UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

SENSITIVITY ANALYSIS OF CODE CARRIER COHERENCE IN THE GPS SATELLITE FLEET TO REDUCE OVERBOUNDING IN WAAS TO INCREASE AVAILABILITY WHILE MAINTAINING INTEGRITY

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By

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SENSITIVITY ANALYSIS OF CODE CARRIER COHERENCE IN THE GPS SATELLITE FLEET TO REDUCE OVERBOUNDING IN WAAS TO INCREASE AVAILABILITY WHILE MAINTAINING INTEGRITY

A DISSERTATION APPROVED FOR THE
DEPARTMENT OF ENGINEERING

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To my grandma, Joy Lee Green, who never gave up on me and never allowed me give up.

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Technical consultation.

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Prototype runs.

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Acronyms and Abbreviations

AMQP Advanced Message Queuing Protocol ... 42
ASCII American Standard Code for Information Interchange ... 43
CCC Code Carrier Coherence ... 1
CNMP Code Noise and Multipath ... 3
DGPS Differential GPS ... 15
DME Distance Measuring Equipment ... 21
DNU Do-Not-Use ... 30
DOP Dilution of Precision ... 17
FAA Federal Aviation Administration ... 19
GBAS Ground Based Augmentation System ... 33
GEO Geostationary Earth Orbit ... 3
GIVE Grid Ionospheric Vertical Error ... 29
GLS GPS Landing System ... 11
GPS Global Positioning System ... 11
GUS GEO Uplink Subsystem ... 30
HDF Hierarchical Data Format ... 45
HDOP Horizontal Dilution of Precision ... 17
ILS Instrument Landing System ... 21
LAAS Local Area Augmentation System ... 11
LGF Local Area Augmentation System (LAAS) Ground Facility ... 33
LPV Localizer Performance with Vertical Guidance ... 1
MEO Medium Earth Orbit ... 11
MLA Multipath Limiting Antenna ... 17
MOPS Minimum Operational Performance Specification ... 28
NASE National Airway Systems Engineering ... 7
NDB Non-Directional Beacon ... 21
NDGPS Nationwide Differential Global Positioning System ... 19
OLTP On Line Transaction Processing ... 43
OLAP On Line Analytical Processing ... 43
OSP Operational System Parameter ... 6
RFU Radio Frequency Uplink ... 31
SA Selective Availability ... 17
SEP Spherical Error Probable ... 1
SOG Satellite Operation Group ... 42

SPS	Standard Positioning Service	1
TOA	Time-of-Arrival	15
VDOP	Vertical Dilution of Precision	17
VHF	Very High Frequency	21
VOR	Very High Frequency (VHF) Omnidirectional Range	21
WAAS	Wide-Area Augmentation System	11
WMS	Wide-Area Master Station	30
WRS	Wide-Area Reference Station	29
WUM	WAAS User Message	29
UDRE	User Differential Range Error	27

Abstract

SENSITIVITY ANALYSIS OF CODE CARRIER COHERENCE IN THE GPS SATELLITE FLEET TO REDUCE OVERBOUNDING IN WAAS TO INCREASE AVAILABILITY WHILE MAINTAINING INTEGRITY

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The University of Oklahoma, 2019

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John W. Dyer

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should contain all letters of the alphabet and it should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content, but the length of words should match the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

The WAAS is enhanced and maintained by National Airway Systems Engineering (NASE) at the FAA.

Chapter 1

Introduction

This dissertation develops an extensive analysis tool for the Wide-Area Augmentation System (WAAS) to show that the statistical overbounding of Code Carrier Coherence (CCC), an integrity measure of WAAS, can be reduced to increase availability without reducing integrity. The WAAS is a navigational aid developed by the Federal Aviation Administration (FAA) with the goal of providing improved accuracy, integrity and availability of the Global Positioning System (GPS), giving aviation users the ability to use GPS in all phases of flight. WAAS augments standard GPS by providing regional range correction values associated with satellite ranging errors in GPS due to the ionosphere, which is the most significant contributor to environmental GPS ranging error. WAAS also provides corrections for any detected system errors from the system itself. Standard GPS allows a user receiver (with an inaccurate clock) to estimate its range to multiple in-view satellites and, with ephemeris information to determine each satellite's position, GPS can compute an estimate of the user position as shown in Figure 1.1.

During normal operations, GPS Standard Positioning Service (SPS) will have a user range error that is at or below a level required to support a positioning accuracy of 16 meters Spherical Error Probable (SEP) [3, p.51]. The WAAS Localizer Performance with Vertical Guidance (LPV) requirement specifies Horizontal Accuracy of $\leq 1.5m$ error 95% of the time Vertical Accuracy $\leq 2m$ error 95% of the time [7, p.4] [8, p.34]. WAAS routinely meets this performance 99-100% of the time [7, p.29]. WAAS estimates regional range correction values and provides these data to user receivers, which can incorporate the range corrections to improve the accuracy

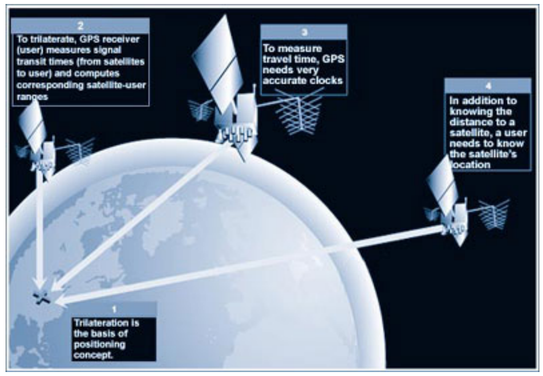


Figure 1.1: GPS Basic Overview. Trilateration is the basis of GPS positioning. A GPS receiver measures the signals transit times from satellites to the user and computes the corresponding satellite-user ranges. To measure travel time GPS needs a very accurate clocks. In addition to knowing the distance to the satellite, a user needs to know the satellites location.

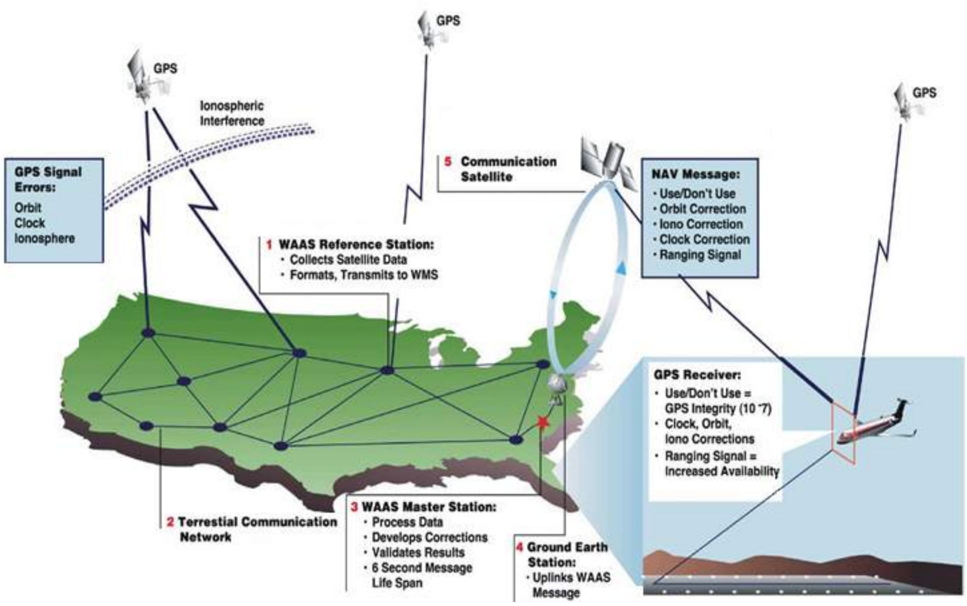


Figure 1.2: WAAS Basic Overview. The WRSes receive GPS measurements and transfer the data to the WMS. Integrity and differential corrections are generated and sent to the GUS. The GUS transmits the WMS messages to a GEO Satellite which is broadcast down to users.

of the position solution, Figure 1.2. However, because the ranging errors are transmitted from a space-based component of the system, integrity checks must ensure that no false range corrections are transmitted that might cause significant erroneous position solutions. There are a number of parameters in the WAAS integrity checks that are statistically overbounded to ensure that no hazardous misleading information is transmitted to WAAS-enabled GPS receivers. Historically, the overbounding has been generous to provide significant safety tolerance [9, p.61], but no systematic study has been undertaken to identify which parameters are grossly overbounded and might possibly be reduced without affecting integrity.

The purpose of this sensitivity analysis is to isolate the performance of the CCC integrity monitor and show the gains made to reduce its bounding variance so that an increase in availability is attained while integrity is maintained. The objective of the CCC monitor is to detect satellite failures that cause the code phase and carrier phase of the GPS or Geostationary Earth Orbit (GEO) signal to be incoherent. Since the Minimum Operational Performance Specification (MOPS) user equipment uses carrier phase measurements to smooth the code phase (pseudorange) measurements, this is a potential source of user error. Further, the Code Noise and Multipath (CNMP) monitor algorithm is based on the assumption that the code and carrier are coherent. Therefore, if the code and carrier are not coherent the multipath corrections can be in error and the User Differential Range Error (UDRE) may not properly bound the users range error to that satellite.

The UDRE and Grid Ionospheric Vertical Error (GIVE) are the final values sent to the user which represent the accumulation of error bounding through the Integrity Data Monitors. The CCC calculation occurs towards the beginning of this flow and ensures the code and carrier are coherent before other monitors like CNMP use the measurements. The final threshold selection for the UDRE floor was based on the impact on system coverage as the UDRE floor is increased. This run was done with 24 hours of data from December 20, 2000 using the prototype algorithm software. A floor of 4 (2.25 meters) was determine to be an optimal error bound based on this 24 hours run.

This dissertation is not intended to rationalize or disprove the setting of the UDRE Floor bases on 24 hours of data analysis. This sensitivity analysis is the initiation of a methodology to isolate the constituent elements that produce the final measurements composing the UDRE and eventually the GIVE. This detailed visibility into the system over a large data-set can be used to determine if the value has been set optimally or if further optimizations should be done base on empirical observations and there has never been an empirical analysis of its performance. Providing system integrity at all points and space at all times requires rigorous mathematical, statistical, and physical analysis. In fact it is estimated that to prove WAAS system integrity through observation alone would require nearly 50 years of data collection [4]. This study is an interim step beyond the 24 hour data run, but less than 50 years of observations. This rigorous study can be used to observe if a steady state he already occurred or can any trending be observed. The complexity of the system, and the volume of data to be analyzed to provide reliable sensitivity results has never been addressed in the literature.

The stated goal of WAAS, to provide improved accuracy, integrity and availability, is a complex set of tasks that may sometimes require tradeoffs between the competing goals. The goals can be described as follows. Accuracy is improved by providing a differential GPS solution, meaning WAAS transmits range correction values for each satellite and the user GPS receiver applies these range correction values to the internally measured ranges prior to the user position computation. This results in a *differentially corrected* position solution that is more accurate than the position solution would be without the range corrections. The WAAS architecture is a geographically diverse sensor network of high fidelity GPS receivers

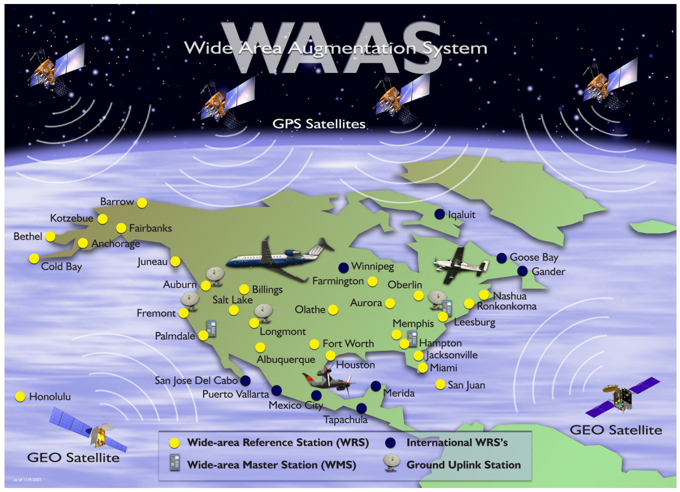


Figure 1.3: The Wide Area Augmentation System. WAAS incorporates a number of reference stations in both the 48 contiguous United States as well as other North American partners: Mexico and Canada. Three Master Stations calculate GPS satellite and ionospheric correction data and three GEO Satellites are use to transmit the information to aviation users.

that track GPS satellites throughout North and Central America and Hawaii. This network consists of 114 GPS receivers at 38 geographically diverse sites. Each *reference station* is precisely surveyed at the antenna phase center, so the range to any in-view satellite is known (assuming accurate ephemeris information allows for accurate satellite position computation. The GPS receivers in the reference stations use receive-time (of the transmitted satellite signal) to estimate satellite range, so any error in local receiver time translates directly into an error in the range measurement to the GPS satellite. To provide the highest degree of accuracy the GPS antennas are designed to mitigate multipath and each GPS receiver clock is disciplined with a cesium frequency standard to provide a highly accurate and precise time source [5]. A quarterly analysis of every second of every day is performed to observe if any change in the environment has occurred that may negatively affect performance. Yearly releases are conducted to update the antenna positions so that continental drift and other environmental factors are mitigated. The rigor put into this infrastructure enables this highly precise network of receivers to detect errors within GPS and the geographic diversity enables modeling of timing delays in the ionosphere. Once an end user within the WAAS coverage area applies the GPS and ionospheric corrections sub-meter level GPS accuracy can be achieved in the best case and in the worst case range errors remain less than 2 meters. There are more than a dozen safety integrity monitors built into WAAS that monitor GPS and ionospheric threats. Protecting users from integrity threats is an integral part of WAAS as it was commissioned as a safety-of-life system, but integrity and availability have to be considered together as there is an inverse relationship between the two. As integrity increases availability is reduced. All GPS threats would be abated if GPS were not allowed to be used; integrity against GPS threats is 100% while utilization of GPS is 0%. To achieve an acceptable level of utilization of GPS availability, confidence bounding is performed for GPS and ionospheric threats. The purpose of this study is to isolate the performance of the CCC integrity monitor and show the gains made to reduce its bounding variance so that an increase in availability is attained while integrity is maintained.

WAAS has ≈2000 Operational System Parameter (OSP) values that define minimum and maximum limits, action thresholds, and timeouts [REF]. The parameters are used to control logic throughout the WAAS system. There is always a balance between usability and safety. For the FAA these two aspects are couched in the terms availability/continuity for usability and integrity for safety. If the system remains off then this is the highest level of integrity, meaning if the user does not use the GPS then they are safe against all GPS related threats. This would not make a practical system, so it led the engineers developing the WAAS application to use values that would allow the system to be usable, but were significantly conservative to protect the user against GPS related threats. At the inception of WAAS there was insufficient empirical data to appropriately set many of the integrity bounding limits. The CNMP has been stated as being grossly overbounded[9, p.61]. The

National Airway Systems Engineering (NASE) organization has now accumulated over 8 years of data, but there is currently no analytical system in place to process this volume of data so that updated OSP values can be set.

A sensitivity analysis of the type proposed in this study is difficult due to the shear magnitude of data to be analyzed. In order to properly analyze the sensitivity of WAAS to the level of statistical overbounding of the CCC parameter, many years of data must be analyzed. This ensures that seasonal effects, a broad selection of significant weather events, and any astronomic effects can be included in the analysis [REF about what external things might affect integrity]. However, the system requirements for just the hardware and software present a significant barrier to achievement. Not only is significant processing power required, but an effective data handling method must also be employed so that the results are discoverable from the plethora of numerical information generated.

The cost of establishing and maintaining the infrastructure for WAAS is significant. In addition to the 3 geosynchronous satellites keeping station above North America, there are the 38 reference station sites, three master reference stations, and six uplink stations, as well as the infrastructure to record and analyze daily information for uplink to the satellites. Indeed, ≈374,284,800 data points are generated every day for analysis. A major obstacle to performing any sensitivity analysis of the various overbounding parameters lies in the sheer volume of data that must be processed. It should be noted that in order to glean any meaningful results, extended periods of historical raw data must be processed to ensure that seasonal variations, weather events, and astronomical transients (solar flares, magnetic storms, etc) are included in the analysis. This research incorporates a system that is novel in itself. The system capable of the desired analysis has taken several years and significant funding to develop. The system approach in this study utilizes commodity hardware and open source databases, programming languages and analytics software, with the goal of processing seven (7) years of data to assess the sensitivity of WAAS to the CCC parameter. However, the system has been designed with the concept of scalability at the forefront, so that it can be expanded to assess other system sensitivities in the future.

The approach outlined in this analysis is innovative in that it can be utilized to increase the availability of any Space Based Augmentation System while maintaining integrity. This infrastructure is limited to all but a few countries, but with the countries that are developing this capability, world wide space based augmentation can be attained. The application of this methodology could lead to the establishment of highly available space based navigational aids on a global level. Further. the generalized approach utilized to solve this big data analytics problems can be utilized in domains outside of this specific aviation application.

1.1 Chapter 1 Notes and Snippets

Global SBAS Picture

https://www.gps.gov/policy/funding/2017/

http://commdocs.house.gov/committees/Trans/hpw106-100.000/hpw106-100_1.HTM

https://www.gps.gov/technical/ps/2008-waas-performance-standard.pdf

Things I need.

PRN SVN Mapping for the last five years. Assign to Hoang.

First sentence what this dissertation has achieved. 30,000ft view of WAAS and the Problem. Pros and Cons of WAAS and the specific area I am looking at.

Paragraph 1: What is the problem?

Not more than 3-4 sentences telling the reader what the problem is, in as simple English as possible

Paragraph 2: Why is the problem hard?

What has eluded us in solving it? What does the literature say about this problem? What are the obstacles/challenges? Why is it non-trivial?

Paragraph 3: What is your approach/result to solving this problem?

How come you solved it? Think of this as your startling or sit up and take notice claims that your dissertation will plan to prove/demonstrate

Paragraph 4: What is the consequence of your approach?

So, now that youve made me sit up and take notice, what is the impact? What does your approach/result enable?

http://commdocs.house.gov/committees/Trans/hpw106-100.000/hpw106-100_1.HTM [4]

Third and most significant, while we can observe that the system is now performing very well, providing system integrity at all points and space at all times requires rigorous mathematical, statistical, and physical analysis. Proving the required level of integrity through observation alone would require nearly 50 years of data collection. Clearly, this is not acceptable. Instead, observation of the signal and collection of data over the next 2 years will be used to support analytical proof of the integrity required for FAA certification. A group of experts has been formed to establish this road map for certification. The WIPP has been meeting almost monthly since February and is making very good progress. If I may say a word in defense of the FAA, which has been criticized for its management of software-intensive programs, in the case of WAAS I would like to urge the committee not to lose sight of the fact that the Wide Area Augmentation System is the first time in the 45-year history of the FAA that a new navigation and landing technology is being commissioned for the entire national air space system. It will replace ILS and

VOR technology that dates to the late 1940s and actually predates the formation of the FAA as we know it today. WAAS is part of a world-wide movement toward satellite navigation. Japan and the European Union are developing their versions of the same technology. Chile has installed test bed equipment in anticipation of a South American WAAS system. This transition to satellite navigation is necessary if we are to avoid gridlock in the skies in the 21st century while also increasing safety.

GPS Error Sources

https://en.wikipedia.org/wiki/Error_analysis_for_the_Global_Positioning_System

GPS Error Sources

https://www.e-education.psu.edu/geog160/node/1924

Chapter 2

Background and Literature Review

2.1 Introduction to the Global Positioning System (GPS)

The GPS is a remarkable system for finding one's location and its success is largely due to the modest needs of the average user. Standard GPS accuracy is approximately 15 meters[6] and this level of accuracy is quite satisfactory for many applications, including land navigation, which is the primary consumer application for GPS. However, when GPS accuracy is discussed it is generally in terms of horizontal accuracy. Vertical accuracy is seldom mentioned in the discussion of accuracy and most GPS manufacturers do not publish the vertical accuracy specification. Due to this, a rule-of-thumb has developed that suggests that the vertical accuracy is only half as good as the horizontal accuracy. So, if Standard GPS is accurate to within 15 meters in the horizontal, then it is considered accurate to about 30 meters in the vertical, which is unacceptable for aircraft landings. This is why the Wide-Area Augmentation System (WAAS) and the Local Area Augmentation System (LAAS) are indispensable for a GPS Landing System (GLS). Many different factors affect the precision of GPS which will be explored during this overview of GPS.

GPS is comprised of 24 well placed satellites. The satellites orbit the earth in 6 orbital planes that are at a 55^o inclination with 4 satellites per plane such that at least 4 satellites will be above the horizon at any given moment. This allows users the ability to use the system 24 hours a day anywhere on the planet. These satellites are not geo-orbital, but are at a Medium Earth Orbit (MEO) and orbit the earth twice a sidereal day with a speed of 3.9km per second. The basic principal of the GPS system is quite simple. A satellite orbits the earth at about 12,600 miles shown

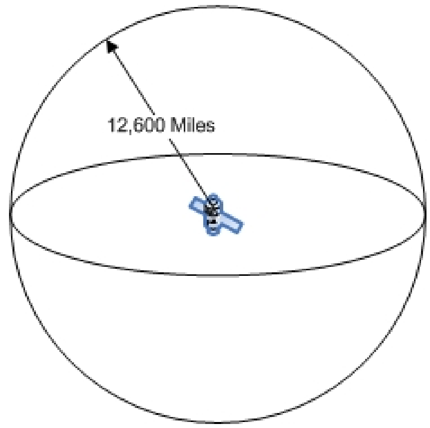


Figure 2.1: GPS Basics: Radius

in Figure 2.1. GPS works by determining the range from the GPS satellite to the user receiver. The satellite acts as a reference point with a known location. With one GPS satellite the user knows that he is on the sphere from the GPS satellite to the receiver. The user can be located anywhere on the surface of the sphere created by the range of the satellite to the user receiver. How this range is known will be discussed later.

Introducing another GPS satellite, the user can now be isolated to the intersection of two spheres which is a circle shown in Figure 2.2. When a third satellite is introduced it intersects the circle at two points shown in Figure 2.3. GPS assumes an earth centered, earth fixed, x-y-z 3D Cartesian coordinate system. Any location in this 3D space requires no more than 3 components to be completely identified. So, even though the intersection of 3 spheres yields two different points, the point located outside the earth's atmosphere is rendered useless by the earth centered earth fixed reference system. One point will be within Earth's atmosphere with an acceptable rate of velocity while the other point will be in space traveling at a high velocity.

If the user measurements were perfect then three satellites would be sufficient to determine the user's location, but to take near perfect measurements would

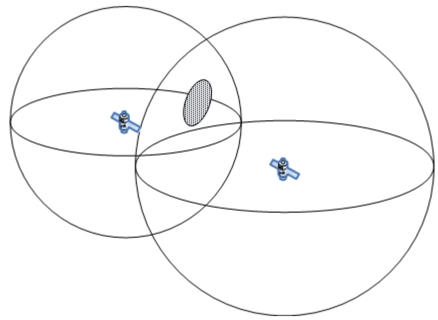


Figure 2.2: GPS Basics: Circle

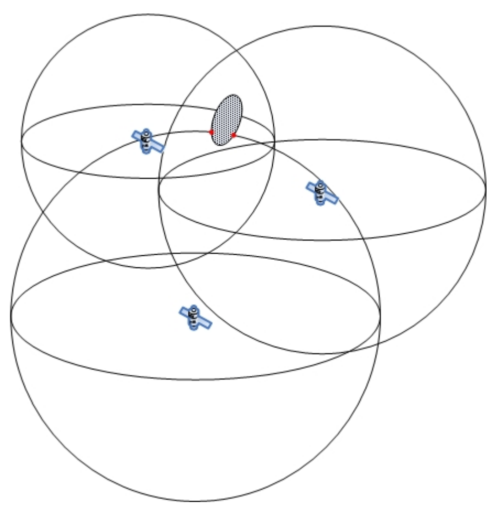


Figure 2.3: GPS Basics: Two Points

require the use of a highly stable atomic or optical clock. These clocks are large, very expensive and require considerable power, so the use of these types of clocks is impractical. Most GPS receivers utilize a quartz crystal oscillator for timing. This oscillator is small, cheap and low power but also very inaccurate, but, as it turns out, if three measurement made with perfect time can be used to produce a position solution in 3-dimensional space then four imperfect measurements can be used to produce the same solution while solving for the receiver clock offset. GPS utilizes a fourth satellite to solve for the user's clock, synchronizing the receiver clock with GPS time. Since any clock offset from GPS universal time will affect all of the measurements, the receiver looks for a single correction factor that can be subtract from all its timing measurements that would cause them all to intersect at a single point. When the clock offset is applied it brings the receiver's clock back into sync with GPS time. The fourth satellite helps calculate the timing correction and in turn a location correction and selects one of the remaining two points as the position. The fourth satellite allows for the solving of a linear set of equations for x, y, z, and t simultaneously. Four satellites are required for (x,y,z,t) but in normal operation users are tracking more than four satellites; typically around 6 to 8. This sets up an overdetermined system of equations and a least-squares algorithm is used to determine the minimum error position solution. An added benefit is that every GPS receiver essentially has atomic-accuracy.

[Link: Getting Perfect Timing Using GPS for Timing][3]
[Link: Trilateration algorithm for n amount of points][4]

The satellites are used as reference points, but how can something moving high above the earth at a high velocity be used for measuring distance? Every aspect of the GPS constellation is precisely monitored by six earth based monitor stations located throughout the world. Any variance in the orbit, position, or velocity of a satellite is compensated and adjusted for at the master control station, located in Colorado Springs, Colorado. These constant adjustments are put into a GPS message called the ephemeris message. The *ephemeris* is a mathematical model of the motion of the orbit of a satellite. This model allows a GPS receiver to know the exact position of a satellite at a given time. Now a method similar to *trilateration* can be used to determine the GPS receiver's range or distance to the satellite. Trilateration uses the known locations of three or more reference points, and the measured distance between the subject and each reference point to determine the subject's location. In the case of GPS the distance is measured using the Time-of-Arrival (TOA) of a ranging signal called the *pseudorandom code*. The code is a very complex set of digital information that is called pseudorandom because it resembles random noise. It is repeated every millisecond. When the receiver receives the pseudorandom code it takes the signal propagation time multiplied by the speed of light to get the range to the satellite. This is simple in concept, but the timing has to be near perfect. If the time is off by even 1/1000 of a second the range could be off by 300,000 meters. The GPS satellites actually keep track of their time using atomic clocks. Each satellite is equipped with four atomic clocks to precisely track time, but atomic clocks are very costly and impractical for producing low cost GPS receivers. Instead manufacturers use a less precise, less expensive crystal clock; but now have to overcome the error introduced by the receiver clock as previously mentioned. Theses techniques allow users to track satellites, correct time and calculate ranges enabling one to find their position, but these ranges still contain errors; therefore they are referred to as *pseudoranges*. GPS has many errors associated with it that cumulatively reduce GPS accuracy. Due to these errors the GPS signal does not meet the accuracy, integrity, availability, and continuity requirements critical to safety of flight. These errors can be accounted for using Differential GPS (DGPS) which is the method of using a GPS receiver at a fixed known reference point to determine the errors in GPS ranging.

The errors can be categorized as follows:

- Ephemeris ($<$ 1 meter Error)

  The ephemeris is a mathematical model of the motion of the orbit of a satellite. This model is provided to the user and predicts where the satellite will be, but the forces acting upon the satellite don't always conform perfectly to the model. Any errors in the model will add to a user's position error, but since the ephemeris data is constantly being adjusted the error introduced is small and can be removed by differential GPS between two observations of short separation.

- Satellite Clock Errors ($<$ 1 meter Error)

  Satellites use atomic clocks to precisely monitor time, but even atomic clocks are not perfect. Since the pseudorange calculation is based on time any discrepancy in the clock will introduce error. This can also be removed with differential GPS.

- Receiver Clock Errors (1 meter $<$ Error $<$ 2 meters)

  A GPS Receiver uses a crystal clock which is much less accurate than an atomic clock; consequently additional timing errors exist. The Receiver Clock produces more error than the Satellite Clock and unfortunately can not be removed with differential GPS, but is treated as another unknown during the estimation process.

- Ionosphere / Troposphere ($\approx$4 meters)

  The atmosphere can be broken down into many layers but the two that most affect GPS are the ionosphere and the troposphere. The *ionoshpere* is the ionized part of Earth's upper atmosphereis and is a dispersive medium. The GPS signal incurs propagation delay as it is bent and changes speed when passing through the ionosphere. Though the delay is generally negligible, the ionosphere increases the speed of the carrier phase and slows down the pseudorandom code, so this source of error must be taken into consideration. Temperature, pressure and humidity in the *troposphere*, the lowest layer of the Earth's atmosphere, can also affect a GPS signal's propagation. The troposphere is a non dispersive medium, so the carrier phase and pseudorandom code are delayed by the same amount increasing the measured distance to the satellite from the actual distance.[1].

- GPS Satellite Geometry

  A Satellite's geometry with respect to other satellites also plays a role in the position solution. The closer the satellites are to one another the poorer the position solution and the more spread out the better the position solution. The Dilution of Precision (DOP) is a number that represents the acceptability of the GPS geometry. It can further be broken down into a horizontal and vertical component known as the Horizontal Dilution of Precision (HDOP) and Vertical Dilution of Precision (VDOP).

- Multipath

  Multipath is a source of error that is introduced when the GPS signal is reflected from surfaces near the receiver's antenna, such as buildings, and the reflections are mistaken for the primary signal. The reflected signal adds additional propagation delay over the true signal, and in turn, additional user error. This is the same occurrence that causes ghosting on a television set. WAAS reduces the potential of this error source by using specialized GPS Multipath Limiting Antennas (MLA's) and a priori siting analysis to avoid multipath generating structures.

- Selective Availability (SA) ($>$ 10 Meters)

The last error that will be mentioned is artificial error. The U.S. Military purposely skewed the GPS signal to artificially inflate the error in the system so that it could not be used against them. When SA was active it was the most substantial source of error, but the use of differential GPS could nearly eliminate SA's effectiveness. The use of SA was discontinued on May 1, 2000.

2.2 Differential GPS (DGPS)

DGPS is the method of using a GPS receiver at a fixed known reference point to determine the errors in GPS ranging. To do this, the GPS receiver's antenna position is accurately surveyed. Next, the difference is calculated between the pseudorange internally measured by the GPS receiver and the pseudorange calculated from a satellite's current GPS almanac, ephemeris information, and the surveyed location. The difference between the measured pseudorange and the calculated pseudorange is the *pseudorange correction* which is the distance that the local user should adjust a respective satellite's pseudorange by to achieve a minimum error position solution. The pseudorange correction is a lump sum adjustment for multiple sources of error which include ephemeris, satellite and receiver clocks, ionosphere and troposphere, and even Selective Availability. However, the pseudorange correction can only be computed by knowing the precise location of the reference receiver antenna. Another thing to note is that most DGPS systems make corrections in the range domain by adjusting the pseudorange measurement of each satellite in view. An alternative approach is to adjust the system in the position domain. This would involve calculating a position solution for the reference point then calculating a position correction vector. This is generally not done due to the fact that position solutions are calculated by manufacturers using proprietary methods, and their behavior is not known a priori.

The many different DGPS solutions that have been developed fall broadly into two categories: post-processed and real time. Surveyors are a primary user of the non-real time post-processing category. They collect GPS data from known reference points, which they call *benchmarks*, and the point needing to be surveyed. The distance between the benchmark and the survey point is called the *baseline*, and it is generally preferred to use the benchmark with the shortest baseline to the survey point. After about 15 minutes to an hour of collecting data at both locations they can post process the data with GPS utilities to produce a position solution accurate to within a centimeter[1]. On the other hand, real-time differential GPS systems acquire the data from the reference points, calculate the pseudorange corrections, and broadcast them out at a rate of 2 to 5 Hertz to be used in navigation applications. Since LAAS falls into the real time category, it and a few other prominent real time DGPS systems will be discussed.

One of the first systems developed actually used the acronym DGPS, but sometimes also goes by Nationwide Differential Global Positioning System (NDGPS) to distinguish DGPS the concept from DGPS the system. The NDGPS is used by the U.S. Coast Guard in harbor regions to give ships better position solutions. Even though the name implies national coverage is it limited to coastal regions. Europe and Canada also have similar solution for their heavily utilized maritime locations. There are even commercial companies like VERIPOS, StarFire, and OmniSTAR that provide DGPS services.

Most of the DGPS systems developed had a very specific function or operated in such a localized area that it precluded widespread use. The Federal Aviation Administration (FAA) wanted to capitalize on the benefits of DGPS while promoting a broad coverage area. To that end they designed WAAS, as shown in Figure 2.4, established reference points throughout the contiguous United States. These fixed reference points were used to establish pseudorange corrections for most of North

[1]Utilizes GPS L1/L2 survey equipment

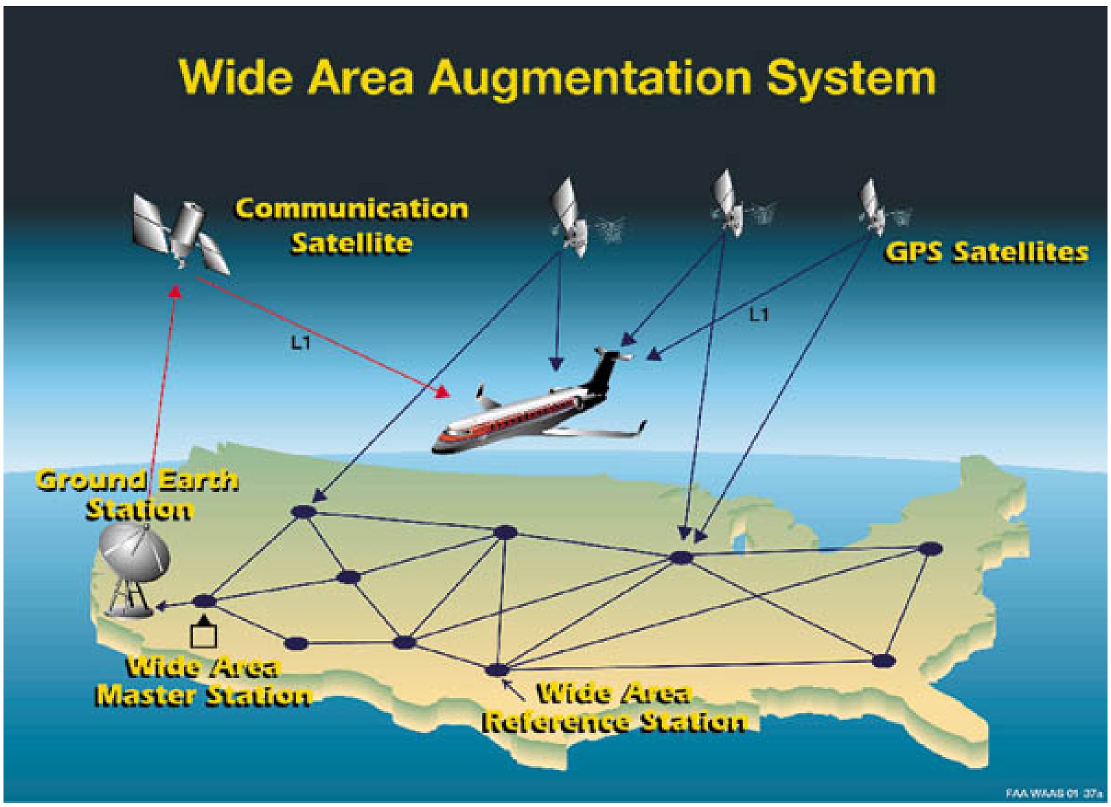


Figure 2.4: Wide Area Augmentation System[10]

America. WAAS corrections are then sent to a geo-orbital satellite and broadcast to WAAS-enabled GPS receivers. WAAS improved the accuracy of GPS to less than 2 meters in the horizontal and less than 3 meters in the vertical. This was a significant enhancement to GPS; an improved GPS position solution free for the end user. GPS manufacturers adopted this readily and now WAAS-enabled GPS receivers are commonplace. A major shortcoming with WAAS is its confinement to North America. Additional Reference Receivers are being installed in Alaska and Mexico, but this is still a United States / North America locale. Large air carriers need GPS augmentation internationally. Furthermore, WAAS accuracy is not as accurate as some other DGPS systems due to its broad coverage area. Because of this the FAA does not consider its accuracy and integrity acceptable for instrument landings beyond CAT I.

2.3 GPS & WAAS Introduction

The are numerous navigation aids supporting the national airways. Many are ground based but with the inception of GPS there is a transition to space based navigation. In regards to utilizing GPS and WAAS for navigation there are questions that need to be answered as to the necessity of WAAS and why GPS by itself is not sufficient for aircraft navigation.

- Why yet another navigation system?
- What are the benefits over other ground based navigational aids?
  - Non-Directional Beacon (NDB)
  - Distance Measuring Equipment (DME)
  - Very High Frequency (VHF) Omnidirectional Range (VOR)
  - Instrument Landing System (ILS)
- What is WAAS?

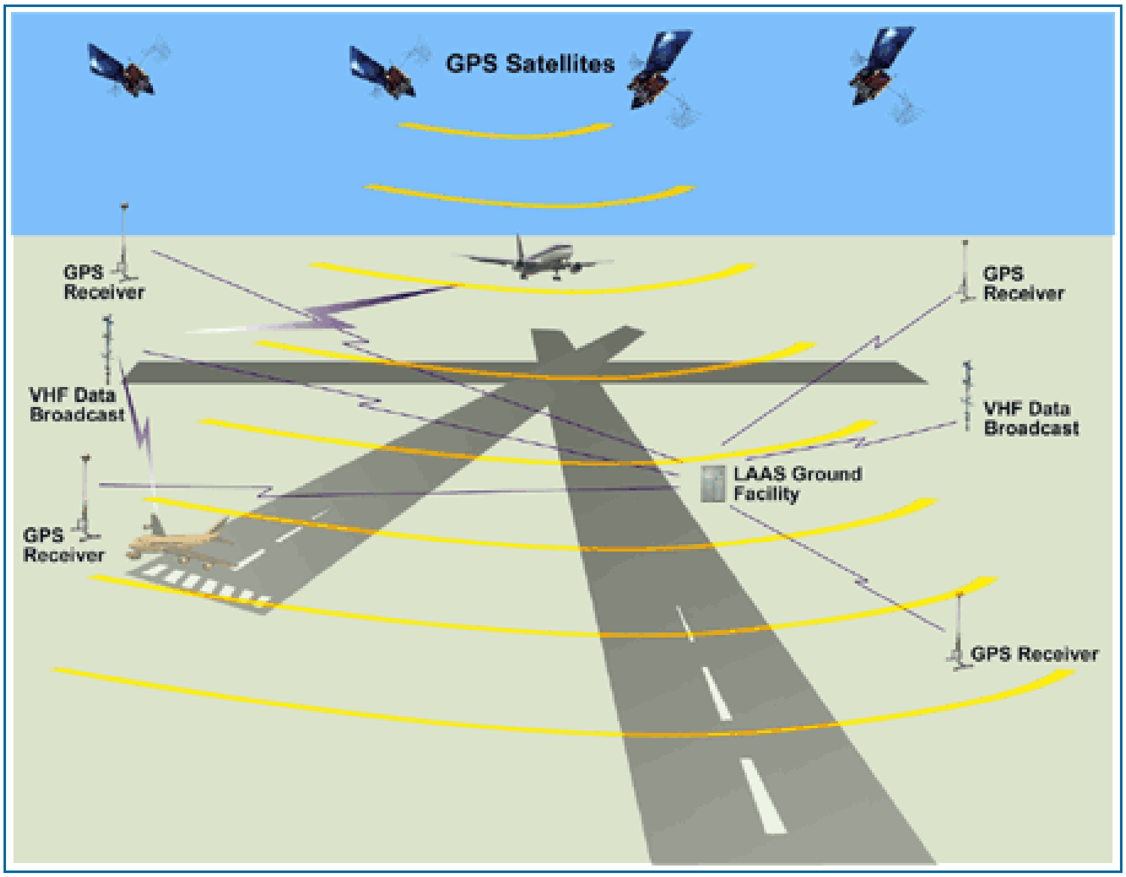


Figure 2.5: Local Area Augmentation System

- Why can GPS not be used on its own?
- What does WAAS do?
- How does WAAS work?
- Where is WAAS used?
- Why use GPS and WAAS?

2.3.1 FAA Air Transportation System Modernization

The FAA has recognized the need to improve the Air Transportation System so that it is more efficient, more predictable, and able to handle more capacity while maintaining the highest safety standards and reducing environmental impacts. The FAA's NextGen modernization initiative is geared toward moving away from ground-based to satellite-enabled technologies for navigation and surveillance systems and from analog to digital systems for communication. While WAAS is not a NextGen program, it is one of the foundational pillars upon which satellite enabled technologies are built.

2.3.2 Benefits of the Wide Area Augmentation System

Primary Means of Navigation

WAAS is a critical component of the modernization's effort to enable the aviation industry's use of space-based navigational aids as a primary means of navigation, including: takeoff, en-route, approach and landing.

More Direct Routes

Space-based navigational aids allows more direct routes to be utilized over ground based navigational aids. It is not restricted by location of ground-based equipment or line of sight as with some ground base equipment. For example, utilizing VOR, which is a ground-based navigational aid, is equivalent to navigating along a highway in the sky. Using a VOR network, aircraft fly from one VOR to another which may not be the most direct path. Utilizing GPS and WAAS aircraft can fly direct routes from their departure point to arrival point.

Approach with Vertical Guidance Capability

Additionally WAAS approaches with vertical guidance capability can be utilized at many airports for landing. The number of airports that utilize WAAS approaches has now exceeded that of airports using the ILS which is another ground-based aid for landing aircraft. The advantage of using WAAS approaches as opposed to ILS approaches is that WAAS approaches do not require ground-based equipment at the destination runways. The infrastructure for an ILS requires antenna arrays at the far end of the runway along with middle and outer markers located along an established line-of-sight route to a destination runway. The middle marker is 3000 to 6000 feet from the runway and the outer marker is 4 to 7 miles. This is just for a single runway end. If aircraft need to land from the opposite runway end all of this equipment is duplicated and mirrored. The ILS infrastructure can be costly and problematic and a full complement of equipment must be installed for each runway end. Adding to the cost, an ILS needs its antennas and markers routinely calibrated. It is an expensive installation, serves only one runway end and requires ongoing calibration for each installation.

ILS Marker Beacon [Link: NextGen Frequently Asked Questions][1] [Link: Performance Success Stories New WAAS Coverage Clears the Way for New Access to Airports][2]

Another deficiency is that it can just land aircraft, but it cannot provide guidance for departures, missed approaches or any other navigational service. If a missed approach is required the ILS cannot aid the aircraft on its outbound route. With WAAS a missed approach route can be defined. This is useful in areas like Kodiak Alaska where the approach leads directly into the base of Barometer Mountain; if a missed approach is required the pilot has to bank hard left between the valley created by Barometer Mountain and Old Women's Mountain. With the ILS or other ground-based navigational aids rugged or mountainous terrain can make line-of-sight systems unachievable. Space based navigation can have issues in areas like urban canyons, but for aviation applications, space based navigation has few impediments.

Kodiak Alask Map

Another benefit of WAAS is that the ground-based infrastructure does not have to be expanded to expand the capabilities of WAAS. More approaches can be added by surveying the runway ends and approach vector utilizing GPS waypoints. The application is separate from the infrastructure. Just as in GPS for vehicle navigation; GPS is providing positioning and timing services and the applications of those services are ever expanding.

Decommission of Older, Expensive Ground-Based Navigation Equipment

As satellite navigation systems become the primary means of navigation and supplants those capabilities of older ground-based navigational aids those aids can be decommissioned. As more approaches are defined more ILSes can be the decommissioned. As direct en-route capabilities are established the NDB, DME and VOR systems can also be decommissioned.

FAA Announces Plan for Reduction in VOR and ILS in Favor of WAAS

Simplified Avionics

With the implementation of WAAS and LAAS, as currently planned by the GPS Product Team, a substantial reduction in the user avionics equipment cost can be realized because of the reduction in the proliferation of navigational devices. A single device can serve all phases of flight.

The Sum of All Performance-Based Navigation Procedures

Increased Capacity

WAAS enabled receivers provide a highly accurate GPS position solution, so an aircraft's position is known to a higher fidelity than has previously been available. This, along with other technologies being pursued by the FAA, will offer opportunities to reduce separation standards. This reduction will be an incremental process based on analysis of the evolving capabilities. Potential reductions include non-radar separations in en route airspace and terminal separations due to smaller obstacle clearance areas and protected airspace. Reduced separation standards will directly translate into increased system capacity that can safely fly in a particular volume of airspace, benefiting the aviation user community.

WAAS Benefits Driving Equipage

Resiliency

WAAS does require a ground-based equipment infrastructure, but that infrastructure is highly resilient and redundant and WAAS enabled applications can be implemented with no need to expand WAAS ground-based equipment. It has a dual ring active/active network along with active standby and backup equipment. If an outage happens with any one piece of WAAS equipment it can be placed in standby mode until such time as it is appropriate to send maintenance personnel to work on it. This is different from the ILS or VOR systems, where if that ground-based navigational aid has a malfunction, that service is rendered unavailable until the repairs are completed. Depending on the criticality of the system, FAA maintainers may need to be out in the field in adverse weather conditions to restore service. Some equipment locations, like Kotzebue, Alaska, are inhospitable most of the year, so it makes it very precarious for maintainers to get out to those facilities to restore equipment and services. For WAAS, a loss of a subsystem does not mean a loss of service. Though it is not optimal, with the redundancy build into WAAS ground-based equipment infrastructure it can run in a degraded state with no system impact until conditions are suitable for the restoration.

2.3.3 GPS Overview

WAAS is a space-based differential GPS system. It is used to detect and correct GPS errors, monitor and correct for ionospheric delay and also provides additional ranging sources from three GEO satellites for improved availability of space based navigation services. It augments GPS and improves accuracy, integrity, and availability. At its core WAAS is a real-time GPS sensor network.

2.3.4 Why can't you use GPS by itself?

WAAS is an enhancement to GPS which monitors and detects these associated errors and provides the necessary corrections for meeting safety-of-life flight requirements. The purpose of WAAS is to monitor the GPS constellation and detect and correct for errors when possible. If corrections are not possible WAAS will alert aviation users when GPS services cannot be used; the most notable being ionospheric storm events where changes in the ionosphere are changing too rapidly for the WAAS ionoshperic model to adapt. WAAS is able to detect errors by utilizing a robust ground-based geographically diverse sensor network. There are 38 WAAS reference stations dispersed throughout Alaska, Canada, continental US, Mexico and Hawaii. Each reference station has three GPS receivers who's location coordinates are precisely surveyed. Errors in the GPS signal can be detected and these errors are grouped into two different classes; the User Differential Range Error (UDRE) and the Grid Ionospheric Vertical Error. One is a per GPS satellite based correction and the other is a geographical based correction to account for the delay of the GPS signal through the ionosphere. How this works for the end user is that their avionics receiver calculates a protection level. If their protection level is within the alert limits specified in the WAAS Minimum Operational Performance Specification (MOPS) then WAAS services available for them and they can utilize WAAS corrections to increase their accuracy. If however, they calculate a protection level that is outside the alert limit then WAAS is unavailable for them and they can not use the WAAS service. There exist a case that a protection level is calculated and it is within the alert limit but the true position of the aircraft is outside of those boundaries. This is the situation where the user determined they are safe when they are not. This is called Hazardously Misleading Information (HMI). This is an area in which National Airways System Engineering spends considerable time evaluating to ensure users are protected.

WAAS has mitigations and corrections for each type of error. First, WAAS mitigates the user clock error by using cesium atomic clocks. This is a highly stable and accurate time source that disciplines the clock of the GPS receiver used by the WAAS reference station. It mitigates multipath interference by using a highly specialized multipath limiting antenna. WAAS has an orbit determination filter to minimize the ephemeris errors of GPS and GEO satellites. WAAS also utilizes a Kriging model for the ionosphere and provides ionospheric corrections for all of North America. By mitigating the error sources in the acquisition of the GPS measurement data, WAAS is able to detect GPS errors and provide corrects for those errors to users to increase their accuracy.

2.3.5 What is WAAS

WAAS is a space-based differential GPS system. It detects and corrects GPS errors, monitors and corrects for ionospheric delay and provides additional ranging sources for improved availability of the navigational service. It augments GPS and improves its accuracy, integrity and availability. At its core WAAS is a real-time sensor network and the sensor is a GPS antenna tracking all GPS satellites in view of that antenna.

2.3.6 What is the purpose of WAAS?

WAAS is designed to protect users from error sources and other threats inherent in using GPS. It does this by broadcasting a UDRE, a Grid Ionospheric Vertical Error (GIVE) and GPS health information to the user. WAAS has predefined alert limits fixed by specification. The aircraft's WAAS enabled avionics will calculate its GPS position while applying the WAAS User Messages (WUMs) which have the UDRE and the GIVE values. The avionics receivers use these values to calculate a protection level based on the algorithm specified in the WAAS MOPS. If its protection level is within the alert limits then WAAS is available for that user. If it calculates the protection level and it is beyond the alert limit then WAAS is not available for that user. If the protection level cylinder becomes too small and does not enclose the true position of the aircraft this is called hazardously misleading information. It is a scenario in which the calculated protection level misinforms the user that the system is available for them to use when it is not.

2.3.7 How does WAAS work?

Wide-Area Reference Station (WRS)

The GPS satellites broadcast their ranging signal and message data down to earth and it is collected at a 1Hz rate by a network of WRS. There are 38 reference stations that are geographically diverse across North and Central America including Alaska, Canada, Continental US, Mexico and Hawaii. Each reference station has three threads denoted as thread A, B and C, so 114 individual threads. The A and B threads of each reference station are primarily utilized and the C thread is an active standby. A WRS can withstand an outage from any one thread. In fact WAAS can withstand the outage of one or more complete reference stations as long as they are not in close geographical proximity to on another. If multiple reference stations are out of service in a local area this will impact the ionospheric model and coverage will be reduced or lost in that area. GPS measurement data from every GPS satellites being tracked by all 114 threads is put onto a high availability terrestrial communications network. The network connects the reference stations to the Wide-Area Master Station (WMS).

Wide-Area Master Station (WMS)

There are three WMS that pull in the WRS data and calculate the differential GPS corrections, ionospheric correction and validates the GPS satellites are operating in a healthy normal mode. If a satellite is not usable WAAS will send a Do-Not-Use (DNU) alert message out to the users. These master stations are what calculate all the integrity parameters and is the computational center point of the system. The software for all the integrity monitors is running on a real-time operating system and is maintained using the guidelines specified in DO-178B, Software Considerations in Airborne Systems and Equipment Certification up to a Software Level of B/Hazardous. Once all the integrity parameters, the corrections and health information are validated and calculated the information is formulated into a series of WUMs and then put on the terrestrial communications network and sent to the GEO Uplink Subsystem (GUS).

GEO Uplink Subsystem

WAAS has three GEO satellites. Each satellite has two uplink stations denoted as primary and backup. The denotation for each system is based on which station is radiating to the satellite. The GUS that is radiating to the satellite is designated as primary and the other, which is radiating into a dummy load, is denoted as backup. If for some reason the primary has a failure it will automatically switch to the backup and the backup will become primary. When the faulted GEO Uplink Subsystem is restored to service it will be brought up into backup mode. It will stay in backup mode until the primary faults and automatically switches over back to primary or the WAAS operator issues a command to initiate a manual GUS switch over. This is done for maintenance activities at GUS sites.

The GUS sends the WUM through the Radio Frequency Uplink (RFU) which broadcast it to the WAAS satellite in geosynchronous orbit. The WAAS GEO satellite broadcasts the differential and ionospheric corrections as well as GPS satellite heath back down to the aviation users. The avionic equipment applies the WAAS corrections to increase the accuracy of its GPS position solution. WAAS provides another service called GEO Ranging. The three WAAS GEO satellites provide a ranging signal that functions like a GPS signal. These additional ranging sources help fill in the usable satellite constellation and also provides better satellite geometry. This increases the availability of using space based navigation services because the GPS constellation has now been augmented with three additional satellites. If a GPS satellite is taken out of service the three FAA GEO ranging satellites will help fill in the constellation. The geometry of the satellite constellation has values associated with it called the dilution of precision. The more dispersed the constellation the better its dilution of precision. The more tightly grouped the satellite constellation is the worse the dilution of precision. The better dilution of precision value the better the position solution will be.

[Link: Dilution of Precision][5]

Operation and Maintenance System

The WAAS system has two operation and maintenance systems located in Warrenton, VA and the other in San Diego, CA. This is where the WAAS operators monitor and control the WAAS system.

2.3.8 Where is WAAS used?

WAAS currently uses three geosynchronous satellites with a footprint that covers the entire Western Hemisphere. Coverage over the northern slope of Alaska is particularly valuable to the FAA due to Alaska having many general aviation users that utilize WAAS. As of May 24, 2018, there are 3,909 WAAS Localizer Performance with Vertical guidance (LPV) approach procedures serving 1,900 airports. 1,138 of these airports are Non-ILS airports. Currently, there are also 661 Localizer Performance (LP) approach procedures in the U.S. serving 495 airports.

[Link: Satellite Navigation - GPS/WAAS Approaches][6]

2.4 Items to look into:

One significant improvement WAAS provides is the elimination of errors for hot and cold temperatures that previously affected baro type vertical navigation systems. WAAS equipped receivers will automatically notify the pilot of the most accurate level of service provided for that given receiver, signal, and approach.

One significant difference between satellite based navigation as opposed to ground based is that distances: Are given Along Track Distance (ATD) during the final approach segment.

One primary difference between an RNAV approach with GPS and WAAS is at the missed approach point GPS suspends while WAAS sequences to the missed approach procedure.

The FAA will seldom, if ever, install a new ILS, opting instead for PBN landing procedures, which save money. Further costs saving are gained by reducing the existing ground-based navigation infrastructure, which remains as a backup in case of disrupted satellite service. [1]: https://www.faa.gov/nextgen/faqs/ [2]: https://www.faa.gov/nextgen/snapshots/stories/?slide=5 [3]: http://www.trimble.com/gps_tutor timing2.aspx [4]: https://gis.stackexchange.com/questions/40660/trilateration-algorithm-for-n-amount-of-points/40678#40678 [5]: https://en.wikipedia.org/wiki/Dilution_of_precision_(na [6]: https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navserv

https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/nav

Q. Is the basic GPS signal sufficient to meet all the needs of civil aviation?

A. This is not a simple yes/no answer. The answer is that it depends on the service requirements of each user or aviation authority. For many countries, GPS supplies a better capability than the existing ground-based systems or lack thereof. Yet for other countries with large infrastructures, the GPS signal does not meet the accuracy, integrity, availability, and continuity requirements critical to safety of flight. Enhancements to the GPS such as WAAS and Ground Based Augmentation System (GBAS) provide the necessary corrections for meeting safety-of-life flight requirements.

This is my line.

LAAS was initiated by the FAA to provide an accurate real time differential GPS solution . The LAAS concept follows that of WAAS, but the reference receivers are generally located within the airport environment as can be seen in Figure 2.5. Further, the differential GPS corrections are only usable within the VDB broadcast range, which is about 20 to 30 miles. By limiting the operating region LAAS is able to deliver accuracy under 1 meter in both the horizontal and vertical axis[2]. A further benefit is that LAAS is only dependent on the GPS fleet; therefore it can be used anywhere in the world. The FAA formalized the interfaces and many of the algorithms that should be used in a LAAS Ground Facility (LGF). Components of a software architecture for a LAAS will be examined in the remainder

Table 2.1: WAAS Sites

City	ICAO airport code	Antenna 1	Antenna 2	Antenna 3
Bethel, Alaska	PABE	60.787916486N 161.841724416W, 52.203 m	60.787897064N 161.841663857W, 52.204 m	60.787881127N 161.841728605W, 52.198 m
Billings, Montana	KBIL	45.803707088N 108.539722283W, 1112.261 m	45.803716383N 108.539780649W, 1112.266 m	45.803756811N 108.539680968W, 1112.255 m
Barrow, Alaska	PABR	71.282765883N 156.789923397W, 15.577 m	71.282798595N 156.789965306W, 15.589 m	71.282793925N 156.789856228W, 15.577 m
Cold Bay, Alaska	PACD	55.200334771N 162.718472052W, 53.648 m	55.200394330N 162.718489390W, 53.652 m	55.200400493N 162.718623936W, 53.657 m
Fairbanks, Alaska	PAFA	64.809630987N 147.847339789W, 149.891 m	64.809681435N 147.847491409W, 149.897 m	64.809748030N 147.847379206W, 149.876 m
Honolulu, Hawaii	PHNL	21.312988930N 157.920824884W, 24.678 m	21.312645960N 157.920980760W, 25.022 m	21.312714586N 157.920825156W, 25.067 m
Juneau, Alaska	PAJN	58.362575024N 134.585705943W, 16.024 m	58.362469451N 134.585487326W, 16.029 m	58.362545895N 134.585292259W, 16.020 m
Mrida, Yucatn	MMMD	20.931909130N 089.662840352W, 29.133 m	20.931901399N 089.662887739W, 29.171 m	20.931946482N 089.662890840W, 29.168 m
Mexico City	MMMX	19.431653203N 099.068389471W, 2236.638 m	19.431676477N 099.068348099W, 2236.625 m	19.431629899N 099.068430820W, 2236.652 m
Puerto Vallarta, Jalisco	MMPR	20.679003359N 105.249202871W, 10.973 m	20.679041461N 105.249177972W, 11.269 m	20.679059454N 105.249221363W, 10.990 m
San Jos del Cabo, Baja California Sur	MMSD	23.160445938N 109.717646195W, 104.297 m	23.160383141N 109.717652895W, 104.285 m	23.160419201N 109.717704568W, 104.277 m
Tapachula, Chiapas	MMTP	14.791366074N 092.367999089W, 54.962 m	14.791334042N 092.367965119W, 54.950 m	14.791319966N 092.368009440W, 54.855 m
Kotzebue, Alaska	PAOT	66.887333160N 162.611372024W, 10.911 m	66.887368005N 162.611390215W, 10.909 m	66.887356742N 162.611304386W, 10.913 m
Iqaluit, Nunavut	CYFB	63.731490169N 068.543181586W, 10.022 m	63.731464001N 068.543402553W, 9.957 m	63.731386362N 068.543596671W, 10.014 m
Gander, Newfoundland and Labrador	CYQX	48.966489496N 054.597631164W, 146.888 m	48.966447606N 054.597532034W, 146.887 m	48.966406383N 054.597433025W, 146.899 m
Winnipeg, Manitoba	CYWG	49.900574663N 097.259396222W, 222.042 m	49.900677586N 097.259217224W, 222.051 m	49.900568446N 097.259226893W, 222.045 m
Goose Bay, Newfoundland and Labrador	CYYR	53.308646665N 060.419467188W, 37.830 m	53.308713007N 060.419365697W, 37.844 m	53.308803193N 060.419371104W, 37.853 m
Albuquerque, New Mexico	KZAB	35.173575457N 106.567349162W, 1620.117 m	35.173574799N 106.567287780W, 1620.181 m	35.173532365N 106.567287878W, 1620.164 m
Anchorage, Alaska	PAZA	61.229202467N 149.780248917W, 80.660 m	61.229118812N 149.780422686W, 80.653 m	61.229202391N 149.780423003W, 80.648 m
Aurora, Illinois	KZAU	41.782657876N 088.331335953W, 195.918 m	41.782595526N 088.331334442W, 195.921 m	41.782596464N 088.331253756W, 195.926 m
Nashua, New Hampshire	KZBW	42.735720140N 071.480425027W, 39.125 m	42.735724128N 071.480358015W, 39.151 m	42.735671312N 071.480352294W, 39.147 m
Leesburg, Virginia	KZDC	39.101595603N 077.542745736W, 80.084 m	39.101523590N 077.542730286W, 80.080 m	39.101548982N 077.542774296W, 80.092 m
Longmont, Colorado	KZDV	40.187303318N 105.127223496W, 1541.399 m	40.187303552N 105.127154188W, 1541.391 m	40.187253096N 105.127167214W, 1541.377 m
Fort Worth, Texas	KZFW	32.830649739N 097.066471191W, 155.617 m	32.830596303N 097.066523654W, 155.576 m	32.830598335N 097.066470282W, 155.620 m
Houston, Texas	KZHU	29.961896297N 095.331425748W, 10.908 m	29.961831785N 095.331449752W, 10.974 m	29.961773563N 095.331512004W, 10.958 m
Hilliard, Florida	KZJX	30.698859379N 081.908184568W, 2.149 m	30.698823791N 081.908152480W, 2.140 m	30.698791217N 081.908198025W, 2.135 m
Olathe, Kansas	KZKC	38.880159315N 094.790833106W, 305.904 m	38.880160009N 094.790643592W, 305.903 m	38.880101810N 094.790710614W, 305.636 m
Palmdale, California	KZLA	34.603517830N 118.083893947W, 763.521 m	34.603517881N 118.083828796W, 763.520 m	34.603473855N 118.083893956W, 763.598 m
Salt Lake City, Utah	KZLC	40.786043564N 111.952176782W, 1287.421 m	40.785990178N 111.952176149W, 1287.416 m	40.785990067N 111.952122320W, 1287.423 m
Miami, Florida	KZMA	25.824611968N 080.319189364W, -7.579 m	25.824659706N 080.319315758W, -8.207 m	25.824661752N 080.319234381W, -7.861 m
Memphis, Tennessee	KZME	35.067394005N 089.955369299W, 68.609 m	35.067437537N 089.955368937W, 68.883 m	35.067439374N 089.955436864W, 68.871 m
Farmington, Minnesota	KZMP	44.637463181N 093.152084552W, 262.679 m	44.637463059N 093.152011267W, 262.693 m	44.637407004N 093.152022108W, 262.628 m
Ronkonkoma, New York	KZNY	40.784328238N 073.097164869W, 6.457 m	40.784275495N 073.097154931W, 5.930 m	40.784275925N 073.097223653W, 5.936 m
Fremont, California	KZOA	37.543053122N 122.015945899W, -3.497 m	37.543025498N 122.015892540W, -3.481 m	37.542981164N 122.015929270W, -3.400 m
Oberlin, Ohio	KZOB	41.297154278N 082.206443927W, 223.689 m	41.297166589N 082.206351733W, 225.187 m	41.297086827N 082.206379312W, 223.468 m
Auburn, Washington	KZSE	47.286993478N 122.188372098W, 82.112 m	47.286907917N 122.188382169W, 82.168 m	47.286856213N 122.188363949W, 82.105 m
San Juan, Puerto Rico	TJZS	18.431335686N 065.993476761W, -28.062 m	18.431218583N 065.993514086W, -28.047 m	18.431198889N 065.993448100W, -28.108 m
Hampton, Georgia	KZTL	33.379688402N 084.296725378W, 261.138 m	33.379691546N 084.296656313W, 261.126 m	33.379634831N 084.296652682W, 261.161 m

of this dissertation, including the host architecture, message formats, and message broadcasting.

Chapter 3

Methodology

3.1 Solution Stack

Reproducibility is one of the main principles of the scientific method and within the FAA having tools and processes that can reliably reproduce results is paramount for a safety of life application. In this section the solution stack will be introduced. And from the ground up the applications selected and process implemented are to ensure results can be reproduced by those that have access to the data store.

A solution stack or software stack is a set of software subsystems or components needed to create a complete platform such that no additional software is needed to support applications. Applications are said to ”run on” or ”run on top of” the resulting platform.

This section covers the following components of the solution stack: virtualization platform, operating system, orchestration, web server, databases, programming language and analytics environment. Further effort is required for a few remaining components of the final solution stack, mostly needed for scaling. The remaining components are orchestration, job scheduling, workload management and horizontal scaling.

3.1.1 Virtualization

Server scaling can come in two varieties: horizontal and vertical. Horizontal scaling is adding more server nodes to an application to handle the additional workload demand, while vertical scaling or scaling up is to add more resources to one node. This solution stack uses virtual machines to scale horizontally; to handle an increase in workload, as well as provide high availability, additional virtual machines can be provisioned and when the demand subsides the virtual machines can be deallocated. The use of virtual machines can streamline development since they can repeatedly be created and destroyed to test out configurations.

Vagrant with VirtualBox Provider

The first component of the solution stack is *Vagrant*. Its primary use is to create and configure virtual development environments. It also helps manage those virtual environments with a few very simple commands. The advantage of using this product is that is can be used by anyone on any platform that Vagrant supports to bring up an identical working environment. Through a Vagrant configuration file it can even constrain the virtual image to a specific version or versions of a image. It also has the capability to automatically install all the additional required applications in the solution stack so that when the system boots up the first time all required software has been installed and configurations have been completed.

This solution stack currently uses Oracle VirtualBox, but it is compatible with other virtualization software like VMware and KVM. The final virtual machines will run on VMWare in a blade cluster.

Vagrant Lifecycle Management

Command: vagrant init [box-name] [box-url]

By default Vagrant will use the containing directory of the Vagrant initialization file, called Vagrantfile, for the virtual machine name. To get started with Vagrant, first create a new directory and change into that directory.

```
mkdir WAASAnalyticsPlatform && cd WAASAnalyticsPlatform
```

The following commands initialize the current directory to be a Vagrant environment by creating the initial Vagrantfile. The Vagrant virtual image is known as a box. If a first argument is given, it configure the Vagrantfile for that type of box.

```
# Example: Create an Ubuntu 14.04 virtual machine.
vagrant init ubuntu/trusty64
# Example: Create a CoreOS virtual machine.
# Exit the WAASAnalyticsPlatform folder
cd ..
# Checkout a CoreOS Vagrantfile from github.
git clone https://github.com/coreos/coreos-vagrant/
# This will create a coreos-vagrant directory in the
# current directory. Rename this directory to the name
# that the virtual machine will be known as.
mv coreos-vagrant CoreOS-Node01
```

Note: Unless otherwise stated the following commands must be ran in the folder containing the Vagrantfile and the command will apply to that environment.

Command: vagrant up

This command creates and configures guest machines according to your Vagrantfile.

This is the single most important command in Vagrant, since it is how any Vagrant machine is created. Anyone using Vagrant must use this command on a day-to-day basis.

Command: vagrant halt

This command shuts down the running machine Vagrant is managing.

Vagrant will first attempt to gracefully shut down the machine by running the guest OS shutdown mechanism. If this fails, or if the --force flag is specified, Vagrant will effectively just shut off power to the machine.

Command: vagrant ssh

This will SSH into a running Vagrant machine and give you access to a shell.

If a -- (two hyphens) are found on the command line, any arguments after this are passed directly into the ssh executable. This allows you to pass any arbitrary commands to do things such as reverse tunneling down into the ssh program.

Command: vagrant status

This will tell you the state of the machines Vagrant is managing.

It is quite easy, especially once you get comfortable with Vagrant, to forget whether your Vagrant machine is running, suspended, not created, etc. This command tells you the state of the underlying guest machine.

Command: vagrant destroy

This command stops the running machine Vagrant is managing and destroys all resources that were created during the machine creation process. After running this command, your computer should be left at a clean state, as if you never created the guest machine in the first place.

Command: vagrant global-status and Using IDs

To interact with any of the machines, you can go to the directory with the Vagrantfile and run any of the preceding vagrant commands. Vagrant also provides a way to interact with the virtual machines without having to change into the directory. The global-status is the command that lists information and status about all known Vagrant environments on the host machine. The first column is the ID for the machine and the preceding commands all take an ID as an ending argument.

```
vagrant global-status
id       name    provider   state    directory
--------------------------------------------------------------------------------
26d0e63  default virtualbox poweroff /home/csherrell/Vagrant/v-Ubuntu-14.04-Bootstrap
d6e2bc0  default virtualbox poweroff /home/csherrell/Vagrant/v-Ubuntu-14.04-Rabbit-02
fc44416  default virtualbox poweroff /home/csherrell/Vagrant/v-Ubuntu-14.04-Rabbit-01
77c195d  default virtualbox poweroff /home/csherrell/Vagrant/v-Ubuntu-14.04-Rabbit-Cassandra-01
```

This shows that all the virtual machines are off. To start the first virtual machines run the following command.

```
vagrant up 26d0e63
...
vagrant global-status
id        name     provider    state     directory
-------------------------------------------------------------------------------------------
26d0e63  default  virtualbox  running   /home/csherrell/Vagrant/v-Ubuntu-14.04-Bootstrap
d6e2bc0  default  virtualbox  poweroff  /home/csherrell/Vagrant/v-Ubuntu-14.04-Rabbit-02
fc44416  default  virtualbox  poweroff  /home/csherrell/Vagrant/v-Ubuntu-14.04-Rabbit-01
77c195d  default  virtualbox  poweroff  /home/csherrell/Vagrant/v-Ubuntu-14.04-Rabbit-Cassandra-01
```

To start the remaining virutal machines run the following command.

```
vagrant up d6e2bc0 fc44416 77c195d
...
vagrant global-status
id        name     provider    state    directory
-------------------------------------------------------------------------------------------
26d0e63  default  virtualbox  running  /home/csherrell/Vagrant/v-Ubuntu-14.04-Bootstrap
d6e2bc0  default  virtualbox  running  /home/csherrell/Vagrant/v-Ubuntu-14.04-Rabbit-02
fc44416  default  virtualbox  running  /home/csherrell/Vagrant/v-Ubuntu-14.04-Rabbit-01
77c195d  default  virtualbox  running  /home/csherrell/Vagrant/v-Ubuntu-14.04-Rabbit-Cassandra-01
```

Vagrant Website:

https://www.vagrantup.com/

3.1.2 Software Development

Python 3

Python version 3 is being used for this development effort. The Python programming language guidance is "if you can do exactly what you want with Python 3.x" then you should use it. During a previous phase of development a NovAtel binary message parser was written in Python 2.7 to parse log messages. This plus some other support software written in Python 2.7 was converted to version 3. The new parsing code is completely object oriented and the new classes for handling NovAtel messages where all written in Python 3 and there were no major issues. The only issue that has reoccurred was in integrating the message parsing functionality developed in Python 2.7 into the new classes. Python 3 strings are Unicode by default and now there is clean Unicode/bytes separation. For the average use case this has little to no affect, but when the purpose of the application is to read in a binary data stream and manipulate bytes this has a significant impact. In Python 2.7 strings and bytearray objects could be use interchangeably. Under Python 3 this is no longer the case. Python 3 will throw a run time exception if a string is cast to a bytearray or vica versa. In Python 3 to convert bytes or bytearray objects to ASCII strings the decode method must be called.

```
# Hello World! in Hex
input_buffer = bytearray.fromhex('48656c6c6f20576f726c6421')
ascii_string = 'Test: '
# Append the bytearray to the string
ascii_string += input_buffer[0:]

---------------------------------------------------------------------------
TypeError                                 Traceback (most recent call last)
<ipython-input-17-f84d039df76b> in <module>()
----> 1 ascii_string += input_buffer[0:]

TypeError: Can't convert 'bytearray' object to str implicitly

# Using the bytearray.decode() method
ascii_string += input_buffer[0:].decode('ascii')
print(ascii_string)
Test: Hello World!
```

This analysis platform uses a producer/consumer architecture. To publish data to a queuing middleware used by the downstream consumers the data must first be serialized. Serialization is the conversion of data structures to a steam of bits to be saved to disk or transported across a communication medium. Under Python 2.7 there is a built-in Python module called pickle that is used for serialization but it was not well optimized, so the msgpack module was use for initial testing. As more involved testing was performed it was discovered that the msgpack module could not serialize all the data elements. Luckily this happened about the same time as the transition to Python 3. The msgpack module has deficiencies and further it has not yet been ported to Python 3. Under Python 2.7 there was an optimized C implementation of the pickle module and under Python 3 the built-in pickle module is the C optimized implementation, so msgpack was dropped all together and pickle was used as the serialization service throughout the software.

Python Website:

https://www.python.org

https://wiki.python.org/moin/Python2orPython3

Messaging / Middleware

Middleware is the software that connects software components or enterprise applications. Middleware is the software layer that lies between the operating system and the applications on each side of a distributed computer network. Typically, it supports complex, distributed business software applications.

This analysis platform uses a distributed producer consumer architecture. Currently this is built upon the RabbitMQ middleware, but the decoupled software architecture will allow for one middleware to be swapped for another or have the ability to use multiple at once. ZeroMQ is another middleware that will be evaluated in the future as other entities in the FAA use it.

RabbitMQ

RabbitMQ is an implementation of the Advanced Message Queuing Protocol (AMQP). AMQP was designed by JPMorgan Chase and is used extensively in the financial industry. Multiple implementation of AMQP have been created, but RabbitMQ is one of the more prestigious implementation. It is used throughout the VMware product line and also used in OpenStack for messaging. It supports several different type of exchanges: Direct, Fanout, Topic, and Headers; and can support persistent queues. The Python library that supports the interaction with RabbitMQ service is called Pika and will be covered later.

ZeroMQ

ZeroMQ is a high-performance asynchronous messaging library, aimed at use in distributed or concurrent applications. It provides a message queue, but unlike message-oriented middleware, like RabbitMQ, ZeroMQ can run without a dedicated message broker. This product will be evaluated in the future and could augment the messaging capabilities in this application. The Satellite Operation Group (SOG) in the FAA use ZeroMQ so some functionality may be required to be able to store and access data in their database.

3.1.3 Databases and Storage Formats

Several databases and storage formats have already been and will be evaluated during this research effort. Databases serve a couple of different purposes. First and foremost they store and retrieve data. The advantage a database has over comma separated American Standard Code for Information Interchange (ASCII) files is that the data comes in as binary and is stored as binary there by avoiding precision being lost when floating point values are converted to ASCII. Another advantage is that databases are useful for performing data analysis. In the past databases were used primarily to do On Line Transaction Processing (OLTP), basically data entry and retrieval transaction processing and run some standard reports. Today new databases support On Line Analytical Processing (OLAP) which provides the capability for complex calculations, trend analysis, and sophisticated data modeling. This application like many modern applications will use polyglot persistence that is to say it will use the best persistence mechanism for the application's needs and that will probably utilize multiple types of storage engines. Beyond the ability to store and analyze data is the requirement to share data. Doing an analysis is one thing, but due to the integrity requirements of a safety of life system other organizations will be evaluating the results, so the input data, final solution and possibly some intermediate values should be save in such a way as to be able to hand over for independent evaluation.

Graphite's Whisper Database

Whisper is a file-based time-series database format for Graphite. Graphite is a web analytics application for time-series data. The upside is that it has good community support and designed specificity for time-series data which is the bulk of the data being used in this research. The downside is that it only support one second resolution. This is acceptable for all the acwaas data that will initially be evaluated. A more advanced time series database may need to be assessed as additional sensors are incorporated that operate faster than 1Hz. Some of the temperature sensors and accelerometers that are currently being evaluated operate at 50Hz.

Graphite Website:

http://graphite.readthedocs.org/en/latest/

https://github.com/graphite-project/whisper

Proofread Completed

PostgreSQL

PostgreSQL is a relational database. Relational databases are probably the most widespread of all database types, but their problem is that they are normally ran on one server and do not scale horizontally, but vertically. Typically this leads to a single point of failure, but there are some system administration paradigms that can support high availability. Also, there is significant overhead for indexing large datasets. Because of there use in data warehousing many of these issues do have solutions or workarounds. Relational databases have been the standard for well over 40 years, so they have there place. This application stack will use a relations database to store small datasets and will be used extensively to development models.

SQLite

SQLite is an in-process library that implements a self-contained, serverless, zero-configuration, transactional relational database engine. The code for SQLite is in the public domain and is thus free for use for any purpose, commercial or private.

SQLite is the most widely deployed database in the world. The data is contained in a single file so this would be a solution for sharing data amongst the various people wanting to use the data.

HDF5

Hierarchical Data Format (HDF) version 5 is not a database but a unique technology suite that makes possible the management of extremely large and complex data collections. The HDF5 technology suite includes: A versatile data model that can represent very complex data objects and a wide variety of metadata. The data is structured and remains in a binary format. Matlab uses this a the base format for its MAT-File starting in R2006b. This file format is designed for very large datasets and since the dataset will be contained in one file it is being strongly considered as the format for sharing data with other organizations.

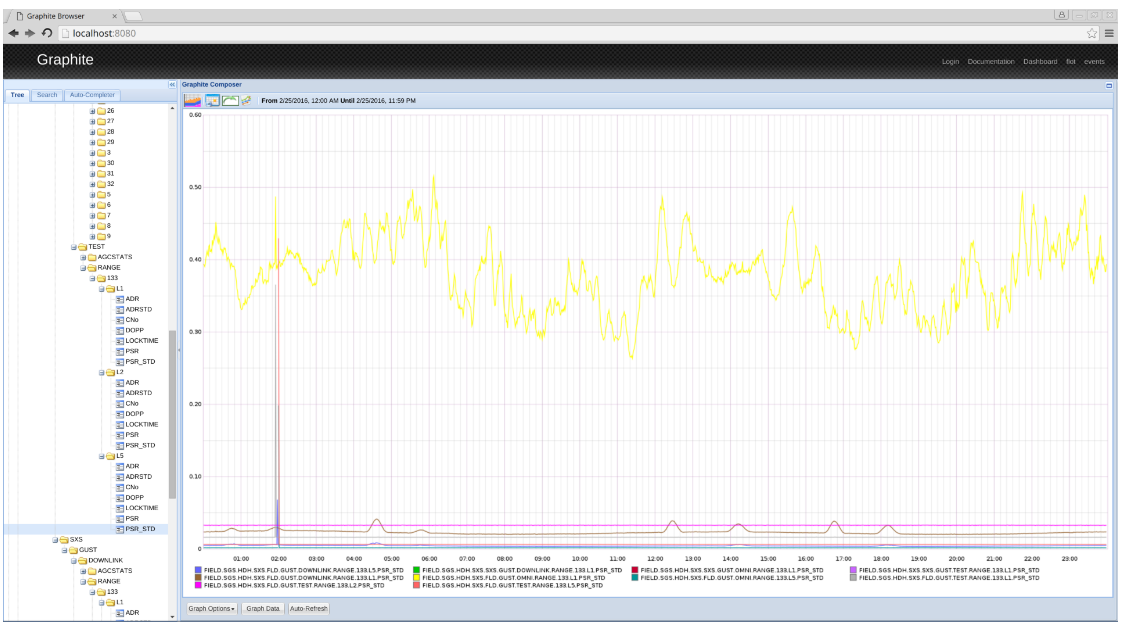
Cassandra

Cassandra is a distributed database produces by Apache designed to handle large amounts of data across many server nodes. It is a big data database.

Chapter 4

Results and Discussion

Currently the graphite database contains 1213 data element. In the plot below each data element is the leaf in the directory tree represented by a file icon. This plot for one the psuedorange and standard deviation from the GPS receiver. Each data element contains a data point for each second of the day, 86400 points. This is just a first cut at getting data loaded into the system, but the design will support many data elements and calculations done between elements.



Chapter 5

Summary and Conclusions

There is still a lot I need to get done, but progress is going well. Currently I am having to interleave this into an already overloaded work schedule. I am hoping to take some time off to devote to more writing. I have more done that I have written here, but I just have not had a opportunity to write everything up.

Ideas for future research.

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Appendices

Appendix A

DO-178B

The software levels as defined by DO-178B are:

Level A Software whose anomalous behavior, as shown by the system safety assessment process, would cause or contribute to a failure of system function resulting in a catastrophic failure condition for the aircraft.

Level B Software whose anomalous behaviors, as shown by the system safety assessment process would cause or contribute to a failure of system function resulting in a hazardous/severe-major failure condition for the aircraft.

Level C Software whose anomalous behavior, as shown by the system safety assessment process, would cause or contribute to a failure of system function resulting in a major failure condition for the aircraft.

Level D Software whose anomalous behavior, as shown by the system safety assessment process, would cause or contribute to a failure of system function resulting in a minor failure condition for the aircraft.

Level E Software whose anomalous behavior, as shown by the system safety assessment process, would cause or contribute to a failure of system function with no effect on aircraft operational capability or pilot workload.

Appendix B

Glossary

Reference Receiver (RR) A Reference Receiver is composed of a Helibowl, Dipole, 2 GG12s, and 2 FreeWave Modems.

LAAS Ground Facility (LGF) The LAAS Ground Facility is the facility that equipment needed for LAAS.

LAAS Processing Unit (LPU) The computing platform and software used to produce the LAAS SIS.

Local Area Augmentation System (LAAS) LAAS designates all the components of this particular GBAS system. It includes the Reference Receiver, LAAS Ground Facility, and any other infrastructure requirements.