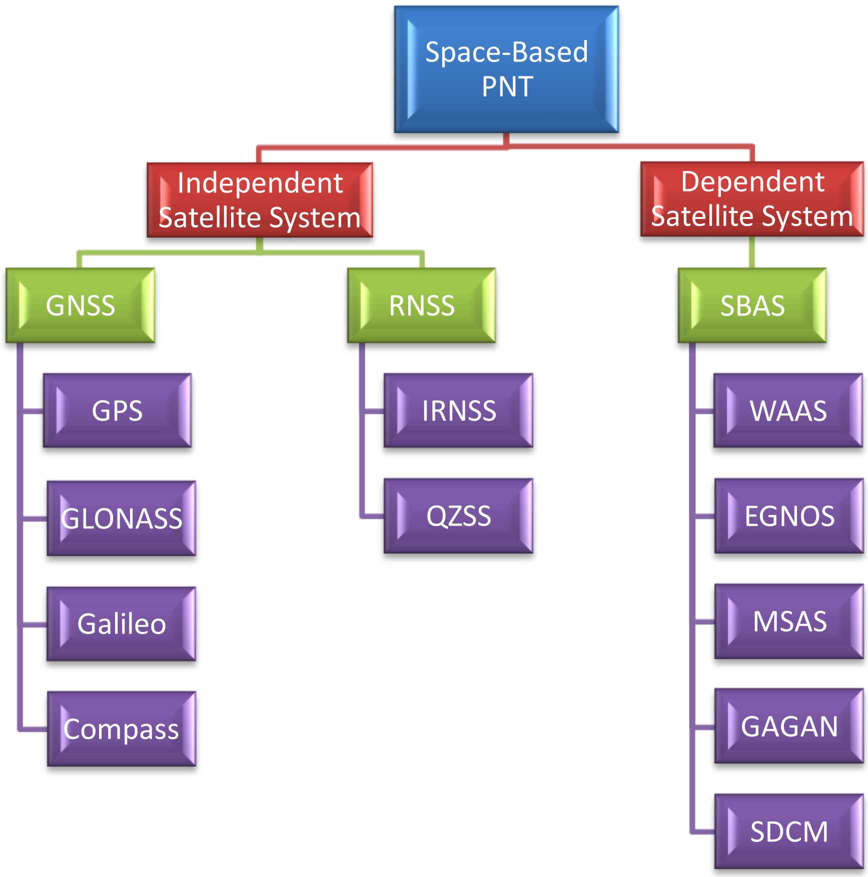
[8] "Global Navigation Satellite System." Wikipedia: The Free Encyclopedia. Accessed 15 July 2010 < http://en.wikipedia.org/wiki/Global_navigation_satellite_system>
[9] Kogure, Satoshi. APEC GIT/14 Conference. JAXA. Renaissance Hotel, Seattle WA. 21 June 2010. Report from JAXA.
[10] Anandan, S. "Launch of first satellite for Indian Regional Navigation Satellite system next year." The Hindu. Accessed 15 July 2010 <http://beta.thehindu.com/sci-tech/article393892.ece>
[11] Trimble. GPS*: .The First Global Navigation Satellite System* Sunnyvale, California: Trimble Navigation Limited, 2007.
[12] Trimble. GPS*: .The First Global Navigation Satellite System* Sunnyvale, California: Trimble Navigation Limited, 2007.
[13] "Global Navigation Satellite System." Wikipedia: The Free Encyclopedia. Accessed 15 July 2010 < http://en.wikipedia.org/wiki/Global_navigation_satellite_system>

System (GAGAN) and is scheduled for completion in the near future. Below, in table 3 is a comparison of different SBAS.

SBAS	Country	Number of Satellites	Status
WAAS	USA	1-2	Operational
EGNOS	EU	2	Operational
MSAS	Japan	2	Operational
GAGAN	India	Plans for 2	Operational by May 2011[14]
SDCM	Russia	3	Operational by end of 2011[15]

(Table 3: Comparison of SBAS)

Image 1, below is a flow chart showing the different space-based PNT systems.



(Image1: Flow Chart of Space-Based PNT Systems)

[14]"India Approves GAGAN System." Asian Surveying & Mapping. Accessed 15 July 2010 < http://www.asmmag.com/news/india-approves-gagan-system>
[15] Forssell. "New GLONASS-M Satellites Head to Pad for September 25 Launch." GPS World. 24 August 2009. Accessed 4 August 2010 <http://www.gpsworld.com/gnss-system/news/new-glonass-m-satellites-head-pad-september-25-launch-8771>.

In order for all of these space-based PNT technologies being deployed to be fully utilized, we need compatibility, interoperability, integrity, and openness between all space-based PNT systems.

Compatibility is for all space-based PNT technologies to work collectively or separately without interfering with each other's signal. Interfering with each other's signal, even unintentional, could easily bring up not only engineering but also political issues. However this could easily happen because of the small bandwidth between each signal. If compatibility did not exist between space-based PNT systems, there would be very little to no PNT accuracy. Initially with GPS being the only space-based PNT system, compatibility was not a concern. However, with upcoming addition of several space-based PNT systems, compatibility has become more of an issue. With these additional space-based PNT systems it is essential that common terminology and measurement units are adopted with every system to also promote compatibility. In addition to compatibility, it is essential that these signals do not interfere with each other but be able to be interoperable between each other's signals.

Interoperability is having different space-based PNT systems be able to work together to provide better services that could not be done with a single space-based PNT technologies. For space-based PNT systems, Interoperability means that the use of multiple-frequency space-based PNT systems are able to produces high accuracy PNT, which is essential in several aspects of transportation.[16] GPS and RNSS has on average between three and 10 meters of accuracy. SBAS has on average one to two meters horizontally and two to four meters vertically of accuracy. However with the use of multiple-frequency GNSS we are able to acquire centimeter accuracy. [17] While the general public is content with this level of activity, there are several areas in

[16] Hein, Gunter. "GNSS Interoperability: Achieving a Global System of Systems or "Does Everything Have to Be the Same?"." Inside GNSS Date January/February 2006, 57-60.
[17] Trimble. GPS*: .The First Global Navigation Satellite System* Sunnyvale, California: Trimble Navigation Limited, 2007.

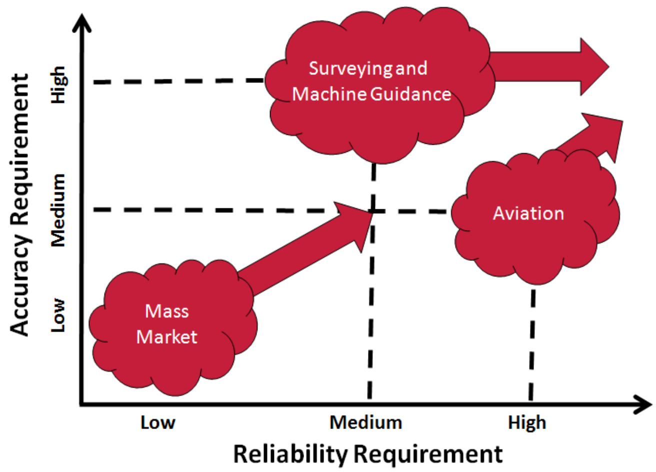
transportation that require high accurate space-based PNT systems to significantly increase efficiency. It is vital for our Nation to promote compatibility to improve its safety, economic competitiveness, and environmental sustainability.

Openness allows for all countries to use space-based PNT systems no matter what political event is taking place. For example if an airplane is traveling from the United States to China, it must be allowed to choose which space-based PNT system it would prefer to use whether it was GPS or Compass. By forcing countries to use specific space-based PNT receivers it would require significantly more money to incorporate these signals. This could be detrimental to smaller countries such as Peru, who currently do not have the resources to install several space-based PNT receivers to comply with political bureaucracy. It could also possibly create a monopolistic environment that would create tensions between not only different countries, but also companies.

Integrity allows for space-based PNT systems to be highly accurate and reliable. As technology is improving the demand for improving integrity has been increasing.[18] Surveying, machine guidance and aviation are the three main areas that require high integrity. Currently surveying and machine guidance require high accuracy but low reliability and aviation requires high reliability but low accuracy. However over time it is predicted that surveying and machine guidance will require higher reliability and aviation will require higher accuracy. This is due to the fact that as space-based PNT systems is incorporated into surveying and machine guidance they engineers will want to improve the reliability to increase production. In aviation, as more planes use highly reliable space-based PNT systems they will demand higher accuracy to deal with the higher congestion that is created with the higher reliability. This leads to surveying,

[18] Azaola-Saenz, Miguel and JoaQuin Cosmen-Schortmann. "Autonomous Integrity: An Error Isotropy-Based Approach for Multiple Fault Conditions." Inside GNSS January/February 2009, 28-36.

machine guidance and aviation to demand higher integrity as technology improves. Image 2, below shows the current needs of integrity and how they are expected to move over time.



(Image 2: Accuracy vs. Reliability Requirements)[19]

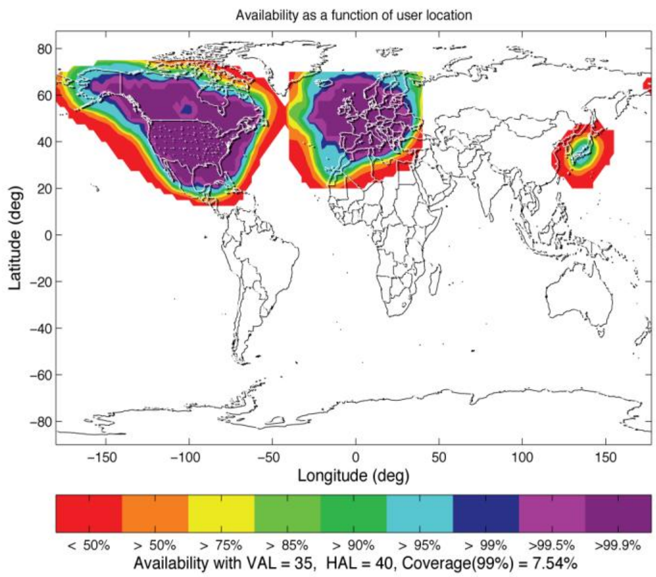
To accomplish all four goals of compatibility, interoperability, openness, and integrity it has been proposed by several government and private organizations to promote dual frequency coverage using space-based PNT systems. The University FAF Munich has estimated that one system would require 100 PNT satellites to have optimal integrity.[20] However the costs associated by creating 100 PNT satellites would be overwhelming by any single country. This problem could be solved by incorporating all countries different space-based PNT systems to create a highly accurate and reliable world PNT system. By using dual frequency coverage all countries' space-based PNT systems must be compatible and open with each other. This can be easily done with SBAS systems, since all of these systems except for EGNOS were created by the Raytheon Company.[21] Also, the SBAS Interoperability Working Group is currently working on making all current and future SBAS have augmentation capabilities to GPS. Image 3, below,

[19] Higgins, Matt. APEC GIT/14 Conference. FIG. Renaissance Hotel, Seattle WA. 21 June 2010. Economic and Environmental Benefits of Precise Positioning: Lessons for Transportation.

[20] Gibbons, Glen. APEC GIT/14 Conference. Inside GNSS. Renaissance Hotel, Seattle WA. 21 June 2010. Prospects and Benefits for Transport Users in a Multi-GNSS World.

[21] Christoffers, Jeff. APEC GIT/14 Conference. Raytheon Company. Renaissance Hotel, Seattle WA. 21 June 2010. Current WAAS Status.

shows the world's current SBAS coverage.[22] By creating dual frequency coverage the world would be create a worldwide high accuracy satellite system, which would promote both the interoperability and integrity goals. Image 3, below is the world's current WAAS, EGNOS, and MSAS single frequency coverage.



(Image 3: Current WAAS, EGNOS, and MSAS Single Frequency Coverage)[23]

Image 4, below is what the world's coverage would be with dual frequency WAAS, EGNOS, and MSAS coverage.

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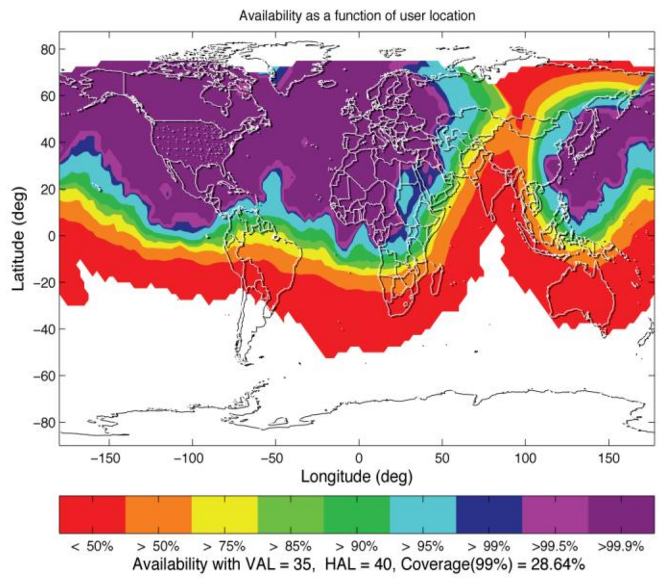
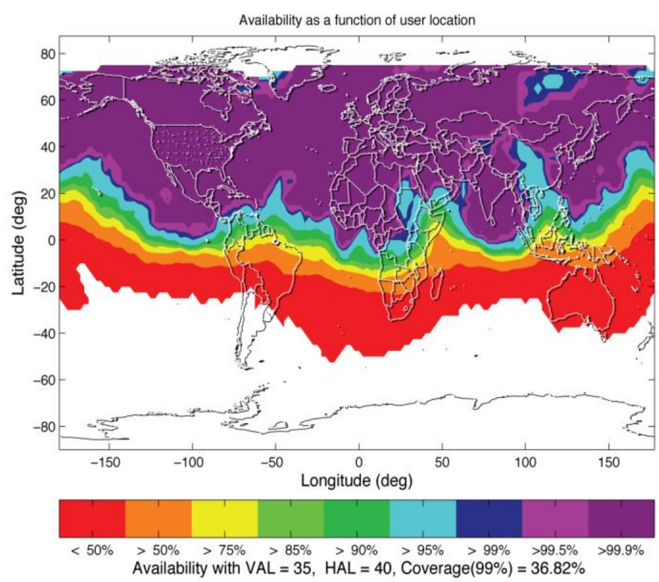
[22] Van Dyke, Karen. Personal interview. August 3, 2010.

[23] Lawrence, Deborah. APEC GIT/14 Conference. Federal Aviation Administration. Renaissance Hotel, Seattle WA. 21 June 2010. FAA Satellite Navigation Status.



(Image 4: Updated WAAS, EGNOS, and MSAS Dual Frequency Coverage) [24]

Image 5, below is what the world's coverage would be with dual frequency WAAS, EGNOS, MSAS, GAGAN, and GLONASS coverage.

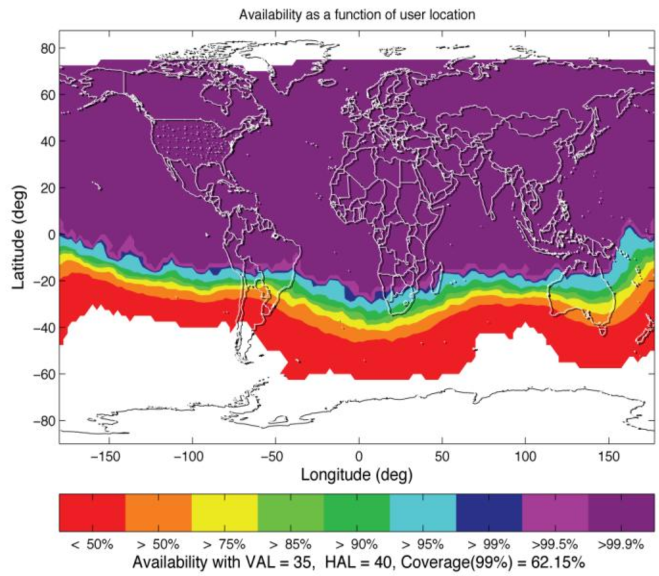


(Image 5: Updated WAAS, EGNOS, MSAS, GAGAN, and GLONASS Dual Frequency Coverage) [25]

[24] Lawrence, Deborah. APEC GIT/14 Conference. Federal Aviation Administration. Renaissance Hotel, Seattle WA. 21 June 2010. FAA Satellite Navigation Status.

[25] Lawrence, Deborah. APEC GIT/14 Conference. Federal Aviation Administration. Renaissance Hotel, Seattle WA. 21 June 2010. FAA Satellite Navigation Status.

Image 6, below is what the world's coverage would be with dual frequency WAAS, EGNOS, MSAS, GAGAN, GLONASS, and Galileo coverage.

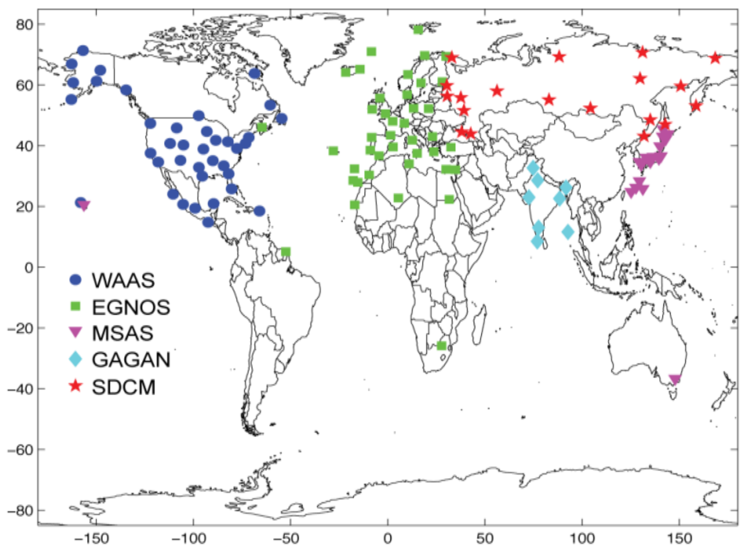


(Image 6: Updated WAAS, EGNOS, MSAS, GAGAN, GLONASS, and Galileo Dual Frequency Coverage)[26]

It can be seen in image 6 that creating dual frequency coverage in the northern hemisphere will significantly improve more of the world's availability in the northern hemisphere compared to the southern hemisphere. This is because of the lack of reference stations in the southern hemisphere. Image 7, below is of the current reference stations. [27]

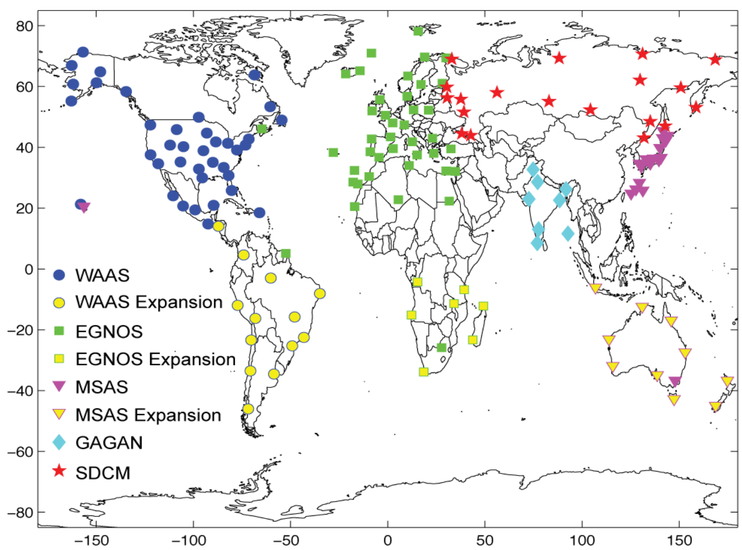
[26] Lawrence, Deborah. APEC GIT/14 Conference. Federal Aviation Administration. Renaissance Hotel, Seattle WA. 21 June 2010. FAA Satellite Navigation Status.

[27] Van Dyke, Karen. Personal interview. August 3, 2010.



(Image 7: Current Reference Stations) [28]

However if we increase the number of reference stations to as seen below in image 8.

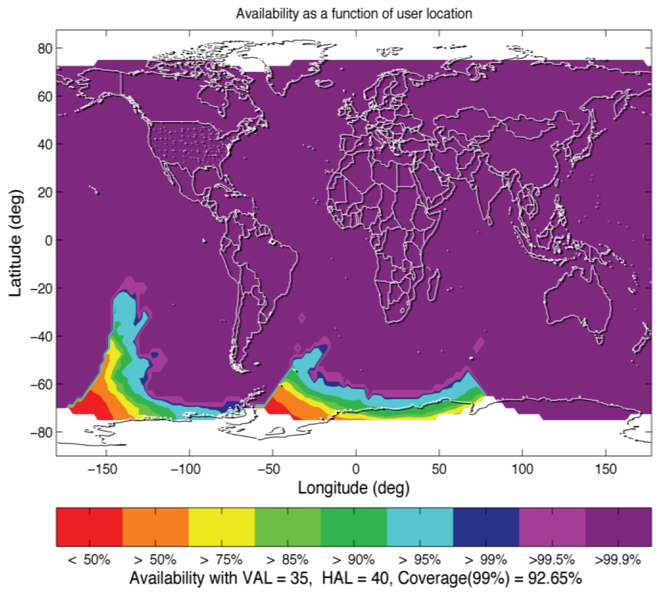


(Image 8: Updated Expansion of Reference Stations) [29]

[28] Lawrence, Deborah. APEC GIT/14 Conference. Federal Aviation Administration. Renaissance Hotel, Seattle WA. 21 June 2010. FAA Satellite Navigation Status.

[29] Lawrence, Deborah. APEC GIT/14 Conference. Federal Aviation Administration. Renaissance Hotel, Seattle WA. 21 June 2010. FAA Satellite Navigation Status.

We would be able to significantly improve SBAS coverage to include most of the southern hemisphere as seen below in image 9.



(Image 9: Updated Expansion of Reference Stations with WAAS, EGNOS, MSAS, GAGAN, GLONASS, and Galileo Dual Frequency Coverage)[30]

Currently the United Nations International Committee on GNSS (ICG) is working on space-base PNT compatibility and interoperability in order to optimize the world's space-based PNT infrastructure for the future. [31] These maps above show the significant improvements made to the coverage of PNT by utilizing several countries systems to create a unified dual frequency space-based PNT system in addition to meeting the four policy goals of compatibility, interoperability, integrity and openness.

Positioning, navigation and timing is one of the biggest struggles in the field of transportation. Currently several countries are developing different space-based PNT systems that will provide global PNT coverage with three to 15 meters accuracy and augmented PNT coverage with one to four meters accuracy. While these augmented space-based PNT systems are

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[30] Lawrence, Deborah. APEC GIT/14 Conference. Federal Aviation Administration. Renaissance Hotel, Seattle WA. 21 June 2010. FAA Satellite Navigation Status.
[31] Van Dyke, Karen. Personal interview. August 3, 2010.

more accurate, they are limited to area surrounding the system's host country. By combining these augmentation systems in addition to increasing the number of reference stations, the world can develop a highly accurate worldwide space-based PNT system. However in order to do so countries must not allow political bureaucracy to impede in promoting compatibility, interoperability, openness and integrity. This also must be implemented now in order to plan for the additional satellites that are expected to become operational over the next few years. Only by following these four principles will space-based PNT systems will reach their full potential to improve humanity's well being.

DGPS	Differential Global Navigation System
EGNOS	European Geostationary Navigation Overlay Service
GAGAN	Geo Augmented Navigation System
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICG	United Nations International Committee on GNSS
IRNSS	Indian Regional Navigational Satellite System
MSAS	Multi-functional Satellite Augmentation System
PNT	Position Navigation and Timing
QZSS	Quasi-Zenith Satellite System
RNSS	Regional Navigation Satellite System
SBAS	Satellite Based Augmentation System
SDCM	System of Differential Corrections and Monitoring
WAAS	Wide Area Augmentation System