INTEROPERABILITY OF SATELLITE BASED AUGMENTATION SYSTEMS FOR AIRCRAFT NAVIGATION

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Abstract

The Federal Aviation Administration (FAA) is pioneering a transformation of the national airspace system from its present ground based navigation and landing systems to a satellite based system using the Global Positioning System (GPS). To meet the critical safety-of-life aviation positioning requirements, a Satellite Based Augmentation System (SBAS), the Wide Area Augmentation System (WAAS), is being implemented to support navigation for all phases of flight, including Category I precision approach. The system is designed to be used as a primary means of navigation, capable of meeting the Required Navigation Performance (RNP), and therefore must satisfy the accuracy, integrity, continuity and availability requirements.

In recent years there has been international acceptance of Global Navigation Satellite Systems (GNSS), spurring widespread growth in the independent development of SBASs. Besides the FAA's WAAS, the European Geostationary Navigation Overlay Service System (EGNOS) and the Japan Civil Aviation Bureau's MTSAT-Satellite Augmentation System (MSAS) are also being actively developed. Although all of these SBASs can operate as stand-alone, regional systems, there is increasing interest in linking these SBASs together to reduce costs while improving service coverage.

This research investigated the coverage and availability improvements due to cooperative efforts among regional SBAS networks. The primary goal was to identify the optimal interoperation strategies in terms of performance, complexity and practicality. The core algorithms associated with the most promising concepts were developed and demonstrated. Experimental verification of the most promising concepts was conducted using data collected from a joint international test between the National Satellite Test Bed (NSTB) and the EGNOS System Test Bed (ESTB).

This research clearly shows that a simple switch between SBASs made by the airborne equipment is the most effective choice for achieving the desired interoperability. It yields at least 95% of the availability benefit achievable with a much more expensive optimal solution. Other more complex scenarios generally do not provide greater benefit, and create greater algorithm complexity and typically have significant infrastructure cost increases. Therefore, the airborne switching approach is highly recommended and should be adopted as the interoperability standard.

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Chapter 1

Introduction

Throughout history, the subject of navigation has had both a romantic and scientific background. It has always been of major concern and interest. Although scientific and technological advancements are occurring at an ever-increasing rate to meet new challenges and serve the needs of mankind, navigation remains a curious mixture of ancient and modern techniques. For example, the thousand year old magnetic compass is still in widespread use, yet newcomers, including inertial, computer and satellite techniques, only a few decades old, have revolutionized the modern navigation world.

1.1 Background

Navigation has many facets, many definitions, and many subsets. The answer to the simplest question, "Where am I?" turns out to be one of the most difficult. Science and technology is changing our perception of what is possible, of space and time. It is drawing people closer together by teaching people that we are all global neighbors. As the rules are changing, there is a higher degree of demand for a seamless global navigation system to improve worldwide aviation services. The Global Positioning System (GPS), a satellite-based navigation system, is designed to revolutionize the art and science of navigation.

1.1.1 The Global Position System (GPS)

The Global Positioning System (GPS) was developed by the U.S. Department of Defense (DOD) in the 1970s, and became fully operational in 1995. It includes three segments [PS96]:

- **Space segment**: The operational NAVSTAR GPS consists of a minimum of 24 satellites, as shown in Figure 1.1. They are orbiting in six planes which are equally spaced 60° apart in longitude and inclined to the equator at 55°. Four satellites are deployed in each of the six orbital planes with unequal spacing between satellites in a plane to minimize the impact of a single satellite failure. (As of this writing, there are 28 operational satellites in orbit ensuring a higher degree of system availability.) Each orbit is nearly circular at an altitude of approximately 20,183 km (10,898 nmi), with a period exactly one-half synchronous, or about 12 hours, and a repeating ground track every sidereal day.

- **Control Segment**: Five ground monitoring stations are used to perform tracking and monitoring functions needed to determine the satellite ephemerides and clock offsets, upload navigation messages and monitor the health of the satellites in the system.

- **User Segment**: The current user segment includes a broad spectrum of applications ranging from surveying to land vehicle, aircraft navigation and spaceborne applications.

Signal Structure These satellites emit special radio signals that allow the user equipment to determine their location in three dimensions. All GPS satellites transmit on the same frequencies, including the L_1 signal centered at a frequency of 1575.42 MHz and the L_2 at 1227.60 MHz [Cor93].

The L_1 signal is modulated by two Pseudo Random Noise (PRN) codes, a 10.23 MHz clock rate Precision (P/Y) code and a 1.023 MHz clock rate Coarse/Acquisition (C/A) code. The C/A code is a repeating 1 MHz PRN code. This noise-like code

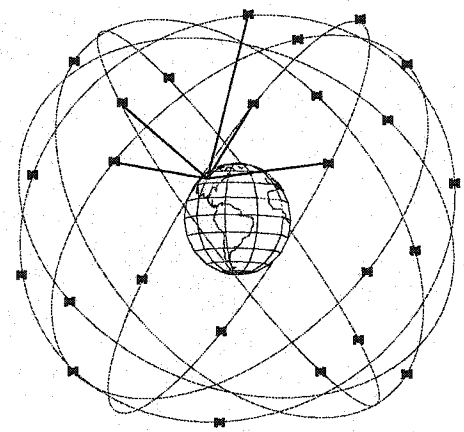

Figure 1.1: The Global Positioning System (GPS) space segment 24 satellite constellation.

modulates the L_1 carrier signal, "spreading" the spectrum over a 1 MHz bandwidth. The C/A code repeats every 1023 bits (one millisecond). There is a different C/A code PRN for each space vehicle (SV). GPS satellites are often identified by their PRN number, the unique identifier for each pseudo-random-noise code. The C/A code that modulates the L_1 carrier is the basis for civil applications.

The P-Code (Precise) modulates both the L_1 and L_2 carrier phases. The P-Code is a very long (seven days) 10 MHz PRN code. In the Anti-Spoofing (AS) mode of operation, the P-Code is encrypted into the Y-Code. The encrypted Y-Code requires a classified AS Module and is for use only by authorized users with cryptographic keys. The P (Y)-Code is the basis for military services.

The navigation message also modulates both C/A and Precise codes, as shown in Figure 1.2. The Navigation Message is a 50 Hz signal consisting of data bits that describe the GPS satellite orbits, clock corrections, and other system parameters.

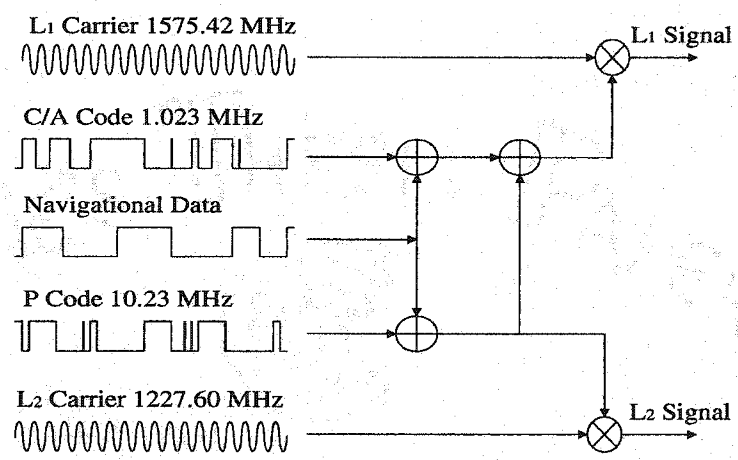

Figure 1.2: GPS Signal Structure

L_1 carrier cycles have a wavelength of 19 centimeters. If tracked and measured, these carrier signals can provide ranging measurements with relative accuracies of millimeters. Tracking carrier phase signals provides no time of transmission information. The carrier signals, while modulated with time-tagged binary codes, do not carry time-tags that distinguish one cycle from another. Though carrier-phase tracking of GPS signals has resulted in a revolution in surveying and many other high precision applications, real-time systems have rarely used carrier-phase navigation because of this ambiguity problem.

Standard GPS Positioning Services (SPS) The standard GPS positioning services (SPS) [DOD95] [Cor93] which are available to the general public free of charge, were originally intentionally distorted by the Pentagon to degrade accuracy. The degradation, called Selective Availability (SA), was implemented by using artificial clock dithering. With SA active, the SPS can pinpoint a position globally to within 150 meters vertically and 100 meters horizontally, or about the length of a football field. Without SA, the system is able to pinpoint a position to within an error the size of a basketball court. For many applications, such accuracy is sufficient. For aircraft navigation, the required navigation performance is much more stringent for certain phases of flight. To meet these more stringent requirements, "differential GPS" correction signals must be employed.

As of this writing, the US government has already authorized civil and commercial use of the SPS without SA. The decision was announced on, May 1, 2000 and went into effect that night. This means a five- to tenfold increase in the accuracy of satellite-based navigation systems used by consumers ranging from commercial truckers and shippers to fishermen, hikers, surveyors and emergency-response systems, as well as various location-based services.

Unfortunately, during the course of this research, GPS SA errors have been the dominant error source and a major concern in the satellite-based augmentation system for navigation. Therefore, in the following documentation, SA errors will still be included as a large part of the discussion.

1.1.2 Required Navigation Performance

No general treatment of the Global Navigation System would be complete without a discussion of the accuracy, integrity, continuity and availability of systems, or the so-called *Required Navigation Performance* (RNP). We define these four parameters as follows:

- **Accuracy** is a measure of the difference between estimated and true position. It is usually defined as the 95th percentile of navigation error.

- **Integrity** is the ability of a system to provide timely warnings to users or to shut itself down when it should not be used for navigation. The integrity requirement is expressed in terms of three parameters shown in Table 1.1: a maximum time-to-alert, a position error alert limit and a probability of Hazardously Misleading Information (HMI). If the true position error is larger than the alert limit and the system was deemed available, the result is hazardous, because the user had no knowledge of the excessive true error. This situation is called Hazardously

Operation	Accuracy (95%)	Integrity			Continuity (Loss of Navigation)	Availability
		Time-to-Alert	Alert Limit	Probability of HMI		
En-route	H 2.0 nmi	5 min	H 4 nmi	10^{-7}/hr	10^{-6}/hr	0.99-0.99999
Terminal	H 0.4 nmi	15 s	H 1 nmi	10^{-7}/hr	10^{-6}/hr	0.99-0.99999
LNAV (NPA)	H 220 m	10 s	H 0.3 nmi	10^{-7}/hr	10^{-5}/hr	0.99-0.99999
LNAV/VNAV (NPV-I)	H 220 m V 20 m	10 s	H 0.3 nmi V 50 m	2×10^{-7}/ approach	5×10^{-5}/ approach	0.99-0.99999
GLS (PA Cat I)	H 16 m V 7.6 m	6 s	H 40 m V 12 m	2×10^{-7}/ approach	5×10^{-5}/ approach	0.99-0.99999

Table 1.1: National Airspace System (NAS) Required Navigation Performance (RNP) for different phases of flight. Major flight operation modes include En-Route, Terminal, Lateral Navigation (LNAV) or Non-Precision Approach (NPA), Lateral/Vertical Navigation (LNAV/VNAV) or Non-Precision Approach with Vertical Guidance (NPV-I), as well as Global Navigation Satellite System Landing System (GLS) or Precision Approach (PA) Category I.

Misleading Information and should be avoided at all costs. In this case, we refer to it as an integrity breech, or a loss of system integrity.

- **Continuity** is the ability of a system to provide navigation functions over the entire course of a flight operation. Continuity risk is the probability that a procedure will be interrupted by a loss of service.

- **Availability** is the probability that the system provides the navigation solution meeting integrity, and accuracy requirements, and the protection level (an estimated error bound) is below the corresponding alert limit for each phase of flight operation (specified in Table 1.1).

Put together, as a primary means of navigation, the system should be capable of satisfying the RNP, including accuracy, integrity, continuity, and availability. The FAA has developed the terms and standards for instrument approaches grouped under the general category of RNAV (area navigation), as listed in Table 1.1 [CHL+99] [ICA99] [RTC98] [ADM00]. Current RNAV instrument approach standards include:

- **LNAV** (Lateral Navigation) is a non-precision approach (no vertical guidance) with a minimum descent altitude (MDA) of 250 feet above obstacles along the flight path.

- **LNAV/VNAV** (Lateral/Vertical Navigation) is a vertical guided approach with precision-like vertical obstruction clearance and a decision altitude (DA) down to 350 feet above the runway touchdown point (HAT).

- **GLS** (Global Navigation Satellite System Landing System) is a vertically guided ILS look-alike approach with decreasing vertical obstruction clearance and smallest lateral protection. **GLS PA** will have the lowest minimums (HAT 200 feet and 0.5 mile visibility) with precision airport infrastructure requirements met. *PA* indicates the availability of a precision approach runway, which includes approach lights, runway lights, runway markings, parallel taxiways, etc. Without the PA designator, GLS is an ILS look-alike, with higher DA due to limited airport infrastructure.

The *zero-accident* policy announced by the FAA requires airlines to have essentially perfect navigation from takeoff to landing. This demands better and better navigation technology as time goes by. GPS-enabled satellite navigation is a revolutionary solution to achieve this goal. The Federal Aviation Administration (FAA) will use augmented GPS as the primary means of navigation and landing for all phases of flight including Precision Approach (PA). This will improve safety, efficiency, and capacity of the National Airspace System (NAS).

1.1.3 Differential GPS

The satellite signal delays observed by a receiver include errors due to many factors. Some of these are *satellite clock errors, satellite position errors, atmospheric delays (caused mostly by the ionosphere and troposphere), multipath, user receiver noise, and user clock errors.* These effects combine to produce horizontal position errors of approximately 10 meters (1σ). For civilian application, the user also suffers the satellite clock errors from SA which have been artificially introduced at an order of 30 meters (1σ).

Notice that most of the errors listed in the previous paragraph are common to all receivers within hundreds of miles. A GPS receiver fixed at a known location can be used to measure these errors, correct for them, and broadcast the corrections to other nearby receivers. This technique is called differential GPS or DGPS. Using code-phase GPS navigation with differential corrections, mobile receivers can reduce their horizontal position errors to approximately 2.2 meters (1σ) [PS96].

The differential GPS corrections come from another receiver planted at a well-surveyed location on the ground. This receiver continuously computes the difference between its known position and the position determined from the satellites. It then transmits this difference, which will be nearly identical for all nearby receivers, on a radio signal that the user receiver can hear. Then the user receiver can apply the corrections and shrink its error down to the size of a pitcher's mound or smaller.

Ground Based Augmentation System (GBAS)

As its name indicates, the Ground Based Augmentation System (GBAS) will broadcast augmentation signals through terrestrial communication datalinks. The typical ground based augmentation is the Local Area Differential GPS (LADGPS). An example of LADGPS is shown in Figure 1.3. LADGPS is based on a reference station located near the runway broadcasting either scalar corrections or raw measurements to the nearby users through a datalink. The location of the reference station receiver is precisely surveyed. Because the users are close to the reference station, common mode errors can be canceled and better accuracy can be achieved. While LADGPS can effectively augment service quality over a geographically limited area around the reference station, its performance degrades as the user moves away from the reference station.

LADGPS is capable of providing guidance for all three categories of precision landing [Law96] [Per96]. The FAA is developing a LADGPS, called the Local Area Augmentation System (LAAS), for such applications [SMS+96].

Satellite Based Augmentation System (SBAS)

The Satellite Based Augmentation System (SBAS) depends on spaceborne communication datalinks as the transmitters to relay augmentation signals to the user segment. The most important SBASs include the FAA's Wide Area Augmentation

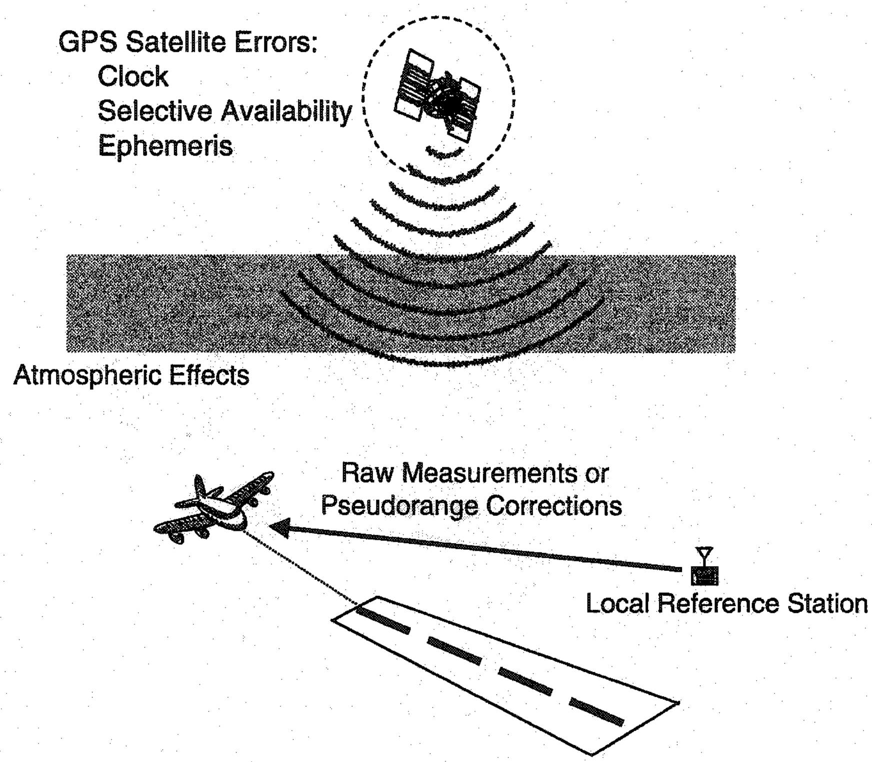

Figure 1.3: An example of the Local Area Differential GPS (LADGPS) concept.

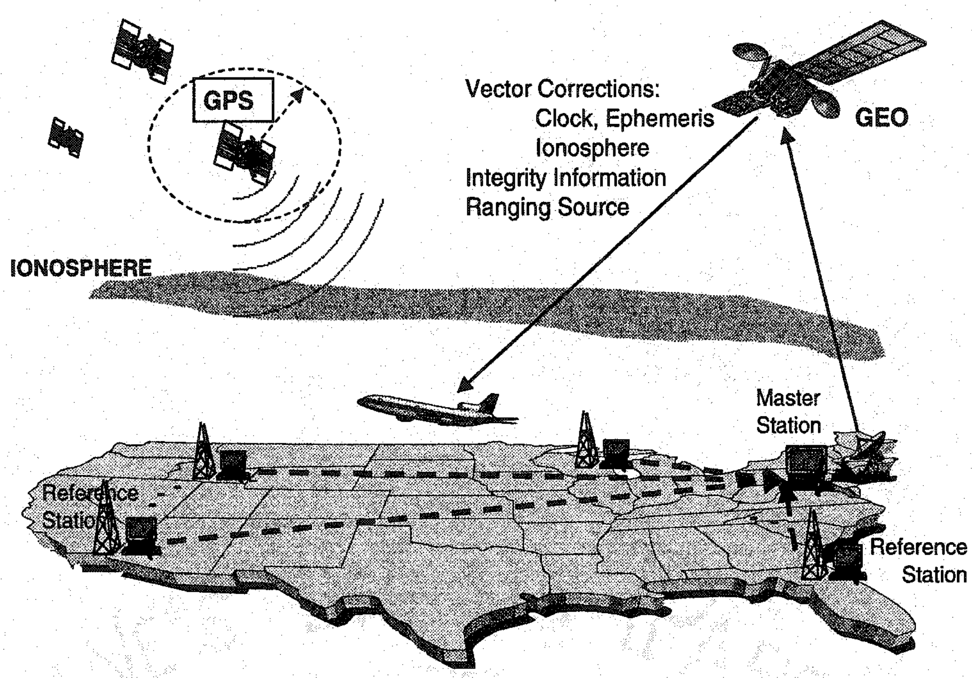

Figure 1.4: An example of the Wide Area Augmentation System (WAAS) concept. The WAAS is a geographically expansive augmentation to the basic GPS service. Similar to the GPS, it contains three segments: *control segment*, *space segment*, and *user segment*.

System (WAAS) and its international counterparts.

WAAS is a geographically expansive augmentation to the basic GPS service. An example is shown in Figure 1.4. Similar to GPS, WAAS also contains three segments: *control segment*, *space segment*, and *user segment*. The *control segment* currently consists of 25 Wide Area Reference Stations (WRS) monitoring the signals coming from the GPS satellites. The measurements from these reference stations are sent to the Wide Area Master Station (WMS) where vector corrections are generated. Vector corrections mainly consist of the satellite ephemeris and clock errors, and a grid of vertical ionospheric delays. Confidence bounds of these corrections and "Use/Do Not Use" messages will also be generated to enhance integrity. These messages are then passed to the *space segment*, including one or more INMARSAT-3 geostationary satellite(s) (GEO), through a Ground Uplink System (GUS) and broadcast on the same frequency as GPS L_1 to user equipment which is within the footprint coverage of the WAAS GEO satellite. The communication satellites also act as additional ranging sources providing further enhancement of service availability. The operational goals of the FAA's WAAS are to provide services for all phases of flight from oceanic to precision Category I landing over the conterminous US (CONUS), and possibly Alaska [EWP$^+$96].

1.2 Motivation

Modern aviation services need increasingly accurate and reliable methods of navigation to compensate for a decreasing tolerance for failures, delays, and costs. As the primary transportation systems that bring people together around the world, seamless global aviation services have become more and more important. The FAA's revolutionary transition from ground based navigation systems to satellite based navigation systems represents great progress in the effort to increase accuracy and reliability. Development of the WAAS has played a huge role in this transition. Other international systems are also striving to reach the goal of seamless global aviation.

Worldwide Development While the FAA was actively developing the Wide Area

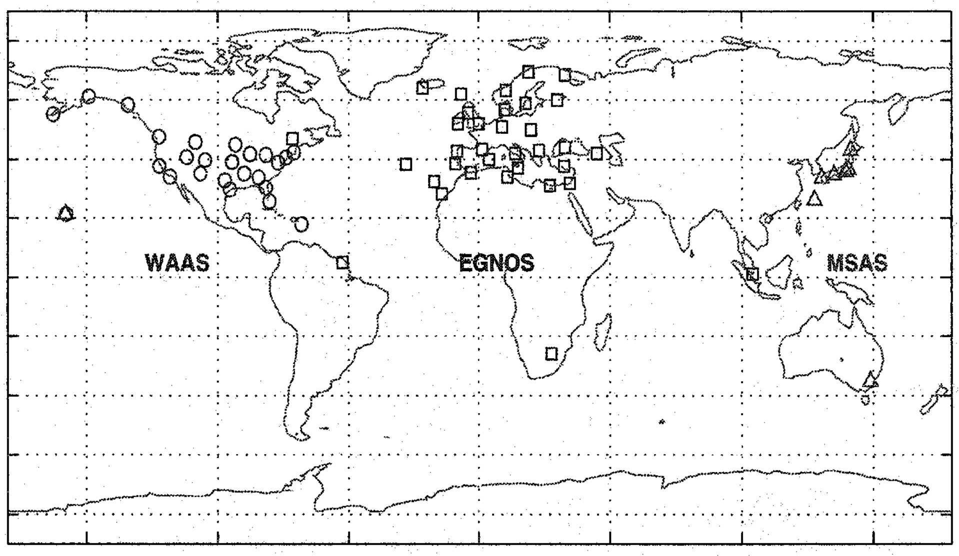

Figure 1.5: SBAS Worldwide Development. The network distribution of WAAS, EGNOS and MSAS. The circles stand for the WAAS reference stations, the squares for the EGNOS stations, and the triangles for the MSAS reference stations.

Augmentation System (WAAS) to enable full coverage over the US [WEA99], other augmentation systems have been independently developed. For example, Europe is developing its own SBAS, the European Geostationary Navigation Overlay System (EGNOS) [BMVT99], and the Japanese Civil Aviation Bureau's MTSAT-Satellite Augmentation System (MSAS) is under development as well [Shi99]. The physical distribution of each SBAS network is shown in Figure 1.5. All of these systems are based on the same concept of using a wide area reference station network to monitor the GPS satellites, generate vector corrections and integrity information, and broadcast information to users through geostationary satellites.

Interoperability Even though each system works well in isolation, there is increasing interest in linking them together to provide seamless global aviation services with reduced costs. This is the point at which interoperability enters the picture. The ultimate goal is to provide each aircraft with one SBAS avionics box such that the desired level of service is achieved anywhere on earth, thus matching the service of the standard GPS system and adding sufficient integrity.

To achieve such a goal, several questions must first be answered: Each individual system works well within its nominal service coverage, but what happens when users fly outside those areas, especially on international and oceanic flights? What kind of benefits can we get by combining signals? What information can be shared among systems and how can the shared information be used to enable those systems to work effectively together?

Answering these questions and developing the optimal interoperability strategies are the primary goals of this dissertation.

1.3 Previous Work

1.3.1 Satellite Based Augmentation System

Although the GPS navigation messages use vector corrections by design, where different error sources are treated separately, the original differential system design focused on scalar correction messages in the pseudo-range domain.

Brown was the first to initiate the comprehensive concept of "Extended Differential GPS" [Bro89], a revolutionary extension of the conventional local area differential GPS concept. A ground reference network was proposed and the corrections were calibrated for each individual error source component. The overall geographical service coverage could be effectively enlarged.

Braff [BS86] initiated a GPS Integrity Channel (GIC) concept, later refined by others [Bro88] [Kal89] [Eng90]. The architecture proposed by Enge [Eng90] uses a global ground reference station network monitoring the signal integrity of GPS satellites and broadcasting integrity flags through the INMARSAT geostationary satellites. The GEO ranging function and the format of the integrity broadcast were also proposed. The relative merits of international versus regional networks were discussed as well.

Kee and Parkinson invented the Wide Area Differential GPS (WADGPS) concept. They developed and demonstrated the concept and feasibility of using a few widespread reference stations to generate vector corrections to the GPS error sources for real time applications [Kee93] [KPA91].

Soon after that, the FAA's Loh and Dorfler proposed the marriage of GIC and WADGPS concepts and came up with the concept of the Wide Area Augmentation System (WAAS) [LWE+95] which became the next major step forward in the civil aviation revolution following the introduction of the GPS system.

Another more recent milestone is the internationalization of the SBAS. International acceptance of GPS in aviation systems has led to a worldwide boom in wide area differential GPS development. This work caused the globalization of the satellite based seamless worldwide aviation services. Following the FAA's WAAS, Canada and Mexico joined the team. Likewise, Europe and Asia are both individually developing their own satellite based augmentation systems. Interoperability related issues therefore inevitably draw more attention.

1.3.2 Interoperability-Related Research

Interoperability-related research is a timely topic and dynamic field. Many people are working toward accomplishing this goal.

The Interoperability Working Group (IWG) has been one of the major players since early 1997. At this time, a group of technical and system managers from each SBAS program office came to the round table and started discussions on interoperability-related issues. Stanford University's WADGPS research group has actively participated in this discussion from the outset and has played an important role throughout.

Fernow initiated the discussions on different meanings that could be ascribed to the term *interoperability*, as well as some analysis of the geostationary satellite service benefit issues [FLHR97].

In early 1998, the IWG defined several major scenarios of interest. Following this, several groups began focusing on the benefit analysis of interoperability and on the spatial degradation of integrity information.

Fuller conducted analysis of the interoperabilty benefits among WAAS, EGNOS and MSAS based on GPS satellite observability [FDW+98]. Ventura reviewed several technical issues from the EGNOS point of view [VTGN+98]. Later, Fernow and Fuller published a joint paper, combining their work, along with the orbital correction spatial degradation analysis [FOH+99].

More recently, research has focused on the implementation-related issues, including the development of algorithms and validation based on real data tests. Nieto conducted tests using EGNOS and MSAS testbed networks and evaluated several associated interoperability algorithms [Nie99b] [Nie99a]. In addition, Kee conducted some tests based on a decentralized WADGPS network in east Asia [KP99].

1.4 Contributions

The primary goal of this research was to deduce and demonstrate an optimal strategy of information sharing among each individual satellite-based augmentation system, e.g., WAAS, EGNOS and MSAS. In the course of this research, it was discovered that a single optimum does not exist. The definition of optimum not only depends on the technical requirements of the overall system, but also relies on multiple external factors, including economic and institutional issues, as well as national security considerations. This dissertation presents several interoperability designs optimized for different conditions. The major interoperability scenarios were tested in a joint international campaign. Results from extensive testing using real data from WAAS and EGNOS prototype systems are presented. In addition, this dissertation describes, as completely as possible, the requirements and tradeoffs which future interoperability activities must consider.

Taken together, these contributions illustrate the strategies, benefits and feasibility of the interoperability of satellite-based augmentation design. The design of each individual SBAS can now achieve systematically the desired level of interoperability and so support a seamless worldwide aviation platform.

The specific contributions of this research are the following:

1. **Interoperability Analysis**

The first systematic analysis framework of SBAS interoperability was developed and demonstrated. It is based on information fusion theory, statistical hypothesis testing theory, and augmented with a service volume model (SVM). The service volume model is a comprehensive tool to characterize the overall quality of SBAS system aviation services. These tools provide a powerful generic, and systematic analysis framework. This framework is the basis of current research of SBAS interoperability-related issues. It also contributes to the research conducted by John Hopkins Applied Physics Laboratory regarding GPS risks for civil aviation applications [CHL+99].

Current research clarifies the meaning and scope of SBAS interoperability, and quantifies the benefits that can be achieved through potential cooperation and coordination activities among SBAS service providers. There are several layers of cooperative efforts, including establishing a common interface standard, providing interoperable system components, and sharing complimentary information. This dissertation focuses on the analysis of information sharing strategies at different levels among SBASs, including space segments, ground control segments, and airborne user segments. This research also identifies the optimal interoperability scenarios for global aviation services.

2. **Interoperability Algorithms**
   Primary issues and implementation factors for major scenarios were identified based on the interoperability analysis. The network common view time transfer (NCVTT) algorithm was created to compensate for the time offset between SBASs. Airborne information fusion algorithms were developed and demonstrated. The developement of these key algorithms enables the feasibility of major interoperability scenarios and leads to their practical solutions.

3. **Interoperability Demonstration**
   The analysis framework and conclusions were clearly demonstrated and verified using live data. The interoperability between WAAS and EGNOS was investigated using real data from each prototype testbed network. The interoperability benefits are demonstrated. Evaluations also focused on justification of the

optimal interoperation strategies in terms of complexity, performance and practicality. Conclusions based on these tests and analyses illustrate a promising future for achievable service levels in the intermediate regions between EGNOS and WAAS.

4. **Signal-In-Space Integrity Analysis**
   Signal-In-Space (SIS) integrity is one of the most challenging issues for SBAS civil aviation applications. This dissertation evaluated SBAS signal-in-space integrity performance, sensitivity, and spatial degradation. Work focused on the integrity and interoperability of the confidence information of SBAS vector corrections, including the User Differential Range Error (UDRE) and the Grid Ionospheric Vertical Error (GIVE).

5. **SBAS Development, Maintainence and Enhancement**
   The Stanford University Wide Area Differential GPS laboratory hosts a master station of the National Satellite Test Bed (NSTB), a prototype system of WAAS. This provides many ideal research opportunities for SBAS system development and interoperability studies. Therefore, this dissertation also emphasizes SBAS development and maintainence, as well as enhancement. Ionospheric monitoring strategies were developed, including optimal use of ionospheric corrections for SBAS single frequency users, and real time ionosphere activity monitoring tools and databases. Meanwhile, several effective multipath monitoring strategies were developed and implemented, including high integrity multipath mitigation techniques for reference stations, as well as real time monitoring, calibration, and analysis tools and databases.

1.5 Outline of Dissertation

This dissertation begins with an overview of SBASs. Chapter 2 describes the WAAS master station data processing algorithms to enable a detailed analysis of interoperability strategies. Integrity issues of the operational SBAS system and design are investigated. A simulation-based probabilistic risk assessment tool augmented with a service volume model analysis for SBAS integrity performance evaluation is used. The SBAS interoperability-related integrity and spatial degradation issues are discussed.

Chapter 3 discusses the definition of SBAS interoperability and identifies various scenarios both vertically and horizontally. The information flows of the major interoperability candidates are analyzed in detail.

Chapter 4 focuses on the interoperability algorithm analysis. The fundamental information fusion theory is introduced. The major interoperability issues are discussed and provided with solution strategies. Major algorithms are discussed for different SBAS interoperability scenarios. The Network Common View Time Transfer (NCVTT) algorithm and its performance are also investigated.

Chapter 5 applies the service volume model analysis to the interoperability benefit evaluation. The analysis framework is introduced and real data results are used to quantify the interoperability benefits.

Chapter 6 primarily describes a joint international test between WAAS and EGNOS prototype systems to characterize interoperability in the real world. The test platform and test results of the major candidate scenarios are discussed in detail. Further investigations of far field and near field interoperability issues also presented here.

Finally, Chapter 7 summarizes the research and also makes several suggestions for future investigations.

Chapter 2

Satellite Based Augmentation System

2.1 Introduction

The FAA's revolutionary transition from ground based navigation systems to satellite based navigation systems represents great progress in the effort to increase accuracy and reliability. The FAA's WAAS is an enormous leap forward in air navigation by providing precision approach guidance to thousands of airports and airstrips where there is no precision landing capability. It is a core element in transitioning to the satellite-based air traffic control (ATC) system of the future. As shown in Figure 2.1, Phase I WAAS uses 25 reference stations, two master stations, two INMARSAT-3 geostationary satellites, and the terrestrial communications network. The INMARSAT-3 geostationary satellites are located over the Pacific Ocean Region (POR, 180° east) and the Atlantic Ocean Region (AOR-W, 55° west). Later phases expect to expand this network to 50 to 70 station locations. WAAS will provide services for all phases of flight from transoceanic to precision Category I landing over the conterminous US (CONUS), and possibly Alaska.

Similar to GPS, WAAS also contains three segments: *control segment*, *space segment*, and *user segment*. The *control segment* currently consists of a ground reference

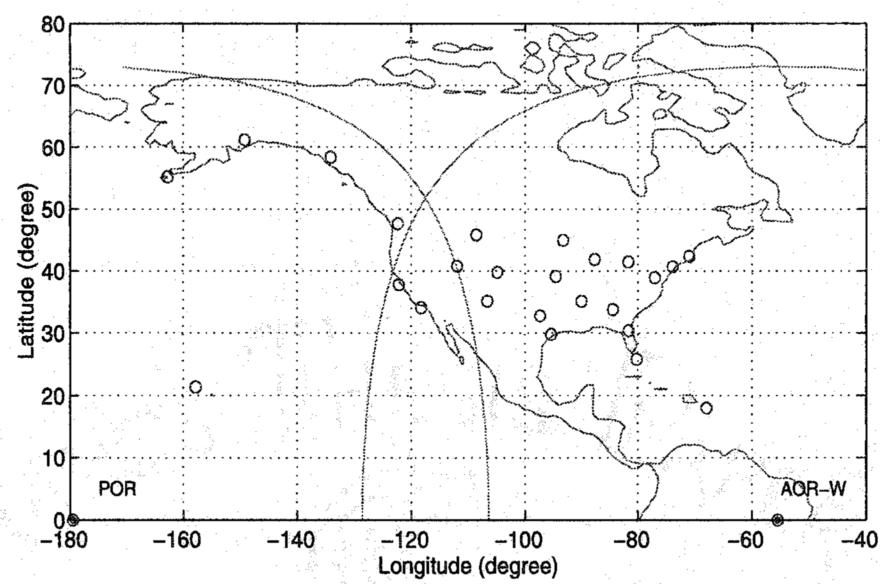

Figure 2.1: Phase I WAAS reference stations and coverage of the POR and AOR-W satellites with an elevation mask angle of 10 degrees.

station network monitoring the signals coming from the GPS satellites. The measurements from these Wide Area Reference Stations (WRS) are sent to the Wide Area Master Station (WMS) where vector corrections and integrity messages are generated. As described in the RTCA MOPS [RTC98], WAAS will provide services including:

(1) *Integrity Messages* contain integrity alerts to flag the failure of navigation satellites; a satellite that should not be used in user navigation solutions will be marked as "Do Not Use." This integrity information improves flight safety.

(2) *Vector Corrections* for the orbit and clock errors of the navigation satellites and the signal delays due to the ionosphere are very important components of SBAS service. The SBAS messages also include the confidence intervals associated with these corrections, such as the User Differential Range Error (UDRE) for clock and orbit correction errors, and the Grid Ionospheric Vertical Error (GIVE) for ionospheric correction errors. With the broadcast of these messages, service accuracy and availability can be improved.

(3) *Ranging Signals* from GEO satellites will enhance the current navigation satellite constellation. The signals will be synchronized to GPS time and will be similar to GPS signals in design. Therefore, these additional ranging sources will be combined with the GPS ranging signals to improve the availability and continuity of service.

Integrity messages and vector corrections are then passed to the space segment, geostationary satellites (GEO), through a Ground Uplink System (GUS) and broadcast on the same frequency as GPS L_1 to user equipment which is within the footprint coverage of the WAAS GEO satellite. The communication satellites also act as additional ranging sources providing further enhancement of service availability [EWP+96].

The US National Satellite Test Bed (NSTB) is a research and development prototype that has been used to demonstrate various technical features of the FAA's WAAS concept. Since 1992, the NSTB initial tests proved the feasibility of the wide area differential GPS concept and led to the development of the current WAAS specifications. The NSTB expanded in 1995 to include 18 reference stations in CONUS, three in Southern Canada, five in Alaska, two in Hawaii and one in Iceland. These reference stations send the data, which include raw GPS range and meteorological measurements, to the FAA Technical Center (FAATC) in real time. Currently, there are three experimental master stations. These master stations receive data through a T1 line via the User Datagram Protocol (UDP). The NSTB also has two uplink stations which are located in Southburry, CT and Santa Paula, CA. The present network of the NSTB provides a complete tool to conduct independent analysis of WAAS algorithms and a host of other related activities. Through the NSTB, the FAA will ensure the success of the WAAS and a future seamless global navigation satellite system (GNSS).

The Stanford University Wide Area Differential GPS laboratory hosts a master station of the NSTB. This provides many research opportunities for SBAS system development in addition to this interoperability study.

2.2 System Overview

2.2.1 Master Station Central Processing Algorithms

The Wide-Area Master Station (WMS) receives and processes the measurements from all of the Wide-Area Reference Stations (WRSs) and generates vector corrections and integrity information [EWP+96]. The WRSs use dual frequency receivers to obtain both code and carrier phase observations at L_1 and L_2 frequencies. Rubidium clocks are used to provide stable frequency standards. Each WRS also has meteorological sensors to measure temperature, pressure and relative humidity information. These measurements are transmitted to the WMS via communication datalinks.

GPS Error Sources

GPS error sources include [PS96] [Kee93]:

- Satellite Clock Error: This is the difference between the time of the actual clock and that of the clock model broadcast by the GPS master control station. It consists of both real residual clock errors and an artificial error implemented by the Department of Defense known as Selective Availability (SA) for security reasons. The error is about 22 meters (1σ) in the range domain, mainly caused by SA [PS96].

- Satellite Ephemeris Error: This is the difference between the actual satellite position and the position predicted by the broadcast ephemeris parameters. This error introduces 3-4 meters in the range domain [ZB96].

- Ionospheric Delay: As the GPS signal travels through the ionosphere, it is refracted by ions. The code phase is delayed and the carrier phase is advanced. The total time delay is proportional to the total electron content (TEC) from the receiver to the satellite. The ionospheric electron distribution is a function of time and location. It is mainly affected by solar magnetic activities and geomagnetic field variations. For a single frequency user, this delay can be corrected to several meters by using the Klobuchar ionospheric model broadcast in the navigation messages [Klo86].

- Tropospheric Delay: This error is caused by the lower atmosphere up to 80km. The error is on the order of 2-25 meters and is a function of local temperature, pressure, and humidity. The tropospheric delay can be reducted to several centimeters by using a standard model [RTC98] [Bla78].

- Multipath Effect: This error is caused by the fact that a signal arrives at a receiver via multiple paths due to reflection and diffraction. Multipath errors can be reduced by using careful siting, a narrow correlator receiver, antenna gain pattern shaping technology, and software-based calibration algorithms [BK85] [Bis94].

- Receiver Clock Error: This is caused by the oscillator used in the receiver. A typical quartz crystal oscillator has a drift rate of $10^{-8} - 10^{-9}$ second per second. A rubidium clock used by a reference station usually drifts on the order of 10^{-12} second per second. Most of the receiver clock error can be eliminated in navigation solutions [PS96].

- Interfrequency Bias (IFB): This error exists inside both GPS satellites and dual frequency receivers. It is due to the different phase shifts between L_1 and L_2 signals in the analog portion of the satellites and receivers. Since interfrequency bias is constant for all the channels, the bias acts like a clock error. IFB affects the WAAS ionospheric delay estimation and is also important for the GPS ephemeris and clock estimation. Calibration can reduce the interfrequency bias [WM93].

- Interchannel Bias: This error is specific to multichannel receivers due to the differences in the hardware of each channel. Calibration can eliminate the interchannel bias [GD86].

- Receiver Noise: This error consists of thermal noise, quantization errors and the residuals of modeling. It can be approximated as white Gaussian noise. The typical receiver noise is on the order of a few meters for code phase measurements and a few millimeters for the carrier phase measurements.

The primary function of an SBAS is to estimate the satellite ephemeris errors, satellite clock offsets, and ionospheric delay parameters for single-frequency users.

Master Station Data Processing

As shown in Figure 2.2, the master station data processing is composed of two layers. First, data collected from each reference station is calibrated and used to generate distributed measurements about the ionosphere and satellite clock and orbit errors. Second, the distributed ionosphere measurements are used for grid ionospheric delay estimation, while the pseudorange residuals are used to generate clock and orbit location errors of navigation satellites. Note that there are two main correction generation function modules, one for the ionosphere and one for satellite errors. The FAA's WAAS also provides the user with two system accuracy metrics, namely the UDRE and the GIVE from which the user can compute the User Ionospheric Vertical Error (UIVE). Finally, the user calculates a conservative bound on his range error from the UDRE, the UIVE scaled by the obliquity factor to slant delay, and his own equipment errors. This bound is then used to determine which satellites to use in the navigation solution, the weights to apply to each range measurement, and a bound on the error of the resulting navigation solution [RTC98]. A thorough description of the WAAS master station central processing algorithm is available in [EWP+96] and in Ph.D. dissertations by Tsai [Tsa99] and Chao [Cha97a].

Orbit and Clock Corrections In general, the GPS clock and orbit corrections can be estimated by using well-known GPS satellite dynamics as the nominal model [CBM+95] [BBSH+97] [PT97]. An independent dynamic orbit estimator in the SBAS context can improve the GPS navigation accuracy and is less vulnerable to errors or transients in the GPS messages. Currently, the Stanford WMS uses a simpler strategy [Tsa99], based on a stochastic model for the unmodeled error residuals, that directly estimates the satellite location errors of the nominal GPS satellite navigation

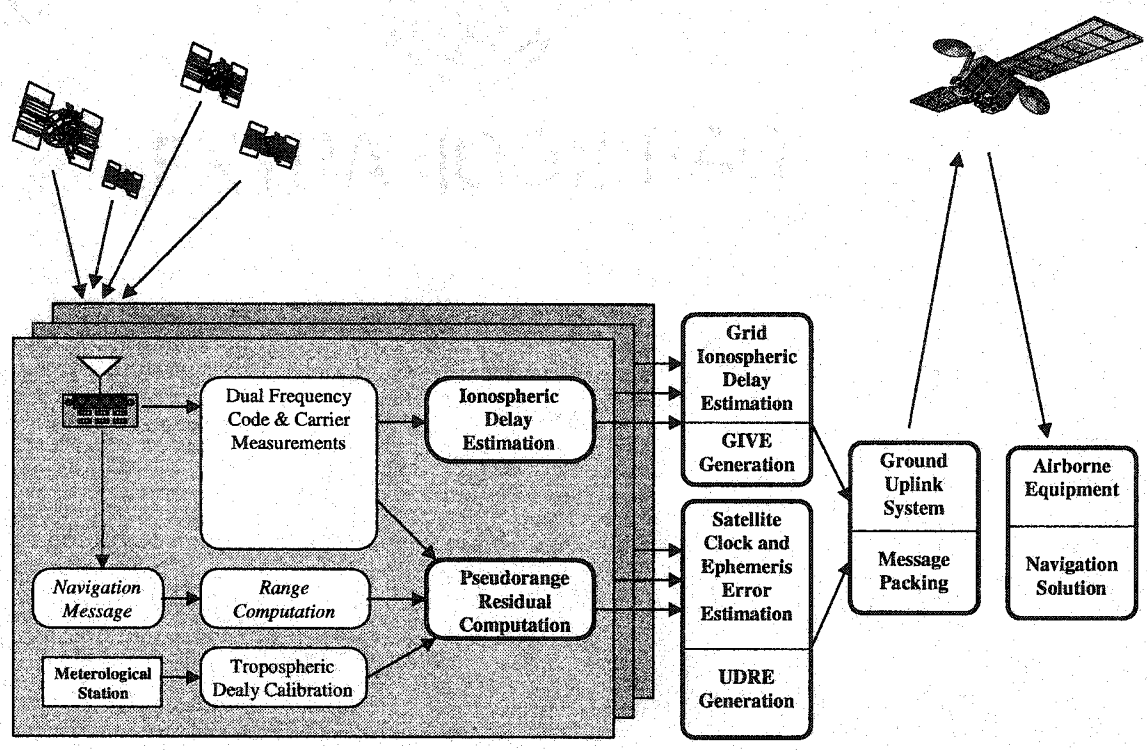

Figure 2.2: A flow diagram of SBAS data processing algorithms. There are two main function modules: the orbit/clock correction generation module and the ionosphere correction generation module. The confidence interval generations, UDRE and GIVE, are built into each function module by default. Here, an example of the kinematic orbit estimator is illustrated, in which the nominal range calculation is directly based on the GPS navigation messages instead of on an independent dynamic orbit estimator.

messages which are generated by the GPS control center dynamic model estimator. Orbit and clock corrections are generated based on the carrier smoothed iono- and tropo-free pseudorange residuals. Nevertheless, after the calibration of the nominal range and clock bias of a satellite, the different methods of orbit and clock correction generation using the range residuals are basically equivalent.

As shown in Figure 2.2, a kinematic orbit estimator calibrates the nominal range by using the Operational Control Segment (OCS)-generated original GPS navigation messages. A dynamic orbit estimator calculates the nominal range by using an independent satellite orbit estimator based on precise dynamic models. Both algorithms use stochastic linear estimators to infer orbit and clock offsets from the measurement residuals following the linearization around the accurate nominal trajectory of a satellite.

The system also calculates a bound on the orbit determination error and clock estimation error impact on the user's range error, namely UDRE. In general, the algorithm is designed to meet the UDRE requirements of WAAS for integrity, latency and precision approach availability [PT97].

Ionospheric Corrections Ionospheric correction are based on the dual frequency reference network receiver observability. The ionosphere is dispersive; consequently, ionospheric refraction will cause carrier phase to advance and code phase to retard. Since the ionospheric delay is different for the two GPS transmission frequencies, measurements at L_1 and L_2 can be used to estimate the delay with high accuracy. The wide area reference receivers measure the slant ionospheric delays to all satellites in view. These measurements therefore can be used to model the spatial distribution of the ionospheric delay. The ionospheric delay spatial model can be two dimensional [Klo86] [Cha97a] or three dimensional [HRS98] [Han98] and may be augmented by an additional dimension of time for real time applications. The current RTCA MOPS uses a two-dimensional grid model to represent the vertical ionospheric delay distribution [RTC98]. Generally, the ionospheric delay spatial distribution modeling uses a linear estimator for parameter calibration.

As part of the integrity monitoring function, the WAAS also generates a bound on the postcorrection ionospheric vertical error at each of the ionospheric grid points (IGPs) of an ionospheric delay correction grid covering the service area. The ionospheric error bound at each IGP is called the grid ionospheric vertical error (GIVE) [RTC98].

Finally, the WMS packs the satellite location, clock, and ionospheric corrections and corresponding error bounds into the WAAS data format [RTC98].

2.2.2 User Avionics

The primary goal of WAAS is to serve airborne users that are equipped with single frequency GPS/WAAS receivers. All WAAS avionics which are certified by the FAA will conform to the appropriate WAAS Technical Standard Order (TSO). This TSO is strongly based on the WAAS MOPS developed by the RTCA. WAAS users are required to employ weighted navigation solutions according to the WAAS MOPS. The WAAS MOPS also specifies how users combine error confidences from the different sources to form a position error bound using the integrity equation [Wal97]. This bound, called the protection level, provides an indication of the service quality.

Weighted Navigation Solutions

A typical WAAS receiver is required to apply the correction messages to its measured range observations. First, the WAAS avionics corrects its measurements using the geometric range and satellite clock bias based on broadcast ephemeris and clock parameters. Second, the tropospheric delay is removed using a standard model described in MOPS. Third, the receiver computes the ephemeris correction which is the projection of the satellite location error estimate onto the line of sight vector from the satellite to the approximate location of the aircraft. Fourth, the receiver applies the clock correction and a rate correction based on recently received corrections. Fifth, the vertical ionospheric delay for each satellite is estimated by interpolating between the grid point corrections. The ionospheric range correction is scaled by the obliquity factor [RTC98].

Finally, the corrected range measurements are used to compute the navigation solution using weighted least squares as follows:

$$\Delta\hat{x} = (\mathbf{G}^T\mathbf{W}\mathbf{G})^{-1}\mathbf{G}^T\mathbf{W}\Delta\hat{y} \tag{2.1}$$

where $\Delta\hat{x}$ contains the linearized position and clock errors. $\Delta\hat{y}$ is the corrected range residual vector. $\mathbf{G}$ is the observation matrix and $\mathbf{W}$ is the weighting matrix for the measurements. $\mathbf{W}$ is a diagnal matrix and the inverse of the i^{th} diagnal element is given by the variance for the corresponding satellite, σ_i^2, which is defined as [RTC98]

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2 \tag{2.2}$$

where the variance terms on the right represent the confidence for the fully degraded clock and ephemeris corrections, $\sigma_{i,flt}^2$, the fully degraded ionospheric correction, $\sigma_{i,UIRE}^2$, the contribution from the airborne receiver, $\sigma_{i,air}^2$, and the tropospheric model correction, $\sigma_{i,tropo}^2$ [WHE99].

Integrity Equation

The integrity equation is based on the concept of using 1) an overbounding normal distribution as the statistic model and 2) linear estimation theory for deriving the weighted navigation solutions. For example, the variance of the vertical position estimate is given by the third diagonal element of the full position estimate covariance matrix,

$$\sigma_V^2 = [(\mathbf{G}^T\mathbf{W}\mathbf{G})^{-1}]_{3,3} \tag{2.3}$$

The Vertical Protection Level (VPL) is given by

$$VPL_{WAAS} = 5.33\sigma_V \tag{2.4}$$

The constant, 5.33, is based on the concept that the actual pseudorange errors can be conservatively bounded at and beyond the 10^{-7} probability level, the tolerable probability of HMI, by a zero mean guassian [Wal97].

Signal-In-Space Performance Evaluation Criteria

The most typically used presentation style of performance is the so-called *triangle plot*. An illustrative example is shown in Figure 2.3, where the performance is evaluated in the user position domain in a two-dimensional space. The horizontal dimension stands for the true position error magnitude, while the vertical dimension stands for the estimated protection level according to the RTCA integrity equation. Although a user does not have knowledge of the true error, he does have the ability to compute the protection level based on information broadcast to the users from the geostationary satellites. There are four key regions which are of great interest and of significant meaning in terms of availability, accuracy and integrity evaluation. As shown in the plot, if the protection level is larger than the alert limit of a certain operation mode, the service will become unavailable. On the other hand, if the estimated protection level is smaller than the alert limit, the service will be treated as available for navigation. In every case, whenever the true error becomes larger than the calculated protection level, there occurs an event of *misleading information* since the protection level is meant to bound the true error. If the true error is larger than the alert limit and the system is deemed available, the result is hazardous, because the user has no knowledge of the excessive true error. This situation is called Hazardously Misleading Information (HMI) and should be avoided at all costs. In this case, we refer to it as an integrity breach, or a loss of system integrity. Therefore, this triangle chart presentation style can intuitively illustrate system performance in terms of accuracy, availability and integrity.

2.3 Integrity Analysis

The FAA's WAAS is designed to be used as a primary means navigation system, capable of satisfying the National Airspace System (NAS) Required Navigation Performance (RNP), including accuracy, integrity, continuity, and availability, as listed in Table 1.1. The SBAS total system integrity comes primarily from two factors: integrity of the signal-in-space (SIS) and integrity of the airborne navigation system.

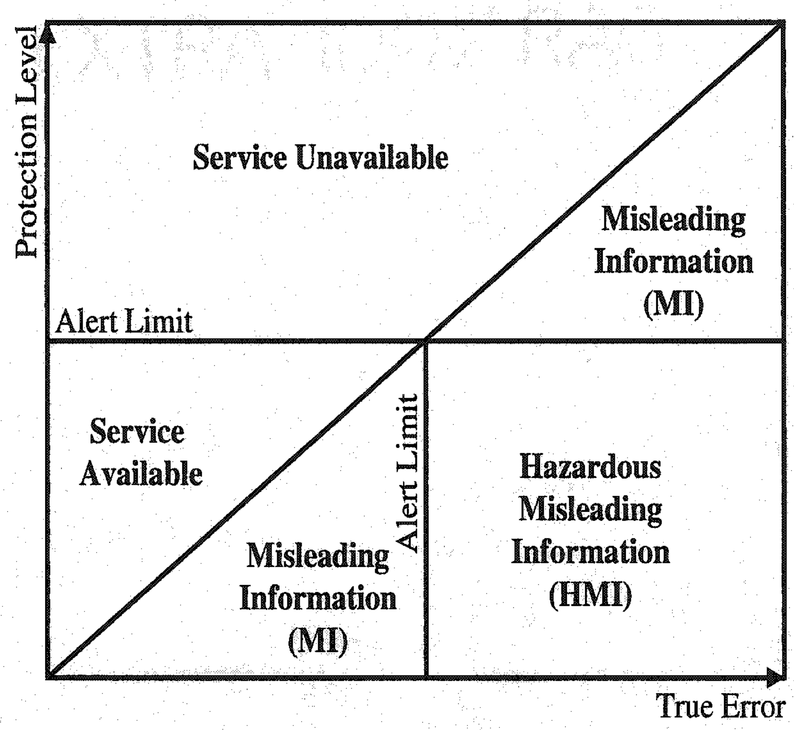

Figure 2.3: Triangle plot for performance evaluation. Notice the system performance is evaluated in a two-dimensional space. The horizontal dimension stands for the true error magnitude, and the vertical dimension stands for the estimated protection level. The entire space is divided into several important regions: Service Available, Service Unavailable, Misleading Information (MI), Hazardously Misleading Information (HMI). Note that the true error is not available to a user while the protection level is calculated by the user to bound the true error. If the true error ever exceeds this bound, the information is *misleading*. If the estimated protection level is larger than the alert limit of a certain operational mode, the system is considered unavailable for that service. If the estimated protection level does not indicate the failure of the system service when the true user position error is larger than the required alert limit, the system suffers an event of hazardously misleading information, or an integrity loss.

The signal-in-space integrity requirements for probability of hazardously misleading information (HMI) are 10^{-7} per flight hour for en route through LNAV or non-precision approach (NPA), and 2×10^{-7} per approach for LNAV/VNAV or NPV-I, as well as GLS or precision approach (PA) Category I.

Generally, such statistical asymptotic integrity performance cannot be *proven* in a strict sense. It can only be *unfalsified* through continuous safe real life operation. However, quantifying the system integrity risks under uncertainties, especially failure modes, will help our fundamental understanding of the system behaviors and lead to potential improvements in system design and operation.

2.3.1 Integrity Threats

To quantify SBAS integrity risks, it is important to characterize the system error sources, identify failure modes, and investigate system responses and their impacts on the user's integrity, especially those due to failure modes. SBAS failure modes include both internal failures and external failures. Internal system integrity risks can occur in each component of the system: the ground control segment, space segment and user segment. External risks mainly come from space and atmospheric anomalies, intentional and unintentional interference, potential failures due to the GPS master control station (MCS) and other outside service providers. An overview of the system integrity threats is shown in Figure 2.4 [DWEP99]. Most of the ground and user segment hard failures can be effectively mitigated through redundancy, but space segment and external failures can pose serious threats or potentially invoke control segment soft failures due to their time-variant uncertainties. Interestingly, many of these failure modes do not necessarily introduce integrity risks. An integrity risk is present only if hazardously misleading information (HMI) is passed to the user while the system fails to provide a timely alert that this has occurred [Per96].

Two major components contribute to the WAAS total system integrity risk: signal-in-space integrity risk and airborne user navigation system risk. Therefore, a fault-free receiver is desired to assess the system SIS integrity risks in the user position domain. Signal-in-space integrity risks are dominated by the fidelity of User

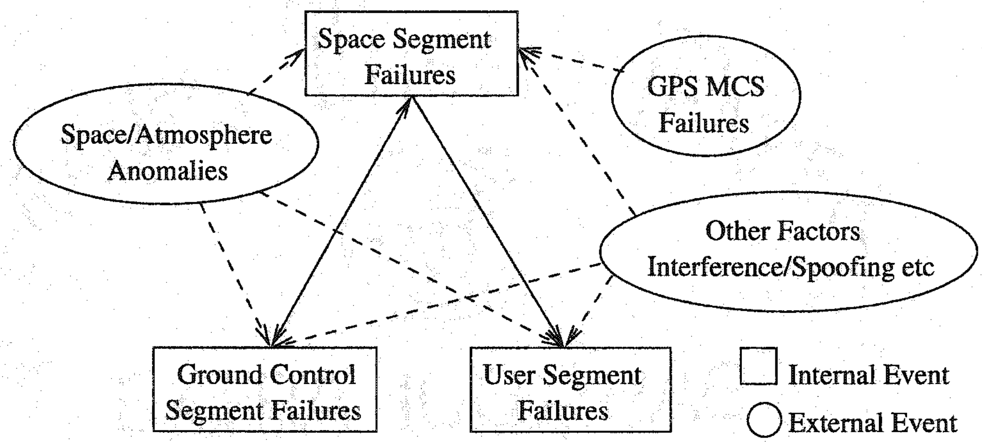

Figure 2.4: Influence diagram of overall WAAS system integrity threats. As marked in the plot, square boxes stand for internal events and circles stand for external threats. Meanwhile, solid lines indicate risk flows of internal threats, and dashed lines represent the propagation of external risk flows.

Differential Range Error (UDRE) and Grid Ionosphere Vertical Error (GIVE), as well as the response time to system failures.

2.3.2 Probabilistic Risk Analysis

SIS integrity risk factors include the satellite integrity information and the correction integrity, specifically, UDRE for clock and ephemeris corrections, GIVE for ionospheric corrections, and the time-to-alert requirement associated with the above messages, as well as the protection level estimation using the MOPS integrity equation that defines the interface between SIS and the user navigation functions.

Optimality and integrity coexist, like two sides of a coin, but present conflicting interests. System optimality forms the foundation for high accuracy services and emphasizes the nominal operation mode. It depends on valid linearization and optimal filtering techniques. System integrity is designed to protect against potential failure modes, in both system nominal models and measurements, to a 10^{-7} level through statistical hypothesis testing and confidence interval generation. This integrity design goal, combined with other objective functions, including accuracy, continuity, and

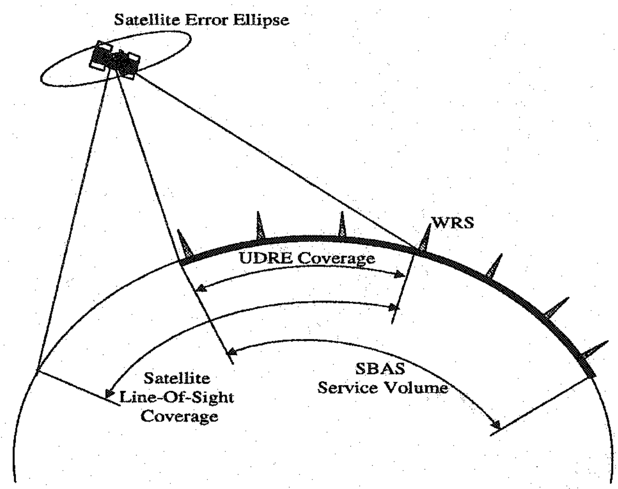

Figure 2.5: UDRE definition for a 2-D illustrative example.

availability, contributes to the overall system design principles.

User Differential Range Error (UDRE)

User Differential Range Error, UDRE, defines the fidelity or confidence interval of the orbit and clock correction information. UDRE is therefore designed to capture the bounding error on the vector corrections against potential risks of fault modes with a certain protection level of probability of missed detection for the worst-case user inside the effective coverage area. This concept is illustrated in Figure 2.5 using a 2-D example. The effective coverage area (the UDRE coverage shown in the plot) is the intersection of a GPS satellite footprint and nominal SBAS service volume.

Grid Ionospheric Vertical Error (GIVE)

In addition to ionospheric vertical delays, WAAS messages also contain the confidence interval information for the IGPs, the Grid Ionospheric Vertical Error (GIVE). Similar to that of the UDRE design, the GIVE values are designed to guarantee the safe

	Radial	A-Trk	X-Trk	3D	Clock
σ	0.77	4.24	1.94	4.72	24.39
95%	1.5	8.39	3.95	8.89	48.18
99.9%	4.05	24.34	8.88	24.56	81.59

Table 2.1: Major nominal operation statistic parameters of GPS satellite broadcast ephemeris and clock errors (unit: meter).

interpolation of ionospheric corrections by users inside each monitored grid cell. A confidence interval is determined by achieving this confidence for the worst case user ionospheric pierce point based on both the physical model and measurement strength.

Because of the uncertainty and lack of general knowledge of ionosphere activities, monitoring the external factors and predicting potential threats are beneficial for the GIVE generation algorithms in order to actively leverage service integrity and availability.

2.3.3 GPS Threat Models

Both nominal error distribution and failure mode modeling are critical in assessing system performance. Here, the performance analyses of GPS positioning are based on conservative models with regard to receiver noise, clock error and multipath, ionosphere, troposphere, satellite ephemerides, unscheduled satellite failures and unavailability of satellites for scheduled maintenance, repair, repositioning, training, or testing.

To assess the accuracy of the satellite information broadcast in the navigation messages, the daily GPS solutions, from the IGS, of satellite positions and clock corrections are treated as the *truth*. One of the key differences between the GPS OCS solutions and the truth model is that the GPS solutions are predictions of the future based on past data, whereas the *truth* solutions from the IGS are based on after-the-fact, postfit smoothed estimates. The difference between the two solutions (in meters) has been calculated in the radial, along-track and cross-track directions for all satellites and days over the period April 10, 1998 through March 6, 1999. As

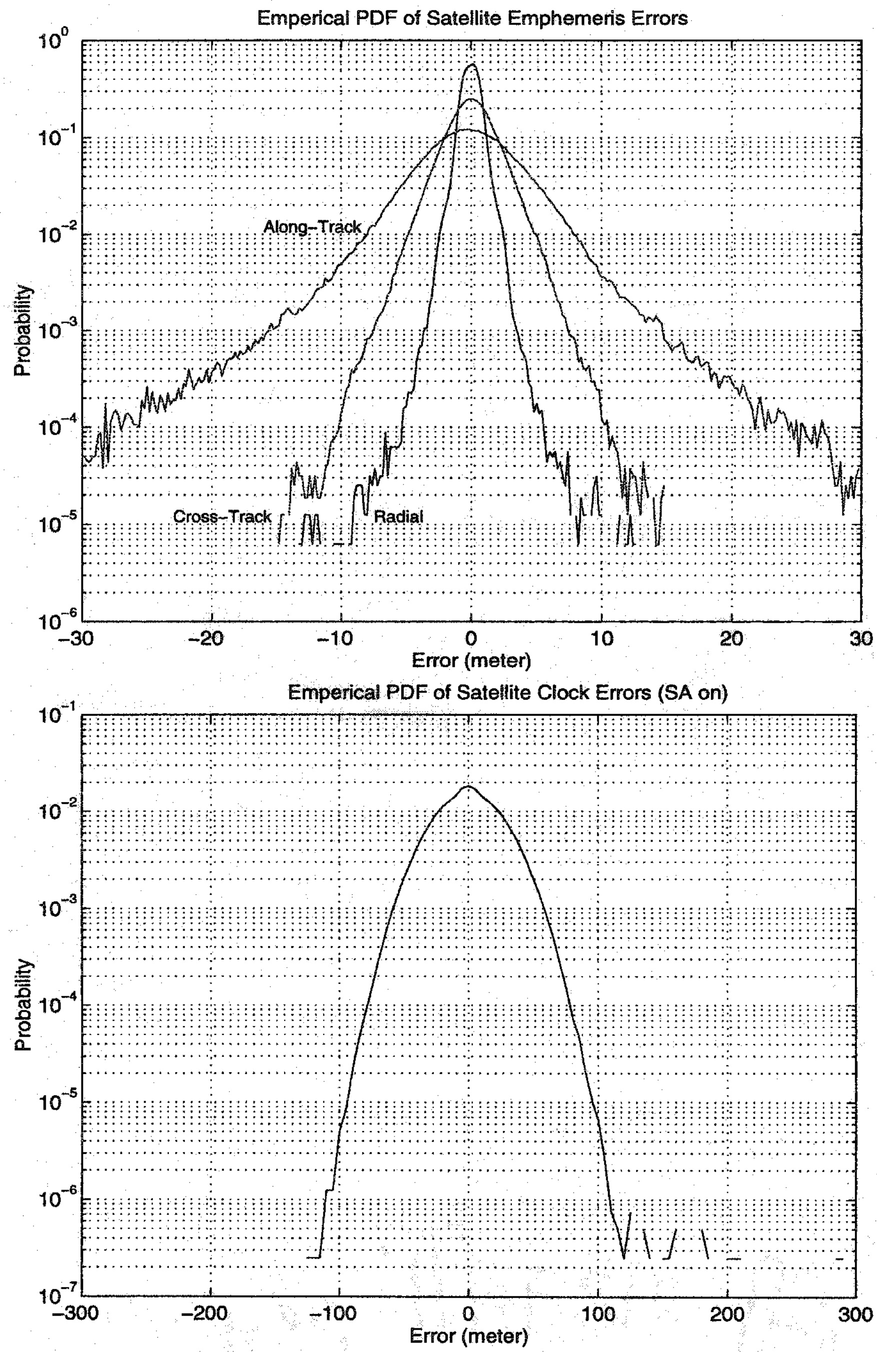

Figure 2.6: Nominal GPS ephemeris and clock error histograms based on IGS precise solutions and OCS broadcasts, including 311 days' data sets available between April 10, 1998 and March 6, 1999 (before SA was turned off).

shown in Figure 2.6, orbit and clock nominal error distributions are extracted from about one year's worth of historical data sets, with some major statistical parameters summarized in Table 2.1.

Though the GPS Operation Control Segment (OCS) does an excellent job in maintaining the integrity of the GPS system, failures on the space segment can still occur. Satellite related clock and ephemeris anomalies may be caused by GPS OCS failures and satellite failures. The GPS OCS may upload incorrect ephemeris and clock parameters. Failures can also result from real satellite ephemeris anomalies and physical failures of the onboard atomic clock. The probability of such GPS failure events is approximately 10^{-4} per hour [Cor93] [LDD+96].

2.3.4 Ionospheric Threat Models

Ionosphere activities have a deep impact on both the availability and integrity of current SBAS services. Though the wide area network reference stations utilize dual frequency receivers to actively monitor the ionosphere electron distribution in real time, the resolution of the ionosphere observability is quite limited due to the relatively sparse distribution of the stations. The GEO satellite communication bandwidth constraint and the RTCA ionospheric grid model also limit the time response and spatial resolution of ionospheric activities. Therefore, ionospheric irregularities become one of the most serious integrity and availability threats for SBAS services.

In general, there are several key parameters [Cha97b] used in quantifying the ionosphere activities of highest interest to the SBAS system design:

- $\partial(TEC)/\partial t$ Temporal variation of the Total Electron Content (TEC) of the ionosphere.
- $\Delta(TEC)$ Spatial variation of the TEC over the service coverage.
- hmF_2 Height maximum of the ionosphere F_2 layer, the so-called hmF_2, is an indication of the approximate conditions of the vertical ionosphere distribution and variation.

- *Nuggets* Local scale variation of ionosphere TEC, including traveling ionosphere disturbance (TID), sudden ionosphere disturbance (SID), and scintillation.

The above ionosphere activity irregularities potentially pose integrity and/or availability threats to SBAS services due to the limited network observability and limited knowledge about their nature. The integrity risk analysis under such uncertainties requires a probabilistic framework.

The ionospheric structures and peak densities vary greatly with time (sunspot cycle, seasonally, and diurnally), with geographical location (polar, auroral zones, mid-latitudes, and equatorial regions), and with certain solar-related ionospheric disturbances. Therefore, ionosphere activities are highly correlated with the geomagnetic activities (Kp index) and solar magnetic activities (sun spot number, SSN). To quantify the ionosphere integrity threat, the ionosphere activity history has been scrutinized. The histogram of the two key parameters, Kp index and SSN, is shown in Figure 2.7. Though the art of predicting ionospheric activities is not very precise, the figure shows the probability of possible conditions within the parameter space of interest.

Considering that the general understanding of ionospheric storms is still lacking, the SBAS design must remain conservative to preserve system integrity. The overall system performance can be evaluated using the probability of all the possible conditions within the parameter space of interest. Therefore, from the design point of view, ionospheric disturbances are of great importance for service availability and integrity threats.

2.3.5 SBAS Control Segment Integrity Threats

Generally, the correlation between correction messages is neglected due to simplicity and its minor impact under nominal conditions. Nevertheless, this simplification opens questions regarding such correlation-induced integrity threats. The MOPS integrity equation performance is justified based on *snapshot* position solutions; therefore, *temporal* correlation in range errors will not change the marginal distribution of errors in the user position fix, which is uncorrelated with the time tag variables. This

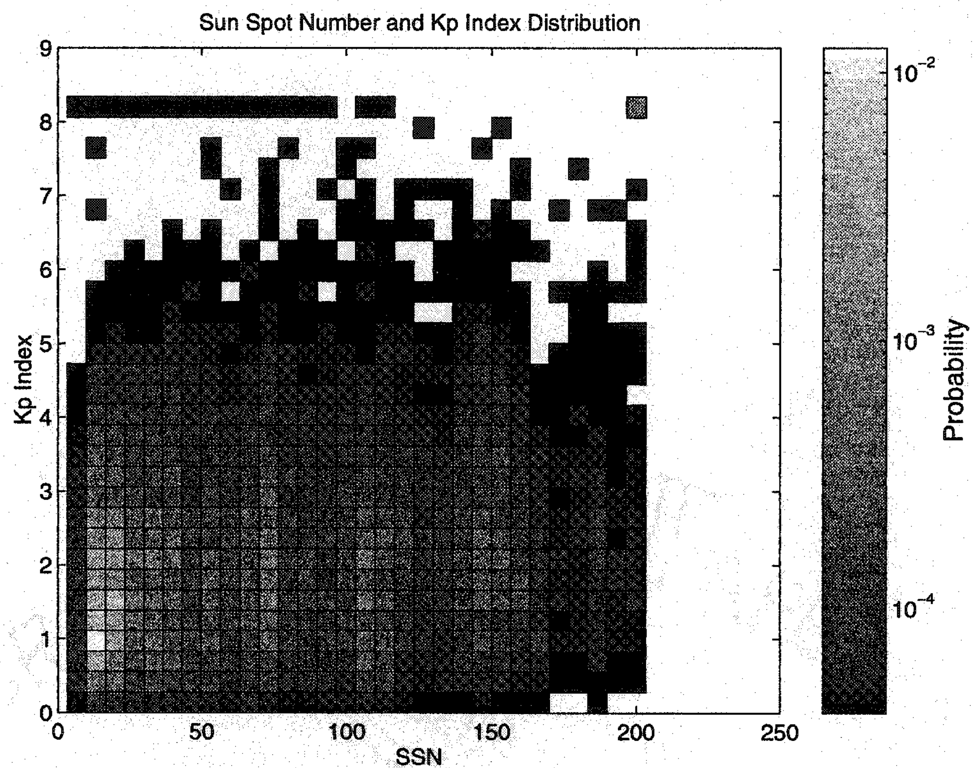

Figure 2.7: Histogram of two key ionosphere activity indices: Geomagnetic activity Kp index, Solar magnetic activity Sun Spot Number (SSN). Data include 3-hr Kp values and 12-month SSN moving average value (R12 index) collected during January 1957 to January 1999.

was verified in [WHE99].

A source of great concern with regard to the MOPS integrity equation is the cross-correlation among satellite errors as well as that between satellite errors (clock and ephemeris) and ionosphere errors. Concern arises due to the uncorrelated assumption among each error source in the MOPS integrity equation.

Error correlations of both types can become potential threats to system integrity. For example, correlated errors can be introduced into the SBAS vector correction domain through failures in the dual-frequency reference receiver interfrequency bias (IFB) calibration process. Such a failure mode would lead to correlated errors among both satellites and vector corrections. A sensitivity test using NSTB data is shown in Figure 2.8. A constant common mode IFB error, (Δ), is added to all the receivers in the network. System responses to this fault mode are then assessed accordingly in the user position domain. Note that a non-zero Δ will seriously degrade the system vertical performance. For negative Δ errors, the introduced fault modes are difficult to detect in the correction domain, and vertical position errors increase in proportion to the magnitude of Δ. It is verified that the error correlation can be a potential integrity threat to the system for operations requiring vertical guidance. Positive Δ errors have limited impact on integrity due to the physical constraint of ionosphere nonnegative delay on the code phase measurements. The Δ values are saturated after their magnitude becomes larger than current ionosphere delays. The saturation effects can trigger master station alerts, which bring the user position error into the unavailable region.

However, the above IFB calibration error induced correlated position domain error that could be monitored and detected by the master station. Therefore it can be detected and mitigated by the ground monitoring system to achieve satisfactory performance.

Note that potential risks could be introduced in a similar fashion by small local effects, such as troposphere error, that are not visible to the sparse reference network. Due to the physically bounded energy of troposphere anomalies and possible augmentation of weather parameter measurements to improve the troposphere model, this risk is effectively mitigated in practical operation.

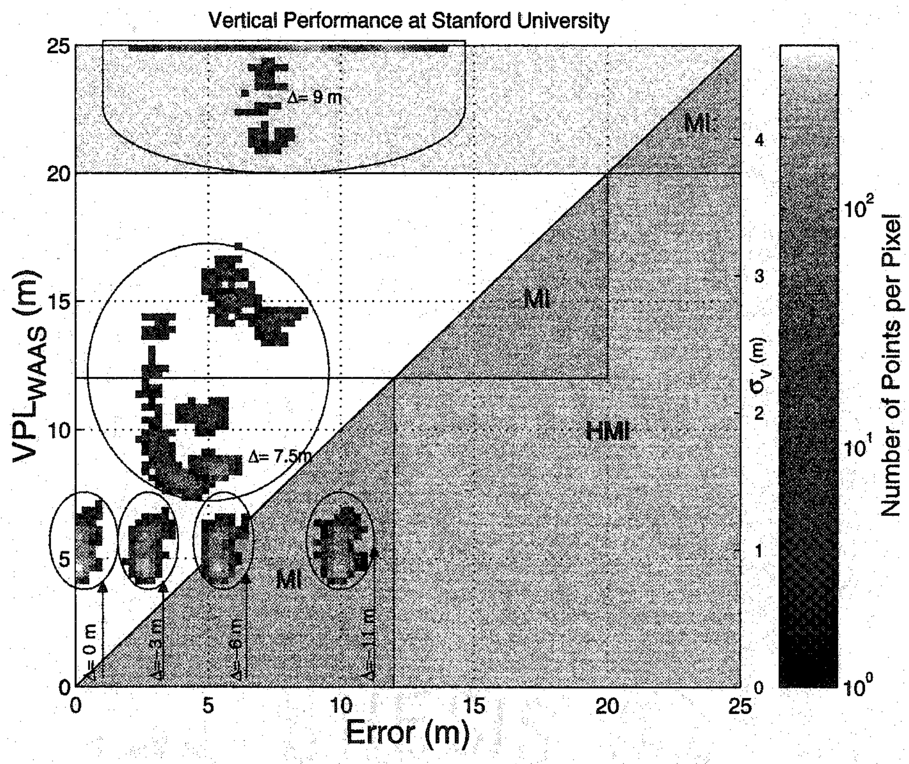

Figure 2.8: Sensitivity analysis of correlated error impacts on the system performance by introducing different sizes of common mode network-wise IFB errors, Δ, into the NSTB live data.

2.3.6 Airborne Integrity Threats

All WAAS receivers are also required to autonomously monitor integrity to provide safety in the presence of local integrity threats which are not detectable by the WAAS monitoring networks. These local threats include interference, receiver malfunctions and exceptional multipath events. Typically, receiver autonomous integrity monitoring (RAIM) includes continuous monitoring of the measurement using step detectors, signal quality and interference monitors, fault detection and exclusion (FDE) based on the measurement residuals from the navigation solutions, and a precision fault detection algorithm during precision approaches [EWP+96].

2.4 Integrity Performance

Simulation tools are used to characterize system performance and responses under both nominal and anomalous conditions to quantify SBAS integrity performance under uncertainties, especially spatial degradation, from an interoperability point of view.

This section focuses on the characterization of SBAS signal-in-space integrity performance. The goals are to understand the integrity threats to the WAAS system design, assess the potential integrity risks, characterize achievable system performance and justify the system integrity function. Use of analyses, simulation and NSTB live data lead to accomplishment of these goals.

2.4.1 Description of Simulation

This simulation study considered several dominant error sources. As mentioned above, orbit and clock failure modes are major integrity threats to the SBAS service. Therefore, the current simulation focuses on the study of SBAS integrity performance under the worst case space segment satellite anomalies.

The simulation top level flow diagram is shown in Figure 2.9. The nominal orbit and clock error distributions, together with worst case satellite failure modes, are injected into the entire navigation system. The SBAS ground control segment

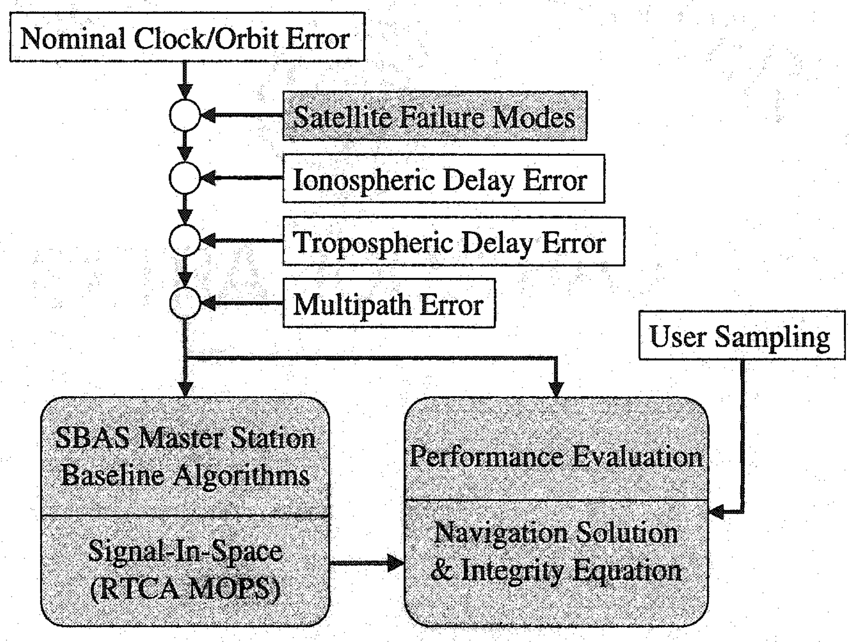

Figure 2.9: Top level simulation flow diagram of SBAS integrity performance study.

constantly monitors the space segment status, and broadcasts vector correction and integrity information to the user segment. The system performance evaluation is done in the position domain at the user segment. The evaluation is accomplished by first uniformly sampling the user over the entire area of interest, then forming the navigation solution and integrity equation, and finally justifying the system performance based on the evaluation of the true position error and the estimated protection level.

Reference station measurement multipath and receiver error distributions use calibrated models based on NSTB live data [DWEP97]. The simulation uses the standard GPS 24-satellite constellation augmented by ranging capable INMARSAT-3 geostationary satellites [RTC98], with POR and AOR-W covering the CONUS. The WAAS Phase I reference station network is also used. Satellite failure mode impacts on availability are based on the study in [SDH95]. As mentioned above, satellite ephemeris and clock errors, due to both external and internal events, are of greater concern for interoperation integrity from a design point of view. Therefore, our simulation will characterize the impacts of the worst-case satellite orbit and clock failures on system integrity performance.

The worst-case GPS ephemeris and clock anomalies are those failures introducing the largest position error to the users without triggering integrity alerts due to the WAAS network observability. Therefore, the worst-case anomalies can be constructed such that they expand the four-dimensional space and can capture the worst directional errors. In our simulation, such errors are generated on-the-fly based on the relative position between the satellite, reference network and user locations. The worst-case satellite errors are injected to excite the system in each simulation run. System SIS performance evaluation is done in the user position domain and relies on the nominal performance of a fault-free receiver requirement. Users are uniformly located at 5 degree intervals in geographic latitude and longitude.

The GPS satellite nominal error models are based on the emperical model described previously, which was based on the actual operation history statistics. Other error sources are based on the nominal model without anomalies. The ionosphere distribution is generated by the well known IRI-95 model. To emphasize the impacts due to satellite anomalies, we selected ionospheric activity from the typical quiet conditions, with a Kp index of 1, and a sun spot number of 20. The ionospheric error spatial decorrelation is in line with the nominal model. Meanwhile, troposphere modeling errors use a first order Gauss-Markov model with σ_V of 2 cm, changing with elevation angle, with time constant of 2.5 hours [PT97] [ABP+97].

2.4.2 Evaluation Method

The simulation results are evaluated in the user position domain. There are two key parameters which will be evaluated using the current simulation-based analysis framework [DWEP99]. For any position fix, the availability is calculated based on the estimated protection level with respect to the alert limit for a certain operation mode. If the estimated protection level is less than the operation alert limit, then the flight operation can be conducted. Otherwise, a loss of availability will occur in the system service. As for the integrity risk evaluation, there is an estimated confidence interval which is derived from the signal-in-space information and airborne equipment error statistics, and an actual position error distribution standard deviation which is based on the injected failure mode with a known distribution. The probability of the integrity risk is based on the potential likelihood of Hazardously Misleading Information (HMI). This occurs when the protection level estimated by the user equipment is less than the alert limit of a certain operation mode, while the actual position error is larger than the alert limit. In other words, a malfunction of the system is not being detected, which potentially could cause hazardous accidents, such as an airplane crash. When this occurs, we claim that the system has lost integrity.

The evaluation of system integrity is calculated based on the following discrete format:

$$Pr(\text{HMI}) = Pr(\text{NM})Pr(\text{HMI}|\text{NM}) + \sum_i Pr(i^{th}\text{ FM})Pr(\text{HMI}|i^{th}\text{ FM}) \quad (2.5)$$

where,

$$Pr(\text{NM}) = 1 - \sum_i Pr(i^{th}\text{ FM}) \quad (2.6)$$

The total probability of HMI is evaluated through two separate analyses: 1) the nominal operation mode (NM) integrity performance and 2) the integrity performance under different failure modes (FMs). The system is designed to work well under nominal operation mode, which leads to a small probability of HMI. Therefore, total system integrity is dominated by the probability of the failure modes and system responses to those failure modes or the probability of HMI under failure mode scenarios.

Note that i ranges from 1 to N for a user with N satellites in view. The i^{th} failure mode indicates that a worst-case failure occurs on the i^{th} satellite. The probability of a single in view satellite failure, $Pr(\text{FM})$, is characterized as a function of N in Table 2 of [SDH95]. The likelihood of each satellite failure is assumed uniform among all the in view satellites.

The worst-case ephemeris and clock errors are dynamically constructed based on the reference observability such that they expand the four-dimensional space and can capture the worst directional errors without triggering an alarm. Assume the SBAS generates corrections based on prior information of a well behaved ephemeris nominal model in Section 3.2 of [Tsa99]. When the worst-case failure mode occurs without trigger an integrity alarm by the network, the true ephemeris uncertainty will only constrained by the snapshot observability of the SBAS network without prior information. The probability of HMI given the occurence of such worst-case failure mode is computed by:

$$Pr(\text{HMI}|\text{FM}) = Pr(\text{HMI}|\text{FM,MD})Pr(\text{MD}) + Pr(\text{HMI}|\text{FM,SD})Pr(\text{SD}) \quad (2.7)$$

The quantity, $Pr(\text{HMI}|\text{FM,MD})$, is the probability that the failure mode is large enough to hurt the user (true position error is bigger than the corresponding alert limit for a specific operation mode), but is not caught by the master station algorithms. We assume that the probability of missed detection (MD) of such failures by the master station, $Pr(\text{MD})$, is expected to be approximately 10^{-3}. The probability of successful detection (SD) is calculated by $Pr(\text{SD}) = 1 - Pr(\text{MD})$.

For example, for GLS operation mode, the user actual vertical position error, in presence of the undetected worst-case error, follows a guassian distribution, $f(x) \sim N(0, \sigma_{V,F}^2)$, and the protection level is computed by using $VPL = 5.33\sigma_V$. Then the probability of HMI is the likelihood of the actual distribution falling beyond the specific VAL:

$$Pr(\text{HMI}|i^{th}\ \text{FM,MD}) = 2\int_{VAL}^{\infty} f(x)dx \quad (2.8)$$

when VPL is smaller than the VAL.

The availability assessment is based on a similar concept and computed in parallel with the integrity performance. The counterpart equation takes the following format:

$$Pr(\text{Avail}) = Pr(\text{NM})Pr(\text{Avail}|\text{NM}) + \sum_{i=1}^{N} Pr(i^{th}\ \text{FM})Pr(\text{Avail}|i^{th}\ \text{FM}). \quad (2.9)$$

where $Pr(i^{th}$ FM) stands for likelihood of the i^{th} satellite failure mode among N in view satellite of the user. Given such failure modes, the system will be counted as available when the estimated VPL is smaller than the VAL for GLS operation mode, and unavailable otherwise. Note that the probability of the nominal operation mode, Pr(NM), is much larger than the failure modes. Therefore, unlike integrity performance, system availability is dominated by the availability of the nominal system operation mode.

The evaluation of system performance will therefore be based on both the integrity and the availability results.

2.4.3 Baseline Platform

Baseline algorithms used in the simulation include both vector correction generation and associated confidence interval determination. For the vector correction generation, based on the nominal operation model, optimal linear estimation theory is applied. Orbit and clock corrections are based on kinematic Kalman filters [Tsa99]. It is noticed that dynamic orbit estimators present a similar level of integrity performance. A minimum of two reference stations are required for a satellite to be flagged as monitored. The ionospheric corrections are generated using the thin-shell grid algorithm [Cha97a].

UDRE and GIVE are calculated based on the confidence interval generation algorithm mentioned in the last section in order to protect the correction of worst-case error up to the 10^{-7} level. In the GIVE algorithm, the 3-out-of-4 selection rule initially proposed for WAAS [ABP+97] is overly conservative, and therefore is not used in the simulation [Wal98].

2.4.4 Simulation Results

Under nominal operating conditions, simulation results of the WAAS availability performance for GLS or PA, LNAV/VNAV or NPV-I, LNAV or NPA operations are shown in Figure 2.10. 99.9%, 95% and 90% availability coverage contour lines for each phase of flight operation are shown in the plots. Note that the system is capable of providing high quality services over a wide area of coverage. Meanwhile, there is no integrity break with probability of HMI above the 10^{-7} level anywhere over the service coverage, inside and outside the nominal service volume.

Under the worst-case orbit and clock anomaly scenarios, integrity degradation becomes visible. Service volume simulation results of the worst-case overall achievable WAAS integrity performance for GLS or PA, LNAV/VNAV or NPV-I, LNAV or NPA operations are shown in Figure 2.11. Obviously, the service is available more than 99.9% of the time with 10^{-7} level integrity for a broad area of users. It is also noticed that the service coverage for LNAV can be much wider than GLS and LNAV/VNAV which require stringent vertical guidance. For GLS and LNAV/VNAV operations, network density and distribution are both critical for system performance. CONUS is well covered for both operations with full integrity, but a remote station at Hawaii still could not pull the intermediate region availability up to 99.9% and integrity degrades to 10^{-6} in the presence of the worst-case satellite orbit and clock anomalies. Since LNAV integrity and availability rely more heavily on the network distribution instead of density, and the ionospheric errors are physically bounded and relatively small compared to the operation alert limit, the network geometry becomes most critical. The worst-case LNAV integrity degrades gracefully, and potentially enables wide oceanic region services for international navigation purposes. For the en-route and terminal operation modes, the service availability and integrity performances behave similarly to those in the LNAV operation mode. Service volume simulations for EGNOS and MSAS illustrate similar performance trends.

The results use the real data model using the Stanford master station processing algorithms. The overall system outperforms the initial WAAS Phase I system. The major reason lies in the underlying ionospheric monitoring algorithms. As mentioned, the 3-out-of-4 selection rule initially proposed for WAAS was proven to be overly conservative and hurt the overall system availability and service volume significantly [Wal98]. The simulation results show that, by using the Stanford algorithms, the current augmentation system can provide very high quality navigation services over a wide area of coverage.

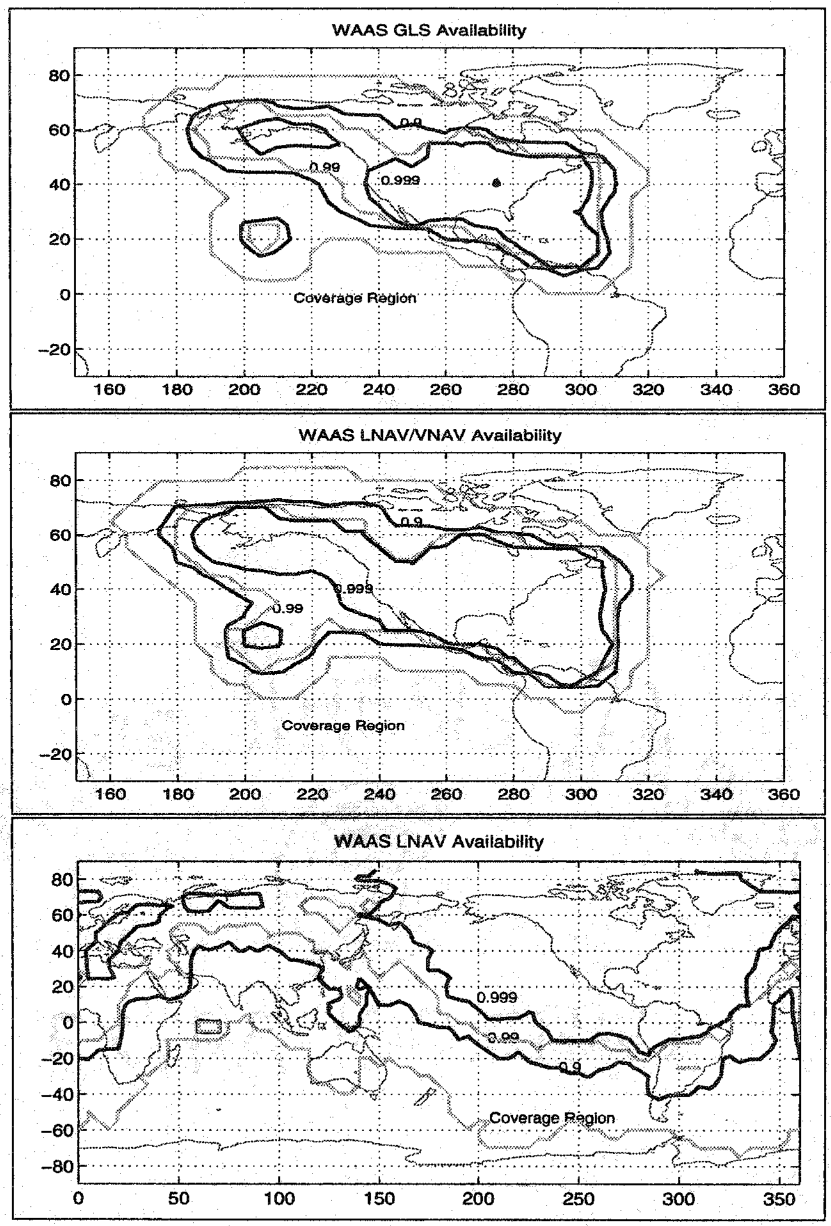

Figure 2.10: Simulation results of WAAS achievable availability performance under quiet ionospheric conditions for GLS, LNAV/VNAV and LNAV operations with SA on. The availability results are better than the Raytheon WAAS Phase I, mainly due to the difference in ionospheric monitoring algorithms.

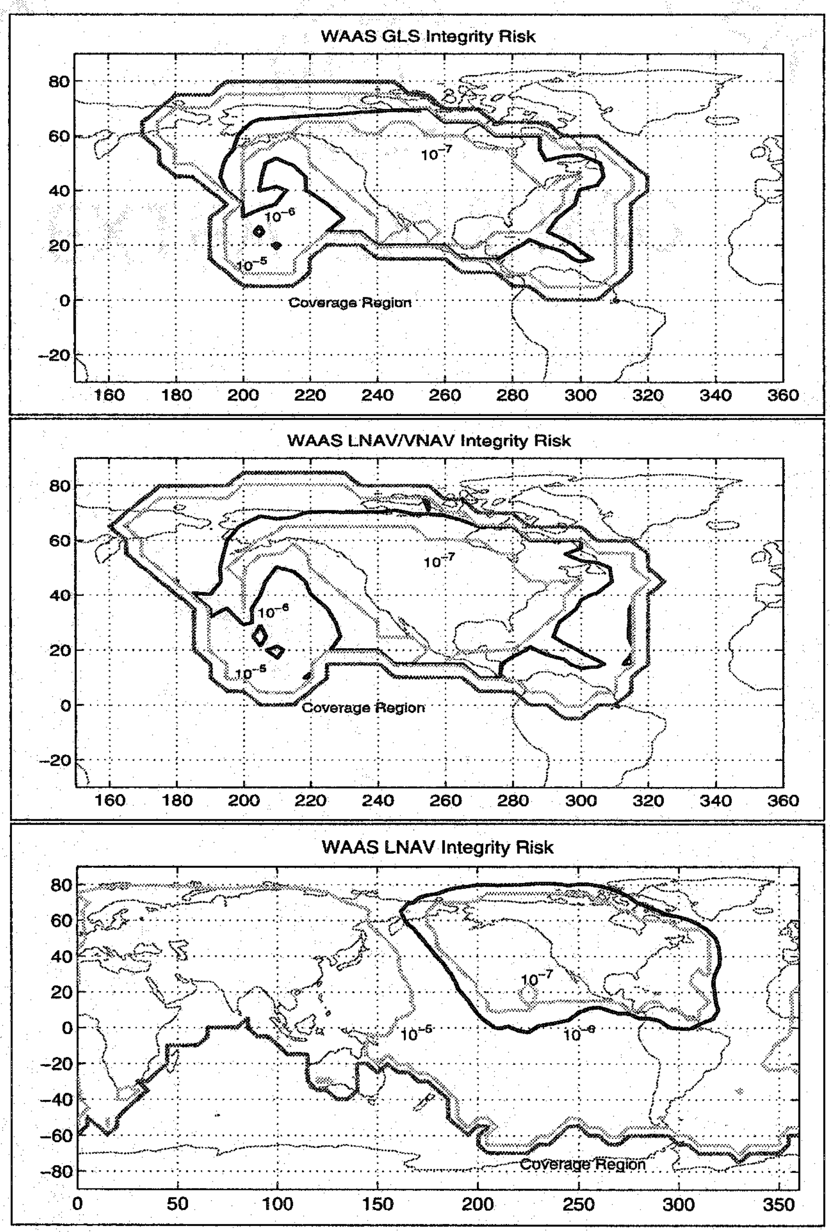

Figure 2.11: Simulation results of WAAS achievable integrity performance under quiet ionospheric conditions for GLS, LNAV/VNAV and LNAV operations under the worst-case orbit and clock anomalies with SA on.

2.4.5 Risk Management

Potential integrity risks due to the worst-case orbit and clock failures illustrated in the above analysis may be overly pessimistic. This is because the probability of those worst-case failure events could be much smaller than what we assumed here (10^{-4} per hour). However, analysis based on such an assumption does provide us with great confidence and a promising outlook for the achievable operation performance in real life.

Furthermore, to protect against the worst-case integrity threats when a user is moving away from the nominal service volume, there are many ways to enhance the integrity level. For example, the SBAS provides a much higher integrity level than stand-alone GPS even for the oceanic region and user RAIM can be employed to augment integrity to satisfy the 10^{-7} level requirements [WE95]. Other augmentation strategies through additional remote reference stations, integrity consistency cross-validation among SBASs, and additional navigational aids can effectively improve the service integrity performance for oceanic users outside the nominal service volumes.

2.5 Integrity Spatial Degradation

2.5.1 UDRE Spatial Degradation

Non-precision approach service is a legacy of GPS. There is no major concern about the nominal accuracy, which is already guaranteed by existing unaided GPS. Availability and integrity are the paramount issues for en-route through non-precision approach services outside the service volume.

Although the UDRE is designed to bound the error in any situation with high confidence for the worst-case user inside the nominal service volume, it may not automatically guarantee the same level of confidence for users outside the service volume. Though ephemeris errors usually are well behaved in nominal conditions, large discrepancies can still occur, mostly during satellite maneuvers or satellite anomalies. A potential integrity threat due to ephemeris spatial decorrelation is one of the most worrisome concerns [Dai98]. Note that each SBAS has its own limitations of guaranteed integrity due to the network distribution. Interoperation of SBASs can effectively mitigate the integrity threats.

The UDRE spatial decorrelation potentially introduces integrity threats and is of utmost concern from an interoperability point of view. For users outside the nominal service volume, the satellite orbital information can suffer potential integrity threats under the worst case satellite anomalies due to spatial degradation of the network observability. Specifically, the message content defined by UDRE that bounds the worst case overall satellite ephemeris and clock correction errors is not necessarily valid for the intermediate regions outside the nominal service volume. Therefore, RTCA MOPS Message Type 27 [RTC99] has been designed to reduce the potential integrity risk by introducing UDRE degradation factors in the intermediate regions. The message design principle is to protect the integrity for interoperability without significantly affecting availability under nominal conditions.

UDRE spatial degradations are administered by means of a multiplicative degradation factor applied by the user in the intermediate regions through the broadcast Message Type 27. Strictly speaking, the degradation factors are time-variant, and depend on the ground control network, satellite geometry, reference station performance, and the user location as well. Due to the potential complexity and pessimism of the UDRE spatial degradations, these additional factors are not taken into account in user navigation solutions when comparing the different interoperability scenarios.

The test results contained no integrity failures. In all of the test scenarios the ephemeris errors were reasonably small and no serious impact due to orbital spatial degradation occurred. Nevertheless, the impacts of UDRE spatial degradation and design of Message Type 27 deserve further investigation. Generally, the degradation is compensated by a multiplicative safety factor. To further characterize the UDRE spatial degradation, a simulation was conducted based on the WAAS Phase I network and its service volume model. In the simulation, a minimum of five valid reference stations are required for a satellite to be flagged as monitored, and no a priori credit is taken for the orbit estimation. The results are presented in Figure 2.12, with the contour lines representing the values of the possible worst-case UDRE degradation

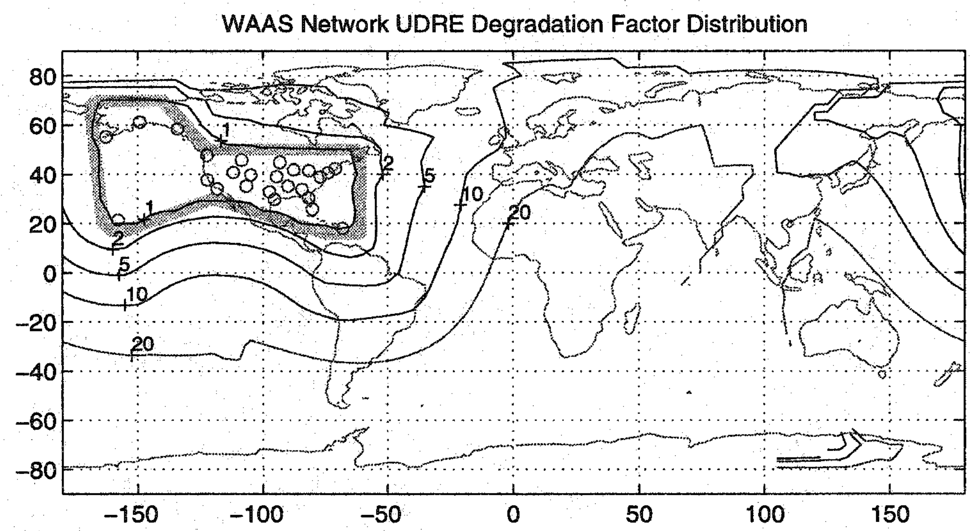

Figure 2.12: The UDRE spatial degradation factor as a function of user location for the WAAS network. The nominal service volume is predefined, as shown by the thick grey lines.

factors of all the satellites visible to a user as a function of location. It is observed that the worst possible UDRE degradation factors increase when users move away from the nominal service volume.

2.5.2 GIVE Spatial Degradation

Short term variations of the ionospheric vertical total electron content (TEC) in space and time are of great concern given the limited resolution of SBAS networks and the stringent bandwidth constraints. Ionosphere spatial and temporal decorrelations are known to be the most serious threats to WAAS accuracy and availability, but due to their physical energy constraints, the ionospheric anomalies are of lesser concern to integrity.

Unlike the UDRE, ionospheric corrections and GIVE are valid only for ionospheric pierce points inside each grid cell. Ionospheric spatial decorrelation is leveraged by two-dimensional vector quantization using the grid representation. As a result, for interoperation purposes, the ionospheric risk spatial distribution is relatively flat and bounded. Threats to the interoperability caused by the ionospheric spatial degradation can be as serious as those affecting the individual SBAS operation. In other words, spatial degradation does not pose a serious overall integrity concern specific to interoperability. En-route through LNAV operation modes are least affected in this regard.

Chapter 3

Interoperability Scenarios

Currently, at least three Satellite Based Augmentation Systems (SBASs) are under development: the European Geostationary Navigation Overlay Service System (EGNOS), the FAA's Wide Area Augmentation System (WAAS) and the Japanese Civil Aviation Bureau's MTSAT-Satellite Augmentation System (MSAS). Even though each system can operate as a stand-alone, regional system, there is an increasing interest in the interoperability of these SBASs. The desired result is potential cooperation and coordination among the different SBAS service providers that would support seamless worldwide aviation services [FLHR97].

3.1 Introduction

Though each current stand-alone SBAS by design only guarantees the specified service levels within its nominal service volume, the SBAS broadcast messages may still be readily available anywhere within its GEO footprints. As an illustration of this, Figure 3.1 shows the early phase networks of two major SBASs: WAAS and EGNOS and their operational INMARSAT-3 geostationary satellites, the Atlantic Ocean Region West (AOR-W, 55° west) and the Atlantic Ocean Region East (AOR-E, 15.5° west) satellites, repectively. Note that the footprints of the GEO satellites have much wider geographic coverage than the definition of the SBASs' nominal service volumes. Especially in the intermediate region over the wide area of Atlantic Ocean, both GEO

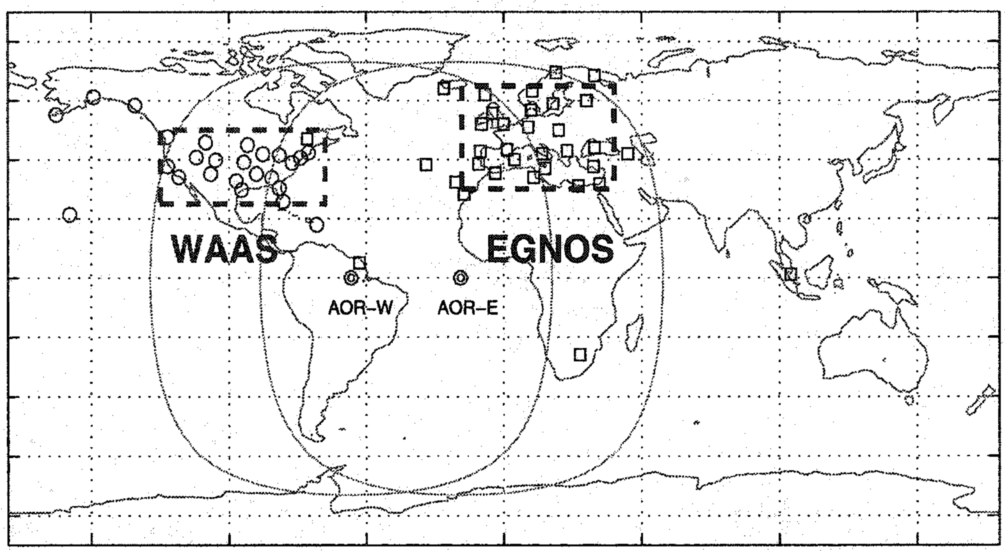

Figure 3.1: The WAAS and EGNOS network distribution and their primary service coverage, as well as the footprints of the GEO satellites, AOR-W (55° west) and AOR-E (15.5° west), respectively. Note: The circles stand for WAAS reference stations, the squares for EGNOS reference stations. The boxes with dashed line borders represent the primary service coverage areas of WAAS and EGNOS.

satellites will be visible, but neither of these two SBAS providers considers this region part of their nominal service area. This means that the level of service available in this region is not defined within the specification of current SBAS designs. Therefore, the intermediate region service quality becomes the major challenge in providing seamless global aviation service and the major issue of SBAS interoperability.

This interoperability analysis clarifies the meaning and scope of SBAS interoperability, characterizes the service levels available in the intermediate regions outside the nominal service volumes of SBASs, and quantifies the benefits that can be achieved through potential cooperation and coordination activies among SBAS service providers. There are several layers of cooperative efforts, including establishing a common interface standard, providing interoperable system components, and sharing complimentary information. This chapter focuses on the analysis of information sharing strategies at different levels among SBASs, including space segments, ground control segments, as well as airborne user segments. The primary goal is to evaluate different strategies and identify the optimal interoperability scenarios to maximize the global aviation service availability.

3.1.1 Definition

Interoperability has different meanings in different contexts [FLHR97]. Interoperability includes a variety of issues regarding all the potential cooperation and coordination activities among multiple SBAS systems. Here, we will address the SBAS interoperability in a systematic manner, from both the technical and institutional points of view.

Interoperability is generally defined as the ability of a system to share resources with other systems and to use the shared resources to enable multiple systems to operate effectively together. This ability to share resources forms the foundation of the potential joint operation of different systems and the operational transparency of each system. Put together for navigation, interoperability will enable the combination of all available resources to provide a more efficient and effective service and lead to a seamless worldwide navigation system.

3.1.2 Interoperability of SBASs

Specifically, there are three major layers regarding the interoperability of SBASs:

- **Interface Standard** is the common ground that enables the interoperability; it guarantees that each system and its components are speaking the same language so that everyone can understand each other. The signals from any SBAS, such as WAAS, EGNOS and MSAS, should comply with the the minimum standards agreed to by the RTCA Special Committee 159 and the International Civil Aviation Organization (ICAO) Global Navigation Satellite System Panel (GNSSP) [RTC98]. The signals should be usable by the same user equipment regardless of which SBAS generates them.

- **System Components** defines the interoperability in the physical layer. Components of the SBAS system are desired to be interoperable among different service providers, including those assets in space, on the ground, and in user aircraft. For example, the GEO satellites used by different SBASs might be used to help neighbor systems, especially when a space failure occurs. The wide area reference stations from one SBAS system might also exchange information with or act as backup for other SBAS systems. As for the user segment, a user equipment box should be interoperable, i.e., it should understand different systems, enabling seamless transition between SBASs.

- **Information** is the most important subject of interoperability. It answers the questions of greatest interest to us, such as, "What information can be shared?," "What information should be shared?," "How can information be shared?," "How can the shared information be used?," etc. The information content within an SBAS control segment mainly includes the raw measurements from each wide area reference station network, vector correction information and integrity information. As for the user segment, signal-in-space information from the SBAS broadcast is of the most interest from the interoperability point of view.

These three layers of interoperability form a complete hierarchy for the interoperability of an SBAS. The interface standards and system components compatibility pave the road for deeper layers of interoperability through information sharing among SBASs. Here, we will focus our attention on the interoperability of the information content, issues and decisions about what information to exchange, how to exchange it and how to use the exchanged information.

3.2 Interoperability Scenarios

SBASs are distributed systems due to their physical independency and spatial separation. The ability of distributed systems to provide complementary, cooperative and independent information has increased interest in the worldwide interoperability

[FLHR97] of continuous navigation services and in the standardization of international aviation.

3.2.1 Distributed Architecture

Each SBAS has a distributed architecture which consists of three segments: the *control segment*, the *space segment* and the *user segment*.

Each control segment has three hierarchical levels of abstraction. First, wide area reference stations (WRS) collect informative measurements and feed them into a wide area master station (WMS). Second, core algorithms and SBAS service messages are generated within the master station. Finally, the service messages are directed to a GEO uplink system (GUS) for broadcast to users through GEO satellites.

The space segment consists of GEO satellites that provide communication links and extra ranging signals to augment current GPS constellations.

3.2.2 Levels of Interoperability

The hierarchical architectures of SBASs allows different levels of interoperation and system optimization. Efficient information exchange and fusion can be conducted by either the control centers, the space segment or the user avionics in the raw measurement domain, the correction domain, the range domain, or the position domain.

Space Segment Scenarios

The potential interoperability activities in the space segment mainly include sharing GEO satellites and coordinating broadcast messages among multiple SBASs. Thus, cooperation in the space segment is desirable for most service providers, since the space segment cost is the dominant fraction of the overall infrastructure investment. The potential risks of launch failure and on-orbit satellite failure will create serious threats to system survivability. Therefore, leveraging this limited, high cost resource among SBASs can effectively reduce the total system risks and improve overall efficiency.

Control Segment Scenarios

Due to the hierarchical nature of the SBAS control segment, there are several possibilities for sharing information among different systems:

- **Sharing Reference Station Raw Measurement Level Information** In this case, the raw measurement level information is shared among SBASs. Each master station is responsible for processing all the available reference level information in order to generate differential correction messages. Figure 3.2 is an example of the information flow diagram.
- **Sharing Master Station Processed Correction Level Information** Each master station is responsible for processing only their own reference station network's raw measurements. The processed correction level information will be shared among SBASs. An additional correction level information fusion will be handled by each SBAS individually based on the shared information. An example of the information flow diagram is shown in Figure 3.3.

In either method, the combined information potentially provides better leverage for the system performance in the intermediate region between two SBASs to enable seamless transitions.

A special case of the above control segment scenarios is to exchange partial information among SBASs by sharing only several ground reference stations or to simply augment each individual SBAS by adding a few remote reference stations such that nominal service coverage is expanded to include the intermediate regions.

User Segment Scenarios

Airborne interoperability has the most flexibility. Even though the space segment and control segment are always independently operated by each service provider, there will be only one common user segment. When the signal-in-space (SIS) information from multiple SBASs enters a single avionics receiver, information fusion becomes natural. An example of the system information flow diagram is shown in Figure 3.4, where WAAS and EGNOS are used to illustrate the idea more intuitively. There are two

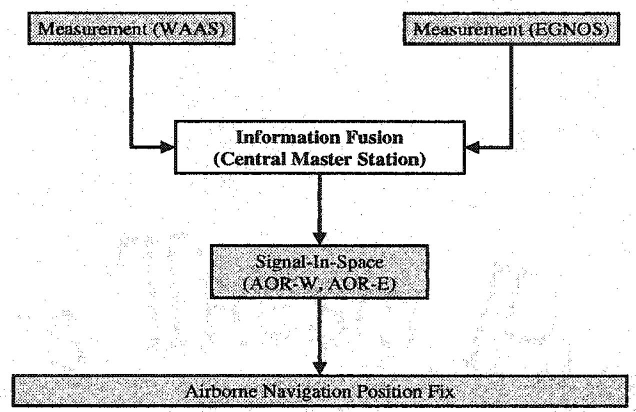

Figure 3.2: The information flow diagram of the *Central Master Station with Raw Measurement Sharing* scenario. For the purpose of illustration, an example of WAAS and EGNOS is used.

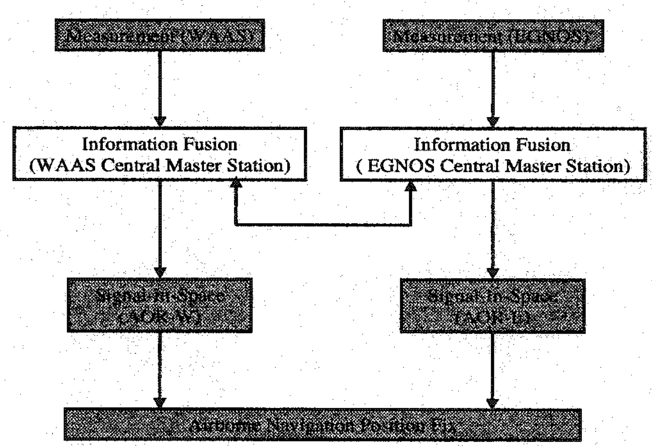

Figure 3.3: The information flow diagram of the *Master Station Level Information Sharing* scenario. For the purpose of illustration, an example of WAAS and EGNOS is used.

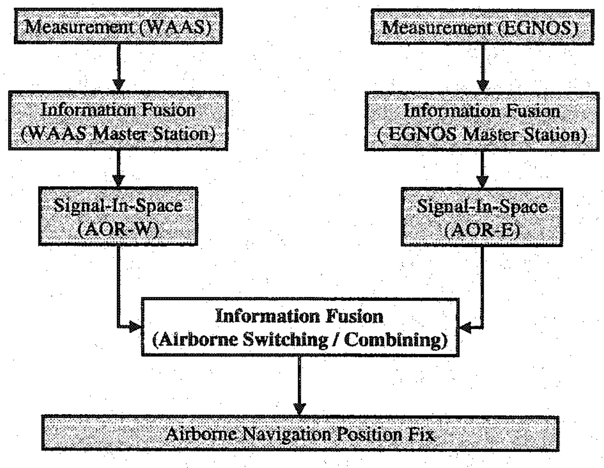

Figure 3.4: The information flow diagram of user segment airborne scenarios. For the purpose of illustration, an example of WAAS and EGNOS is used.

major possible scenarios for airborne equipment to use all the available information:

- **Airborne Switching** is the most straightforward and intuitive scenario. There are different SBAS switching rules. A simple way will be to switch at a fixed boundary between two SBASs. A second alternative is to maximize the number of monitored satellites in a navigation solution. Another possible option is to monitor both SBASs and calculate two independent position solutions, and select the one that provides higher availability. For example, one would use WAAS when it gave the lowest VPL and HPL and switch to EGNOS when it provided lower protection levels. This scenario achieves the best availability performance among different switching rules, and is the method selected for airborne switching throughout this thesis.

- **Airborne Combining** is a scenario combining all the signal-in-space information that is available from different SBASs in order to generate a combined

Component Layer	Information Layer				
	Raw Measurement Domain	Correction Domain	Range Domain	Position Domain	
Space Segment			2.1 GEO Ranging Sharing		
Control Segment	2.4 WRS Info Sharing	2.3 WMS Info Sharing			
User Segment		2.2.d Correction Combining	2.2.c Range Combining	2.2.b Position Combining	2.2.a Position Switching

Figure 3.5: The Major Interoperability Scenarios at different layers of the SBAS system in various domains, where the scenarios are indexed according to the IWG standards.

position fix. The achievable performance can be improved due to such information fusion. Within this category, there are several ways of combining the information, including use of the correction domain, range domain or position domain. Further discussions regarding airborne combining strategies follow with greater detail.

3.2.3 Major Scenarios

Put together, the major interoperability scenarios are listed in Figure 3.5. These major candidate operation modes for the interoperability regions, indexed according to the Interoperability Working Group (IWG) standards [Nie99a], include the following conceivable scenarios:

Scenario 2.1 Each SBAS provides integrity and correction information for the ranging signals from other visible geostationary satellites belonging to neighboring SBASs. For example, WAAS monitors the ranging signal of AOR-E and provides vector corrections and integrity information for AOR-E in the WAAS broadcast message. This scenario is based on the interoperability of the space segment layer where the signal-in-space specifications are compatible with each other. This increases the number of monitored satellites in the intermediate regions.

Scenario 2.2 The airborne receiver has access to signal-in-space (SIS) information from multiple SBASs simultaneously. Therefore, there are different ways of combining information. Specifically, the information fusion can take place in different domains, such as simple switching in the position domain (2.2.a) or combining information in the position (2.2.b), range (2.2.c) and correction (2.2.d) domains. For example, an airborne receiver has access to signals from both WAAS and EGNOS. Therefore, the user can simply switch between WAAS and EGNOS, or combine their information to improve service availability.

Scenario 2.3 Each SBAS integrates correction domain information from other SBASs into its own SIS. In this situation, processed information–instead of raw measurements–is shared among SBASs. Each individual SBAS master station will be responsible for integrating all the available information into the correction generation. For example, WAAS and EGNOS will independently process their own reference network's raw measurements first. Then the processed correction and integrity information will be exchanged. Finally, WAAS and EGNOS will be responsible for combining external information with their own observations and providing integrated navigation messages.

Scenario 2.4 Each SBAS expands its network geographic coverage and interoperation service volume to include the intermediate regions by adding some far field reference stations. Regarding implementation, the raw measurements are collected and centralized at the master station for correction generation. Therefore, the main strategy of this scenario is to enlarge service coverage by using extended network distribution. For example, WAAS can provide certain levels of services over the Atlantic Ocean region by employing additional remote reference stations in Europe. WAAS master station will be reponsible for processing the raw measurements from all the reference stations. Similarly, EGNOS can expand its coverage by adding some reference stations in America.

3.3 Major Scenario Analysis

This section discusses the four major candidate scenarios in greater detail.

3.3.1 Scenario 2.1

Each SBAS provides integrity and correction information for the ranging signals from other visible geostationary satellites belonging to neighboring SBASs.

Among all the alternatives, Scenario 2.1 is a first step towards interoperability. This scenario increases the number of monitored satellites in the intermediate regions [FLHR97]. For example, WAAS ground segment monitors the ranging signal of AOR-E and provides long-term and fast clock corrections and UDRE information on AOR-E in the WAAS broadcast message. Then the avionics can use AOR-E as an additional monitored ranging source in the navigation solutions. This scenario is based on the interoperability of the space segment layer where the signal-in-space specifications are compatible with each other. Furthermore, this scenario is part of the baseline plan of each SBAS development and is compatible with other scenarios. Since there are no significant design implications associated with this scenario, it will not be treated in further detail.

3.3.2 Scenario 2.2

The airborne receiver has access to signal-in-space (SIS) messages from multiple SBASs simultaneously, and conducts information fusion accordingly.

Scenario 2.2 encourages information fusion within the airborne receivers; this requires the least ground infrastructure augmentation costs and achieves a high flexibility and enhancement of interoperability performance. In this case, an airborne receiver in the intermediate regions has access to the SIS from multiple SBASs. The navigation solution is then calculated based on all the available information.

Scenario 2.2.a The most straightforward way is to switch among navigation solutions based solely on each individual SBAS. Information is not combined between the two SBASs. An airborne receiver can actively monitor signals from multiple SBASs and calculate independent position solutions, and select the one with the highest availability. For example, one would use WAAS when it gave the lowest VPL and HPL and switch to EGNOS when it provided lower protection levels. This scenario provides the highest availability among different switching rules and will be investigated further.

For the intermediate regions, the LNAV, and possibly the LNAV/VNAV, are among the most demanding service levels of interest. In these operation modes, unlike the stringent procedure required for GLS, airborne receivers are free to conduct and benefit from higher levels of information fusion to improve the achievable service performance. Typically, a mixture of satellite constellations monitored by different SBASs can be used in the position solution. There are several ways of combining information from multiple SBASs.

Scenario 2.2.b Position solutions based solely on each individual SBAS can be combined directly. In this scenario, the user would compute a navigation solution based solely on WAAS and a solution based solely on EGNOS. Then, these solutions can be combined to provide position estimates to achieve higher availability. Note that the network time difference between two SBASs is absorbed by the receiver clock component estimates instead of position components in the navigation solutions. Therefore, no specific process for clock synchronization between two SBASs is required. However, the combination algorithm should take into account the correlation between these two position solutions due to local error sources in the measurements. Furthermore, the benefit of this scenario is less significant when compared with the following two options, because simultaneous navigation solutions based on WAAS and EGNOS may not always be achievable. Therefore, it will not be discussed further.

Scenario 2.2.c Information from multiple SBASs can be combined in the range domain. The user will compute the full range corrections based on each SBAS separately. The range corrections for the commonly viewed satellites by two SBASs can be combined. Finally, all the corrected range measurements will be used to calculate navigation solutions. This scenario could provide higher availability than Scenario 2.2.b. For example, a user has five range measurements available, three of them can be corrected by WAAS and the other two by EGNOS. Though Scenario 2.2.b cannot help this user, Scenario 2.2.c will enable the user to compute a valid navigation solution.

Scenario 2.2.d The number of usable satellites can be maximized to enhance the aviation service level in the intermediate region. In this scenario, the user will combine all available information from WAAS and EGNOS in the correction domain to maximize the number of corrected satellites. For example, all the satellites monitored by either WAAS or EGNOS will be used to form a combined navigation solution after taking into account the clock offsets between WAAS and EGNOS networks. The fully degraded clock and ephemeris corrections from WAAS and EGNOS will be combined for the commonly view satellites. The fully degraded ionospheric corrections for the commonly monitored line-of-sight signals will be combined separately. The corrected range measurements will be used to calculate navigation solutions as if they were corrected by a single SBAS. This scenario provides the highest availability among all the possible airborne scenarios and will be discussed further.

For Scenario 2.2.c and 2.2.d, when mixed constellations are desired in the user position fix, the time offset between the different SBASs must be taken into account to guarantee the desired navigation performance. There are several candidate algorithms that can be applied to achieve this goal. Generally, the time offset can be estimated by the centralized master stations of SBASs or by each airborne receiver. The time offset estimation as well as the airborne receiver information fusion algorithms are described in the next chapter.

Of the four possible airborne scenarios discussed, Scenario 2.2.a is of great interest for its simplicity, and Scenario 2.2.d achieves the best possible availability. The performance of these two scenarios is further investigated in Chapter 6.

3.3.3 Scenario 2.3

Each SBAS integrates correction domain information from other SBASs into its own SIS.

Scenario 2.3 includes information exchange and fusion at the correction level among the SBAS master stations. The outcome of Scenario 2.3 should be virtually identical to 2.4 in terms of accuracy under nominal conditions. However, the methods of achieving these benefits are very different.

There are significant advantages to the exchange of information between SBASs. Information exchange has the potential to greatly improve availability for airspace in between the service volumes of the two SBASs. For example, the orbit estimation accuracy would be improved, and SBASs could share notification of outages and anomalies on satellites.

In this scenario, each SBAS provides navigation messages based on its own measurements plus information independently generated by other SBASs. There are serveral alternatives on how to exchange information. A possible alternative is to use separate terrestrial or satellite communication links to exchange information between master stations. However, this scenario requires some significant modifications on the SBAS design. Additional interface standards and algorithms have to be developed. Latency of information could be increased. Potential costs would also increase due to the required extra data links. Meanwhile, there are issues of security of accepting information from an outside source, highly cooperative efforts and trust between SBASs. Serious certification and liability risks prevent us from considering this scenario as a suitable interoperation candidate.

Another possible alternative is for an SBAS to listen to the broadcast of a GEO controlled by another SBAS without extra inter-SBAS communications facilities. The information could be rebroadcast by the receiving SBAS. However, this alternative is closer to Scenario 2.2, and latency of information would increase.

3.3.4 Scenario 2.4

Each SBAS expands its network geographic coverage and interoperation service volume to include the intermediate regions by adding some remote reference stations.

In this scenario, each individual SBAS ground design will take interoperability into account. Every SBAS will be independently responsible for a service provision in the intermediate regions by expanding the geometric coverage using additional external reference stations. This could also be achieved by exchanging all or part of raw measurements between SBASs to share costs. The exchange of raw data would provide the most benefit in orbit determination accuracy and enable the most complete integrity checks. It is desirable to provide LNAV service in the intermediate region as well as LNAV/VNAV in a subset of that region. However, the volume of raw measurements could be large.

In terms of algorithm complexity, there are no additional serious implications for the design of an SBAS in this case. There is, however, interest in the decision of where to place the additional remote reference station and, therefore, the subsequent optimization of the network geometry, latency and reliability of the signal, and potential economic considerations. For example, a few remote reference stations can be added to the current WAAS at a reasonable cost to expand its current service coverage over the southern portion of the U.S., and facilitate an eventual transition to an operational WAAS capability in Mexican airspace, as was the case with Canada.

Chapter 4

Interoperability Algorithms

4.1 Introduction

Information fusion by user avionics is flexible and efficient in the sense that no infrastructure interconnection, modification or extra investment is required on top of each fully functional individual SBAS. This flexibility leads to automatic compatibility with future participators, impressive benefit-cost ratio and efficiency. Only fully standardized services from all SBASs are suggested. A highly integrated system could then become a paramount character of future avionics. Multiple SBASs are simply treated as multiple independent sensors, and therefore can be readily integrated to provide high quality services.

The development of the key interoperability algorithms enables the feasibility of major interoperability scenarios and leads to their practical solutions. When mixed constellations are desired in the user navigation solutions, the time differences between SBASs must be taken into account to guarantee the desired navigation performance [RTC98]. Clock synchronization is therefore an important issue in terms of interoperation, especially for transient users between two independent SBASs. The high accuracy network common view time transfer (NCVTT) clock synchronization algorithm introduced here suggests that mixed constellation and multiple SBAS information fusion by avionics can be done to achieve seamless global high performance navigation services.

4.2 Information Fusion Theory

Information fusion theory is based on two fundamental theoretic frameworks: linear estimation theory and statistical hypothesis testing theory. While linear estimation theory defines the system optimality under nominal operating conditions, statistical hypothesis testing theory protects the system integrity during system anomalies. Put together, they form an optimal and robust platform for information fusion.

4.2.1 Linear Estimation Theory

Since an SBAS is a very complicated system, exact modeling is impossible. Appropriate abstraction and approximation is inevitable in system analysis, development and implementation.

Linear estimation theory uses the concept of linearizing about a nominal condition. This is a well-known, powerful, systematic design and analysis tool for complex systems. This is definitely applicable for the realization of an individual SBAS [EWP+96]. For example, different orbit determination algorithms are fundamentally based on the same linearization concept using different nominal trajectories. The nominal trajectory generation can be highly nonlinear, but due to its deterministic nature, as long as first-order linear approximation provides enough accuracy around the reference, it only decides at which point the linearization is conducted. A kinematic orbit estimator calibrates the nominal range by using the OCS-generated original GPS navigation messages [Tsa99]. A dynamic orbit estimator calculates the nominal range by using an independent satellite orbit estimate based on precise dynamic models [CBM+95].

Linear estimation theory is also crucial for interoperability of SBASs. The exchange of information between SBASs would potentially improve availability for airspace significantly. For example, the exchange of raw measurements would provide the most benefit in ephemeris determination algorithm accuracy and enable the most complete integrity checks. However, the volume of raw data could be large. Fortunately, linear estimation theory provides flexible alternatives. Generally, the exchange of information between multiple SBASs can be modeled as follows.

Linear System Description Let $\mathbf{y}_1, \cdots, \mathbf{y}_N$ be N separate vector observations of the same state vector, $\mathbf{x}$, such that

$$\mathbf{y}_i = H_i \mathbf{x} + \mathbf{v}_i \tag{4.1}$$

where $\{\mathbf{v}_i, i = 1, 2, \cdots, N\}$ are random errors uncorrelated with each other and with $\mathbf{x}$. H_i is the observation matrix. We assume that $\langle \mathbf{v}_i, \mathbf{v}_j \rangle = R_i \delta_{ij}$. We denote system state prior information by $\mathbf{x}_i^0$, its covariance by Π_i, and the linear least-mean-squares estimate (l.l.m.s.) of $\mathbf{x}$ by $\hat{\mathbf{x}}_i$. The corresponding error covariance matrices are defined as $P_i = \langle \mathbf{x} - \hat{\mathbf{x}}_i, \mathbf{x} - \hat{\mathbf{x}}_i \rangle$.

Here, multiple SBASs are simply treated as multiple independent sensors. For example, a satellite is commonly monitored by N SBASs. Each SBAS generates the ephemeris and clock corrections ($\mathbf{x}$) for the satellite independently. In other words, the i^{th} SBAS estimates the ephemeris and clock errors of the satellite as $\hat{\mathbf{x}}_i$ with covariance matrix P_i, solely based on its own raw measurements ($\mathbf{y}_i$).

Given the above linear system, the l.l.m.s. estimate of $\mathbf{x}$ given all the observations, $\{\mathbf{y}_i, i = 1, 2, \cdots, N\}$, can be obtained by [Kal60]

$$P^{-1}\hat{\mathbf{x}} = \sum_{i=1}^{N} (P_i^{-1}\hat{\mathbf{x}}_i - \Pi_i^{-1}\mathbf{x}_i^0) + \Pi^{-1}\mathbf{x}_0 \tag{4.2}$$

$$P^{-1} = \sum_{i=1}^{N} (P_i^{-1} - \Pi_i^{-1}) + \Pi^{-1} \tag{4.3}$$

where we assume a global prior, $\mathbf{x}_0$, and its error covariance matrix, $\langle \mathbf{x}, \mathbf{x} \rangle = \Pi$.

The global optimal estimates of the ephemeris and clock error ($\mathbf{x}$) based on all available information ($\mathbf{y}_1, \cdots, \mathbf{y}_N$) from N SBASs can be achieved by directly combining the state estimates from each individual SBAS. Therefore, exchanging processed data instead of raw observables would significantly reduce the volume of data exchanged without loss of optimality under nominal conditions.

The key conclusion from the above theorem is that, under certain conditions, each individual SBAS could achieve equivalent global optimality as a centralized processor by sharing only a minimum amount of high level information: state estimates, their error covariances and prior information. Furthermore, information fusion conducted at different levels, say the raw measurement, the correction, the range, or the position domain, could be equally optimal under certain nominal operating conditions.

However, above conclusions have their limitations during the system transition states when convergence could become an issue or linearity could not be applied. For example, special treatments are recommended for under-determined orbit and clock estimation. If we have three WRS observations at WAAS and two at EGNOS for a commonly viewed satellite, individually either could form a solution if no a priori assumed, but together they could. Therefore, certain amount of raw measurements could be exchanged between SBASs to handle such transition states.

Generally, optimal nominal solutions could not guarantee the service integrity by default. Therefore, certification requirements selectively recommend possible implementations in practice [RTC98]. Furthermore, statistical hypothesis testing theory has to be applied to protect the system integrity against anomalies.

4.2.2 Statistical Hypothesis Testing Theory

As linear estimation theory forms the foundation of optimal correction generation algorithms [EWP+96] and information fustion, statistical hypothesis tests can be applied to monitor the system consistency and protect the system integrity against anomalies.

Statistical hypothesis testing enables the justification of both nominal model fidelity and real time measurement quality. The relationship between testing statistics for nominal model fidelity and measurement quality based on the linear hypothesis testing theory is illustrated in Figure 4.1 [Leh97].

As shown in the figure, the origin represents the nominal reference point of Bayes prior [Leh97]. The innovation vector, $\mathbf{y}$, is the distance between the reference point and the measurement. The least square solution, $P\mathbf{Y}$, is the orthogonal projection of the measurement onto the observable subspace (the range of the observation matrix, H, column space). The regression residual, $\tilde{\mathbf{Y}} = (I - P)\mathbf{Y}$, is orthogonal to the

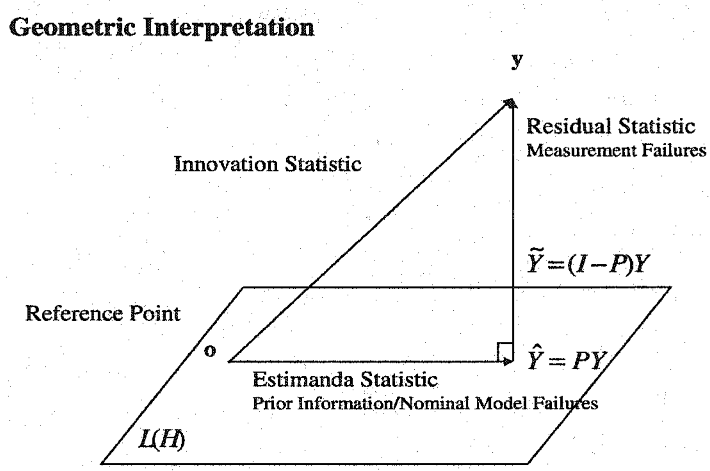

Figure 4.1: Relationship between testing statistics for nominal model fidelity and measurement quality based on linear hypothesis testing theory.

subspace, $\mathcal{L}(H)$. Notice the nominal reference points are relative, and depend on the choice of the Bayes prior information or the nominal model.

Under normal theory [Leh97], the norm distance between the nominal model and the measurement can be used to check system consistency. A commonly used norm distance is the Kullback distance measure [Cov91]. Typically, the first test statistic used for checking the consistency between the measurement and the reference point is the so-called innovation test statistic [PS94] [Pat89], i.e., the norm distance between the measurements and the reference point. This is an important consistency criteria. A second test statistic for checking the consistency among measurements themselves is the so-called residual test statistic. This is a important tool for monitoring the measurement outliers or anomalies. A third test statistic for checking the consistency between the nominal model and measurements is the so-called estimanda statistic, which is commonly used for checking the real system divergence from the nominal design model. These three test statistics are not independent test statistics; rather, they check the consistency between the nominal parameter space and the measurement space from different perspectives.

Such consistency tests should be conducted whenever information fusion is desired to protect the system integrity. For example, the optimal information fusion is based on the assumption that all SBAS converge on the same point in the linearization stage, which might not occur. The fidelity of such assumption can be tested using the divergence test. The consistency between the corrections generated by different SBASs can be monitored. Therefore, the following discussions of combining information from multiple SBASs will always be based on the assumption that information to be combined should pass the consistency tests. Furthermore, the clock synchronization algorithm in Section 4.4 treats the differences between the clock corrections from multiple SBASs as measurements to estimate the time offsets between these networks. Therefore, the residual test will be conducted to guarantee the consistency.

Statistical hypothesis testing has also been widely used in SBAS control segment master station data processing, including data screening, fault detection and correction generation [PT97] [Tsa99]. For example, the Stanford master station algorithm extensively utilizes these tests for measurement processing and correction generation. Measurement quality monitoring techniques have also been widely applied to receiver autonomous integrity monitoring (RAIM) algorithms [Kal98].

4.2.3 Interoperability Algorithms

Ephemeris Corrections Ephemeris information fusion can also be achieved straightforwardly at each control center by using the above optimal fusion theory. Ephemeris information is given by vector corrections with error covariances in matrix form. Full information about ephemeris corrections should be exchanged for both an optimal fusion and a full integrity cross check if extra communication links are available between master stations.

From the user side, an SBAS might only broadcast partial information. An example of this is WAAS sending out a combined confidence bound for clock and ephemeris corrections known as the user differential range error (UDRE) [RTC98]. Fully degraded clock and ephemeris range corrections from WAAS and EGNOS can be easily combined by users.

Ionospheric Corrections Sharing ionospheric information can be helpful not only for side-by-side networks, but also for far field networks to pre-adapt ionospheric estimators by providing early warning to each other, especially during ionospheric storm seasons. Integrating ionospheric information from neighboring networks might greatly enhance system integrity.

For typical compatible grid algorithms [RTC98], correction domain integration can be conducted equivalently by both control centers and users by employing the scalar version of information fusion for each commonly pre-defined grid. For incompatible systems, such as a tomographic scheme being used in an ionospheric estimator [Han98], correction domain integration is generally not applicable. For example, the non-linear obliquity factor transformation prevents being able to use two dimensional grid data for three dimensional tomography. Fortunately, range correction domain fusion conducted by each individual user can be always efficient and straightforward.

Besides ionospheric correction information from each SBAS, user autonomous information can also be integrated to improve service quality. Specifically, single frequency code-carrier divergence effects provide precise autonomous information about user ionospheric variations. This information can be fused with the ionospheric corrections from SBASs to generate more accurate and specific ionospheric corrections for each individual user [DWEP98a].

Integrity Information Fusion This method is normally straightforward: clock failures on a common view GPS satellite will be consistently detected and flagged by all monitoring SBASs. However, integrity warning due to satellite ephemeris anomalies can cause different integrity information among SBASs. Decision fusion must take into account UDRE spatial decorrelation and the ephemeris failure detectability of each SBAS network.

4.3 Clock Synchronization

When mixed constellations are desired in the user position fix, the time differences between SBASs must be taken into account to guarantee the desired navigation performance [RTC98]. Clock synchronization is therefore an important issue in terms of interoperation, especially for transient users between two independent SBASs.

According to RTCA MOPS design, the WAAS network time (WNT) will be synchronized to within 50 nanoseconds of GPS time, and 20 nanoseconds of Coordinated Universal Time (UTC) [RTC98]. It could be problematic to require the network times of different SBASs to remain within small tolerances of each other. In order to achieve such tolerances, it would require the time determination algorithm of at least one SBAS to steer its time towards that of another [FLHR97]. Generally, the potential time discrepancies among SBASs may not be a serious problem for the LNAV operation mode. Nevertheless, for the LNAV/VNAV operation mode, the time offset compensation is critical to the service availability due to the stringent requirements of vertical guidance.

The clock difference between two independent SBASs can be significant. An illustrative test result is shown in Figure 4.2, where the networks' master station clock difference is presented over about eight hours of data. Here, the National Satellite Test Bed (NSTB) networks were split into two independent networks for wide area correction generation. The master station clocks are maintained independently. Each SBAS processes its reference station measurements and generate corrections based on the master station clock. Due to the large discrepancy between the two independent master clocks, the corrections, even for the same satellite simultaneously monitored by both networks, are different by an amount similar to that between the master stations. The *true* time difference between two master station clocks were calibrated using the conventional Common View Time Transfer (CVTT) [EWP+96]. Note that the discrepancy between the two master station clocks reduces to a lower level for about 4 hours during the whole observation span. This is due to the fact that the SA degradation on one of the common view satellites, PRN 15, was turned off. Note also that, outside of this period of time, discrepancy on the order of several meters

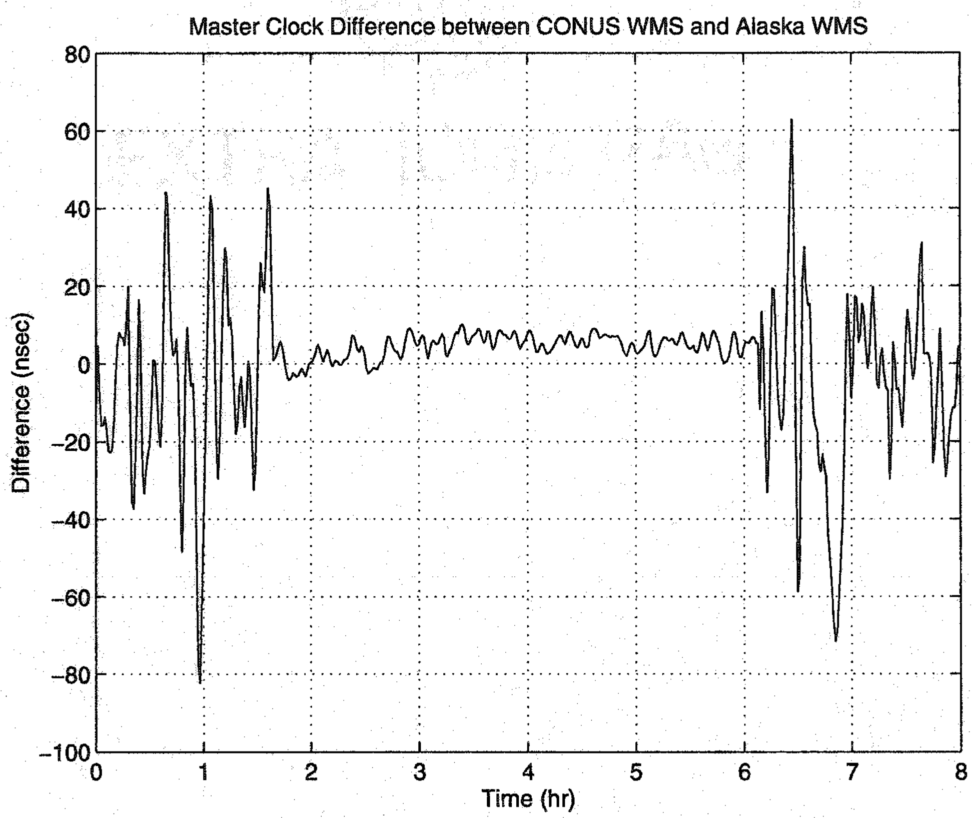

Figure 4.2: An example of clock difference between two independent SBAS networks. The data was collected from the National Satellite Test Bed (NSTB), where the network was split into two independent subnetworks. One subset was based on five Alaska reference stations with the master station at Sitka, and the other subset was based on the CONUS stations with Stanford as the master station. The result shows about eight hours of data. During the observation, a satellite (PRN 15) in view of both networks had SA turned off from 1.8 hours to 6.1 hours. Note the dramatic reduction of the clock discrepancy between these two networks during this interval (1 nano second is equivalent to 0.29979 meter range distance). Each network used the best weights for PRN 15 in clock estimations.

(1 nano second equals 0.29979 meter range distance) is normal.

Even though WAAS Message Type 12 defines the time difference between its network time and coordinated universal time (UTC), a more accurate network clock synchronization scheme is desired.

4.3.1 Network Common View Time Transfer (NCVTT)

A Network Common View Time Transfer (NCVTT) scheme is given by the expected value of the difference of estimated clock corrections for the commonly viewed satellites by two independent SBAS networks.

Denote estimated clock corrections for the jth satellite by $\hat{B}^j$, where $j = 1, \cdots, N$ is the index of the common view satellites by two independent SBAS networks, α and β. Then the difference between two network clocks can be estimated by, $E\Delta\hat{b}_{\alpha,\beta}(t)$, where

$$\Delta\hat{b}_{\alpha,\beta} = E_W[\hat{B}_\alpha - \hat{B}_\beta] \quad (4.4)$$

$$= \sum_{j=1}^{N} w_j(\hat{B}_\alpha^j - \hat{B}_\beta^j) \quad (4.5)$$

with weighting function, $\sum_j w_j = 1$, based on their covariance information. This algorithm is just a straightforward scalar version of the optimal fusion theorem, which is a short-cut equivalent to the full states matrix format estimation of the network differential clock. Note that this correction domain information fusion requires the decoupling of clock and ephemeris corrections. Otherwise, the variance estimation should take the cross correlation into account to protect the system integrity.

This clock synchronization algorithm only relies on corrections from both SBASs for commonly monitored satellites, therefore it can be easily implemented by either ground control segments or airborne receivers. The two different implementation examples, Ground NCVTT (GNCVTT) and Airborne NCVTT (ANCVTT), are illustrated in Figure 4.3 and Figure 4.4 respectively. GNCVTT is performed at the ground master stations with the result broadcast to the users through GEOs. ANCVTT is performed in the airborne receiver directly by listening to both SBASs.

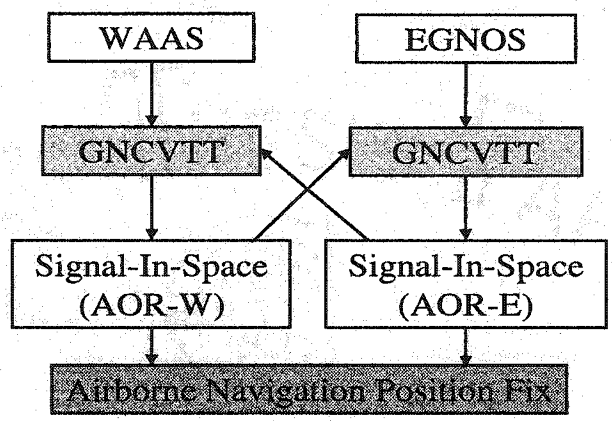

Figure 4.3: An implementation example of Ground Network Common View Time Transfer (GNCVTT).

An example of the common view satellite clock correction residuals after the Ground Network Common View Time Transfer is shown in Figure 4.5. It is observed that the correction residuals are well-behaved and within a meter level of agreement. The consistency between the common view satellite clock corrections guarantees the superior performance of this NCVTT algorithm.

4.3.2 Temporal Degradation Concerns

Considering the clock dynamics, the performance of the NCVTT synchronization algorithm will degrade with message latency and age and inter-system broadcast message time difference (IMTD).

Note that the NCVTT algorithm uses the clock corrections for the commonly viewed satellites by two independent SBAS networks. However, the correction messages are scheduled and broadcast by each individual SBAS. For example, one SBAS broadcast the clock correction message for a specific satellite at time T_1, and the

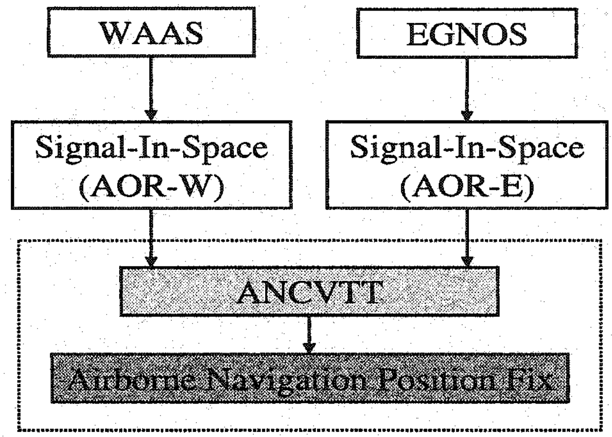

Figure 4.4: An implementation example of Airborne Network Common View Time Transfer (ANCVTT).

other SBAS broadcast the correction for the same satellite at a different time, T_2. We define the difference between the two time stamps, $|T_1 - T_2|$, as the inter-system broadcast message time difference (IMTD). The NCVTT algorithm requires that the corrections from each SBAS be fully degraded to compensate for errors due to IMTD. The major error source is correction message latency and age effect.

In general, message latency is defined as as the time taken to generate the correction messages plus the time spent for the SBAS error corrections to arrive at the user via a geostationary satellite. In practice, WAAS users must use the old correction message until the new correction message arrives. So we define message age, or total time delay, as latency plus the time interval between arrival of the old correction message and the application of the new correction message. Usually the major source of the GPS satellite clock error caused by the time delay is SA, which has a two to three minute time constant and changes quickly. Therefore, the clock corrections are part of fast correction messages and are sent much more frequently than any other message (every six seconds) [RTC98]. Though they do not decorrelate spatially, they tend to degrade fast temporally mainly due to SA.

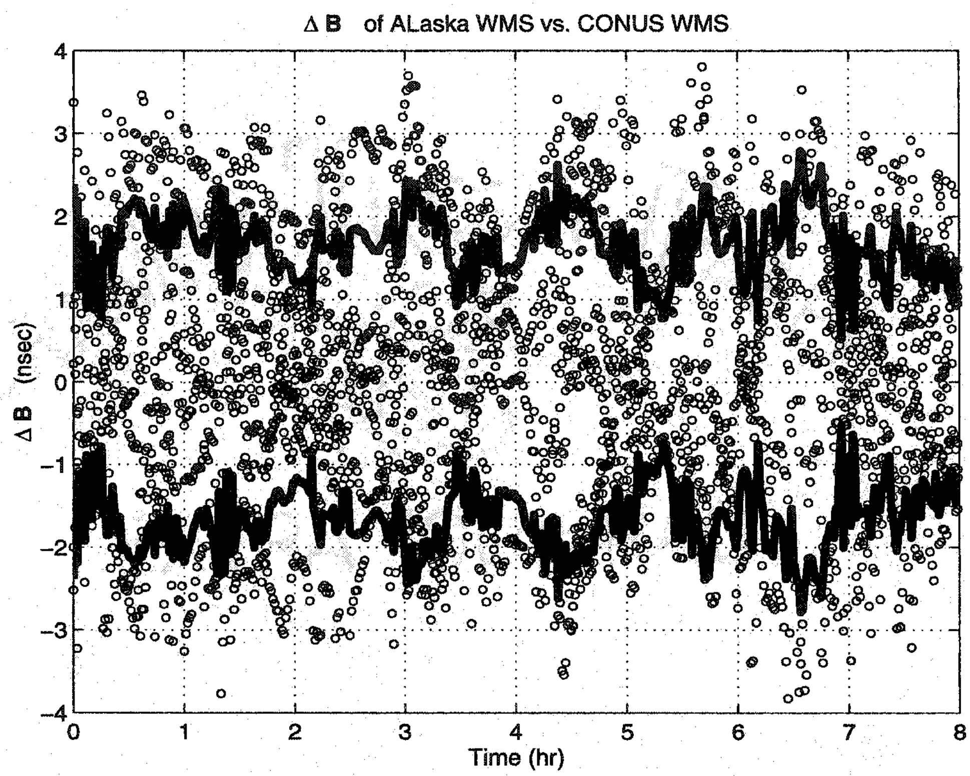

Figure 4.5: Clock correction residuals (ΔB) of common view satellites between two independent wide area networks after synchronization using the Ground Network Common View Time Transfer (GNCVTT) algorithm. The real data were collected from two independent wide area networks, the Alaska subset and CONUS subset of the NSTB networks. The circle stands for snapshot residual of the GNCVTT clock synchronization algorithm. The solid black lines present the corresponding snapshot sample standard deviation error.

There are different ways of using SBAS clock corrections. The clock correction can be applied directly as a constant bias during its age span, the so-called constant-corrected scheme. Another option is to develop a rate correction based on recently received corrections, known as the rate-corrected algorithm [RTC98].

We also define the NCVTT age effect as the time interval between calculation of the estimate of the clock difference between two SBAS network times based on old correction messages (via the NCVTT) and formation of the new estimate based on more recent correction messages from both SBASs. The performance degradation caused by IMTD and age effects is shown in Figure 4.6 based on real data. The data were collected from NSTB CONUS and Alaska independent subnetworks, where kinematic orbit estimators are used for both. The satellite clock corrections generated by each network independently. the NCVTT is conducted to estimate the clock different between these two networks. The NCVTT results are compared with the direct solution by calibrating the two master station clocks using the conventional CVTT. By changing IMTD between the correction messages from both network, the NCVTT performance changes accordingly. The results are shown in the Figure 4.6. It is also shown that the NCVTT age effect is negligible due to the stable high quality atomic frequency standard for both master stations. Error grows quickly with IMTD mainly due to SA. The rate-corrected algorithm, i.e., developing a rate correction based on recently received corrections [RTC98], performs better in the presence of IMTD compared with the constant-corrected scheme.

Note that the above synchronization process can be conducted equivalently by either control centers or avionics users simply by listening to the broadcasts from each SBAS. Normally, high performance atomic clocks will be used by each network, thus the mean clock differences between networks generally drifts slowly. As long as satellite clock corrections from independent SBAS networks are generated and received by users within a reasonable time interval (IMTD), the age effect would not become a serious issue.

However, if the clock synchronization is conducted at the ground control segments using the GNCVTT algorithm, the clock differences between networks has to be broadcast to users through GEOs. Since the time synchronization message chews up

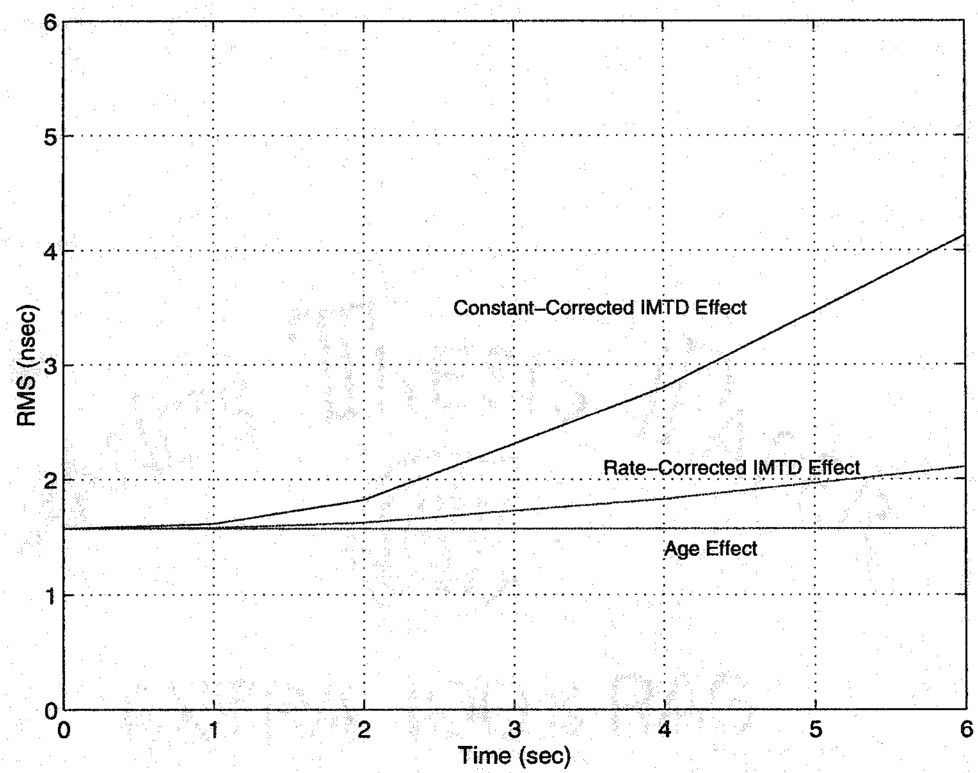

Figure 4.6: Network-CVTT clock synchronization algorithm performance in the presence of inter-system broadcast message time difference (IMTD) and age effects. Data from NSTB CONUS and Alaska independent subnetworks.

bandwidth and the ANCVTT algorithm can be applied as well or better in the air, this will be implemented in the air and not the ground.

This clock synchronization scheme enables mixed constellations in user position fixes. The integrity or consistency can be readily guarded by remote integrity monitoring stations. Multiple satellites commonly monitored by both SBASs are desirable from both integrity and accuracy viewpoints and can be generally guaranteed, especially with GEOs augmentation.

High accuracy NCVTT clock synchronization suggests that mixed constellation and multiple SBAS information fusion by avionics can be done to achieve high performance navigation services.

4.4 Airborne Navigation Algorithms

The airborne receiver algorithms can compensate for the time offset between SBASs and combine information from multiple SBASs in navigation solutions for enhanced availability in the intermediate regions. Here, we will illustrate the algorithms in detail. We assume that an airborne receiver has access to SIS information from both SBASs, specifically, the clock corrections and integrity information (UDRE) for navigation satellites.

Airborne Network Common View Time Transfer (ANCVTT)

The clock offset between SBASs can be estimated using Airborne NCVTT by simply listening to signal-in-space from both SBASs. The clock differences between the two networks and the corresponding confidence interval can be estimated by

$$\Delta\hat{b}_{\alpha,\beta} = \bar{E}[\hat{B}_\alpha - \hat{B}_\beta] \tag{4.6}$$

$$= \frac{\sum_{j=1}^{K} \frac{1}{({\sigma_\alpha^j}^2 + {\sigma_\beta^j}^2)} (\hat{B}_\alpha^j - \hat{B}_\beta^j)}{\sum_{j=1}^{K} \frac{1}{({\sigma_\alpha^j}^2 + {\sigma_\beta^j}^2)}} \tag{4.7}$$

$$\sigma_{\Delta\hat{b}}^2 = \max[\min_{j=1,\cdots,K} ({\sigma_\alpha^j}^2 + {\sigma_\beta^j}^2), \frac{1}{K-1} \sum_{j=1}^{K} (\hat{B}_\alpha^j - \hat{B}_\beta^j - \Delta\hat{b}_{\alpha,\beta})^2]. \tag{4.8}$$

where $\sigma_\alpha = \sigma_{\alpha,flt}$ is the fully degraded confidence interval, and $\hat{B}_\alpha$ is the combination of the fast and long term clock corrections:

$$\hat{B}_\alpha = PR_{corrected}(t) + \Delta t_{SV} + \delta\Delta t_{SV} \tag{4.9}$$

where $PR_{corrected}(t)$ is the fast clock correction and is calculated by using Equation A-16 of [RTC98]. The long term satellite clock correction, $\delta\Delta t_{SV}$, is computed by using Equation A-18 of [RTC98]. This correction will be added to Δt_{SV} as computed in Section 2.5.5.2 of [DOD95]. The above information can be easily applied to compensate for the clock difference between corrections from two SBASs. The estimated confidence interval uses a minimax function to achieve the highest availability with guaranteed integrity performance. Notice that the sample variance is used in calculating the prediction errors for each satellite clock correction. This is intentionally done for robustness and integrity considerations.

Airborne Navigation Solutions

As we mentioned before, there are many choices in airborne navigation algorithms. The information from multiple SBASs can be integrated at different levels. Scenarios 2.2.a to 2.2.d represent the different possibilities for information fusion, from simple position solution switching to combination of information in position domain, range domain or correction domain. As mentioned above, airborne switching requires the simplest logic.

Airborne Switching (Scenario 2.2.a) The airborne receiver listens to both SBASs simultaneously. Navigation solutions can be calculated using the weighted navigation algorithms described in Section 2.2.2 based on information from each individual SBAS. The protection levels for each position solution can be computed simultaneously. If only a single SBAS data can be used to form a solution, the airborne receiver will navigate using that SBAS. When two independent position solutions can be achieved based on the correction messages from individual SBASs, the user can simply select the one with lower estimated protection levels. For example, when a user flys from WAAS service volume to EGNOS primary coverage, airborne switching (2.2.a) can increase the overall availability in the intermediate regions and provide an effective transition between WAAS and EGNOS.

Airborne Combining (Scenario 2.2.d) Combining information based on mixed constellations can be quickly implemented in the airborne navigation solutions by applying the time offset estimates based on ANCVTT. A full state estimation achieves the optimal fusion of all the available information. With simplification, one can keep the set of corrections with higher availability as a master SBAS, say α, and slave the other one, β, by applying the time offset to all its monitored satellite clock corrections $(\hat{B}^i_\beta + \Delta\hat{b})$. The confidence interval is augmented correspondingly as $({\sigma^i}^2_\beta + {\sigma_{\Delta\hat{b}}}^2)$. The principle of master and slave selection between two SBASs is to keep the combined navigation solution with higher availability or lower protection levels. After this synchronization process, all the information available can be readily used in the navigation solutions as if it were from a single SBAS.

For example, the user has access to the correction information from both WAAS and EGNOS. Some satellites are monitored by WAAS only, some can be corrected by EGNOS only, and some are commonly viewed by both WAAS and EGNOS. By applying ANCVTT algorithm, the clock difference between WAAS and EGNOS $(\Delta\hat{b})$ and its variance $(\sigma^2_{\Delta\hat{b}})$ can be estimated therein. Assume more satellites in view can be corrected by WAAS than by EGNOS. Therefore, WAAS is selected as the master SBAS. The corrected range residual variance for the satellites monitored by WAAS only will be calculated directly using Equation 2.2. The error residual variance for range measurement corrected by EGNOS only will be inflated by $\sigma^2_{\Delta\hat{b}}$ after applying the network clock correction, $\Delta\hat{b}$. The fully degraded clock and ephemeris corrections for satellites commonly monitored by both WAAS and EGNOS will be combined and apply to the range measurements.

The fully degraded ionospheric corrections for the commonly monitored line-of-sight signals will also be combined separately. Consistency of information from different SBASs must be checked before integration based on the test described in Section 4.2.2. When the corrections to be combined are consistent with each other, the scalar version of optimal information fusion, a weighted average approach based on their variance information, will be used to combined them together. However, for the integrity consideration, the estimated variance of the combined correction will conservatively use the smaller variance of the two corrections being combined. Therefore, the corrections for a single range measurement might not necessarily come from a single SBAS alone. Note that MOPS currently requires that all corrections come from a single SBAS (Scenario 2.2.c) [RTC98]. The weighted navigation solution will be computed by using Equation 2.1 based on all the corrected range measurements as if they were from a single SBAS. Finally, the protection levels can be estimated using the same integrity equations in Section 2.2.2.

Airborne combining will further improve the service availability. For example, the user could have three satellites corrected by WAAS and another two different satellites by EGNOS. For this case, airborne switching (Scenario 2.2.a) is not applicable. However, by applying Scenario 2.2.d, all five satellite measurements could be combined to form a navigation solution in the airborne receiver after applying the ANCVTT to compensate for the time differences between WAAS and EGNOS.

The network common view time transfer technique is a very powerful tool for synchronizing the clocks of different independent SBASs. It can be readily applied to airborne equipment or applied to the ground control master stations of SBAS service providers for maintaining their own network clocks precisely synchronized to some common standard or to each other. The ANCVTT algorithm performance is justified by a real data example of results from an international joint interoperability test described in Chapter 6.

4.5 Time Offset Estimation Performance

Infrastructure requirements for interoperability can be minimized in airborne scenarios, leading to a high benefit-cost ratio. No modification of either original central processor or uplink module is required, thus preserving the independence of each original SBAS system design, operation, and maintenance. Therefore, it is recommended that

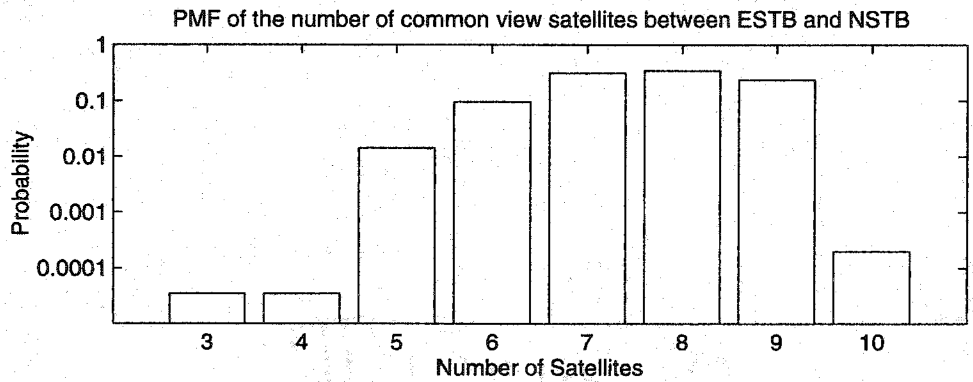

Figure 4.7: The probability mass function (PMF) of the distribution for the number of common view satellites monitored by both WAAS and EGNOS test beds during the interoperability tests.

the time offset between SBASs be compensated for by the airborne receiver to maximize the achievable availability, especially when the LNAV/VNAV operation mode is desired in certain intermediate regions. The recommended airborne navigation algorithm for Scenario 2.2.d and the associated time offset estimation method were given previously. Here, real data test results are presented to justify the availability of the scheme and validate the performance of the algorithm.

The availability of the common view satellites between WAAS and EGNOS test bed networks in Chapter 6 real data tests is presented in Figure 4.7, in terms of probability mass function (PMF) of the number of satellites that are commonly monitored by both networks. The overall performance of ANCVTT algorithm is evaluated in a 2D space of the true errors versus the estimated error confidence, as shown in Figure 4.8. The true errors are computed as the differences between the airborne estimated clock offsets and the master stations' clock offsets directly calibrated using conventional CVTT. The estimated error confidence is calculated by the airborne receiver using Equation 4.8. Note that both the availability and performance support the clock offset compensation requirements for the LNAV and LNAV/VNAV operation modes. Considering that the operational EGNOS and WAAS have more reference

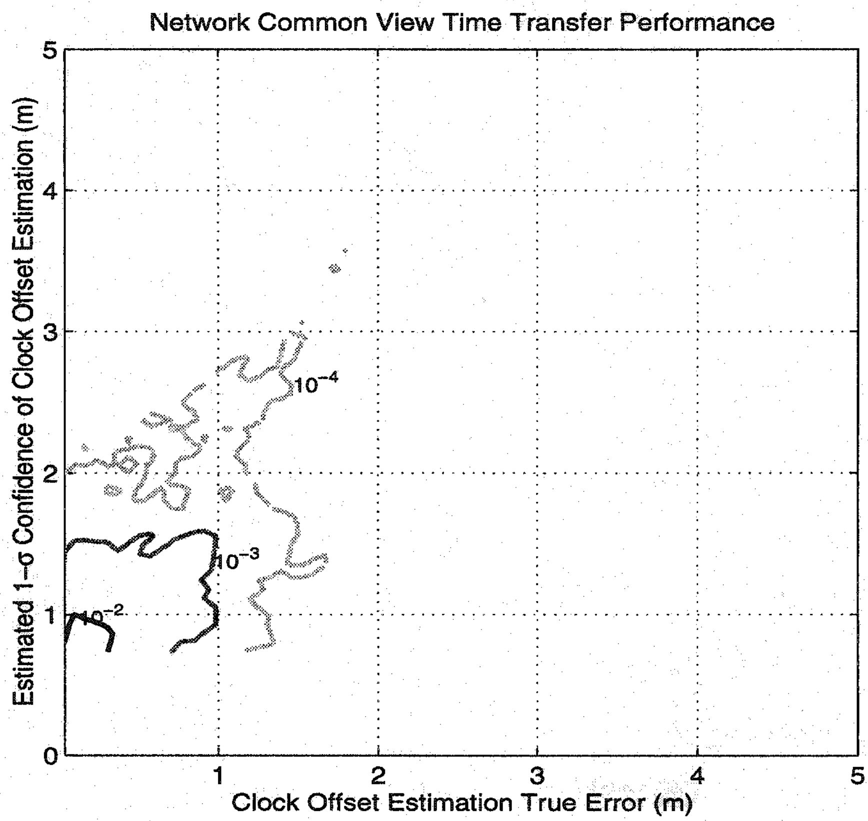

Figure 4.8: The performance of the time offset estimation method during the interoperability tests using SIS and the network common view time transfer algorithm conducted by airborne receiver under Scenario 2.2.d. The true errors are computed as the differences between the airborne estimated clock offsets and the master stations' clock offsets directly calibrated using conventional CVTT. The estimated error confidence is calculated by the airborne receiver using Equation 4.8. The results are presented in terms of a probability distribution in a two-dimensional space of true error versus estimated 1σ confidence interval. Contours of 10^{-2}, 10^{-3} and 10^{-4} likelihood of the error distribution are shown in the plot.

stations available, the statistic shown here projects a promising outlook for the applicability of the time offset estimation algorithms at airborne receivers for Scenario 2.2.d.

Chapter 5

Interoperability Benefit Analysis

Interoperability benefits can be characterized based on the fundamental performance requirements in terms of accuracy, integrity, continuity and availability. This chapter quantitatively evaluates the service performance improvement due to interoperability using real data results from the National Satellite Test Bed (NSTB) network. The method used here established an easy and powerful analysis framework for benefit evaluation.

5.1 Introduction

In order to justify the SBAS interoperability benefits, we partitioned the current NSTB networks into two independent subnetworks with each one functioning as an individual SBAS service provider. The two subnetworks include the CONUS subset and Alaska subset. Since the centralized combination of both subnetworks provides the best performance that can be achieved with the current available resources, the interoperability benefit evaluations are based on the the comparisons of the system nominal results between two stand-alone systems and the overall combined network benchmark scenarios.

The NSTB network partition is shown in Figure 5.1. The CONUS subset consists of all the continental reference stations with the master station located at Stanford University. The Alaska subset contains a total of five reference stations including a

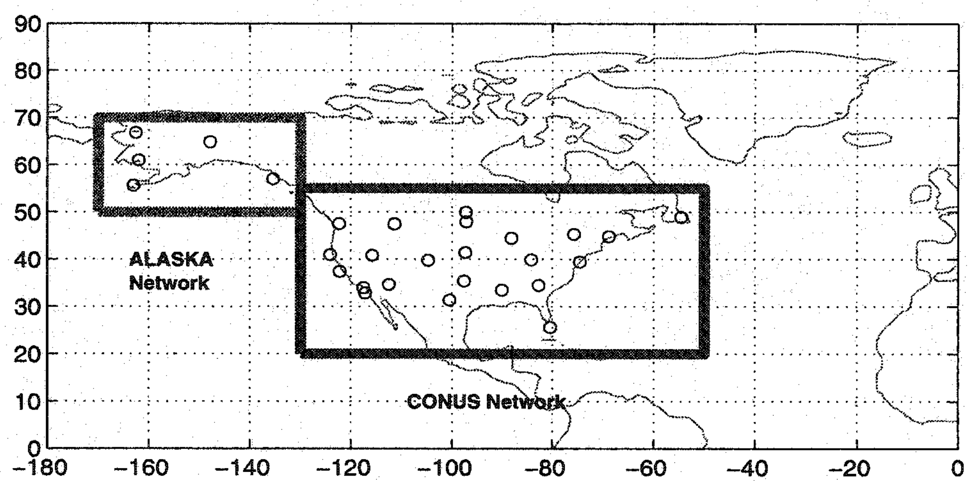

Figure 5.1: NSTB Network Partitions of CONUS and Alaska Subsets for interoperability analysis.

master station at Sitka.

5.2 Service Volume Model Analysis Framework

In order to quantify the benefits of interoperability, we established an easy and powerful availability performance analysis framework, or service volume model (SVM) analysis, for concept validation using real data analysis. The top level flow diagram of the availability analysis framework is shown in Figure 5.2.

The standard GPS constellation is used with the failure mode probability based on [SDH95][LDD+96], and both unscheduled and scheduled satellite unavailability models considered. The nominal clock/orbit and ionospheric correction error models are based on UDRE and GIVE distribution obtained from real data results for each specific network scenario, including Alaska, CONUS and combined networks. UDRE and GIVE distributions were spatially characterized based on the Stanford master station estimation output errors with a real data feed from NSTB networks. The troposphere residuals, multipath and noise models are based on real data statistics as well. User location is selected based on uniform sampling within the entire area

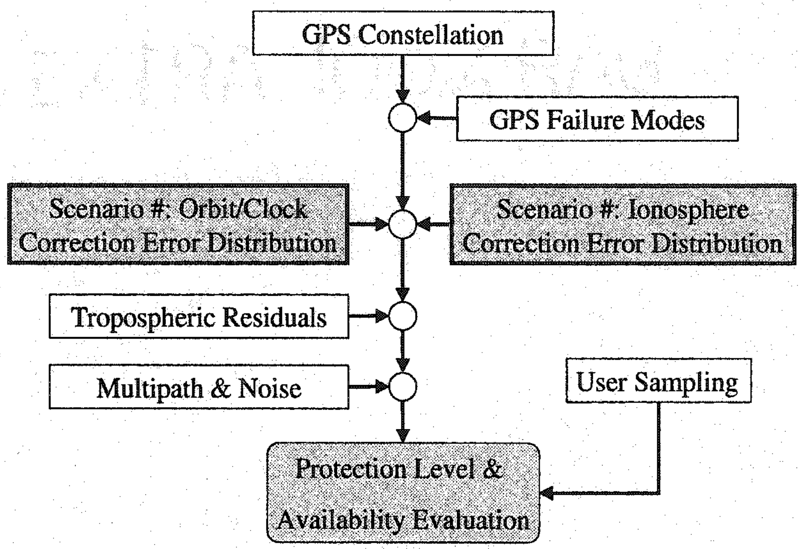

Figure 5.2: Flow diagram of interoperability availability analysis framework. The GPS failure mode probability is based on [SDH95]. The nominal clock/orbit and ionospheric correction error models are based on UDRE and GIVE distribution using Stanford master station estimation outputs with a real data feed from NSTB networks.

of interest. Navigation availability performance is justified based on the comparison between the estimated protection level and the alert limit for a certain operation mode.

The evaluation of the performance is based on the achievable service volume model (SVM) results of each network distribution. The availability performance of different scenarios, including each stand-alone network scenario, combined network Scenario 2.4, and airborne switching Scenario 2.2.a, therefore can be evaluated by simple substitution of the nominal orbit/clock and ionospheric correction error distribution models. The performance comparisons between different scenarios therefore can be obtained using results based on this same framework.

The current analysis framework provides a powerful real data-based simulation analysis tool for quantifying the SBAS interoperability service volume model. The concept is generic and effective and has been used in the *GPS Risk Assessment Study* [CHL+99] by the Applied Physics Laboratory at Johns Hopkins University as part of the underlying fundamental analysis tools.

5.3 UDRE and GIVE Distributions

The SBAS nominal performance for each scenario is evaluated in terms of user differential range error (UDRE) and grid ionosphere vertical error (GIVE) distributions based on the Stanford master station operation results using a real data feed from the NSTB network. UDRE distribution is determined by the error upper bounds on the true satellite ephemeris and clock errors in the satellite location domain based on the real NSTB network geometry and real data processing results. The GIVE distributions are determined in the ionospheric grid geometry domain. The distributions of these UDREs and GIVEs are conservative statistics of the true errors by definition and system design.

Nominal performance of NSTB CONUS, Alaska, and combined networks, quantified by UDRE and GIVE, are investigated and shown in Figures 5.3 and 5.4. The Stanford master station data processing algorithm is the underlying control engine for these evaluations. The results are based on data collected over three days, from

May 25th to May 27th, 1998, which were processed and averaged as the final nominal system performance baseline. In both plots, 99.9% level contour lines are quantized according to WAAS MOPS specifications. These values define the service performance that is going to be guaranteed through SBAS signal-in-space. Considering that these distributions provide an upper bound for the true confidences by design, the results are a conservative estimation of the nominal system availability performance.

For the UDRE distribution, a kinematic orbit estimator is assumed [Tsa99]. It is shown that each subnetwork provides high quality corrections for both satellites and the ionosphere within its local coverage. However, the vector correction estimation error of the satellite clock and ephemeris degrades quickly in the satellite location domain, as illustrated in Figure 5.3. Similarly, it is observed that GIVE is also a strong function of the wide area monitoring network distribution.

The performance of the combined CONUS and Alaska networks, characterizing the mutual benefits from the interoperation of two distributed SBASs, presents satisfactory services over a wider area than that of each individual subnetwork. Interoperability combines the strength of each individual network. Furthermore, information sharing among networks extends the service's overall coverage and enhances performance throughout a wide overlaying region.

5.4 Availability Benefits

The precision approach service is a significant challenge to SBASs. The current evaluation is a real-data analysis-based simulation framework [DWEP98b]. Therefore, there are several fundamental assumptions used in the analysis. The standard 24 GPS satellite constellation augmented by the optimally located 4 GEOs [PP97] (141.5°W, 113.5°W, 85.5°W, 57.5°W) is assumed, along with the standard probability of failures [SDH95]. GEO ranging errors are modeled as a function of elevation angle using [RTC98]. Figures 5.5 and 5.6 present the service availability of two independent subnetworks and performance of different interoperability scenarios, including airborne switching and combined network scenarios. 99.9%, 95% and 50% availability coverage contour lines are shown in the plots. The system nominal performance is

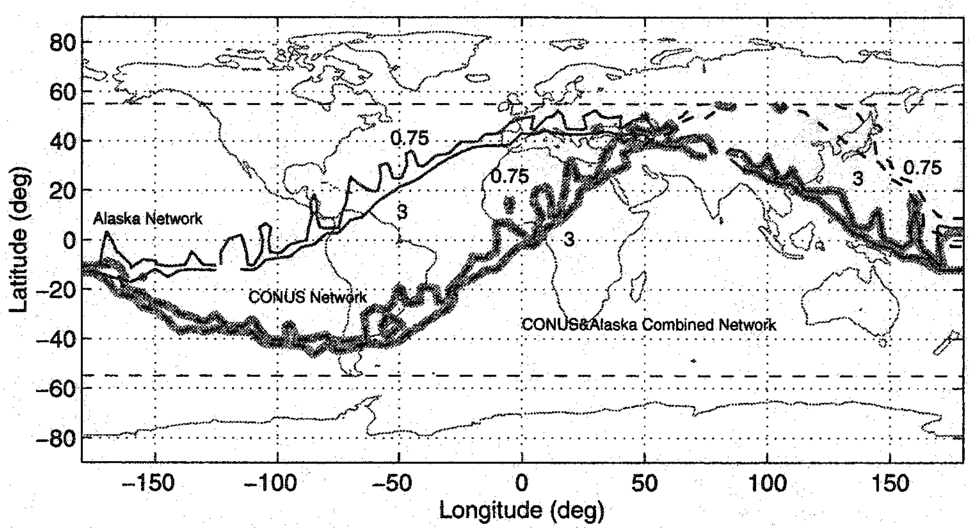

Figure 5.3: Nominal condition satellite UDRE distributions of NSTB CONUS (dashed lines), Alaska (solid lines), and Combined networks (thick grey lines). These contour lines show the comparison of 99.9% UDRE values among these three networks.

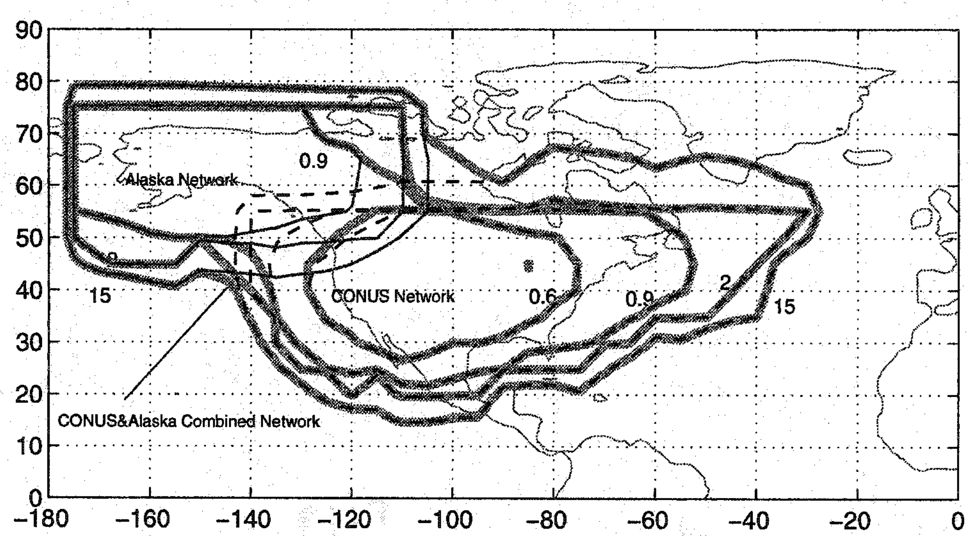

Figure 5.4: Nominal condition GIVE distributions of NSTB CONUS (dashed lines), Alaska (solid lines) , and Combined networks (thick grey lines). These contour lines show the comparison of 99.9% GIVE values among these three networks.

evaluated using the analysis framework described previously. The nominal orbit/clock and ionospheric correction error distribution is based on the NSTB live data as mentioned above and the nominal UDRE and GIVE distributions.

Note that precision approach service volume is mainly determined by ionospheric correction coverage, which is a strong function of network distribution. Meanwhile, each SBAS will be designed to provide inherent integrity within its service volume. Therefore, there are also potential trade-offs between service volume and nominal UDRE distributions due to spatial decorrelation [Dai98]. Interoperability can leverage these trade-offs and provide precision approach service for a larger area.

It is shown that each local network provides wide coverage of GLS full services with an availability of 99.9%. As shown in Figure 5.5, a user can achieve higher availability over the region in between by simply switching between two neighborhood SBASs. High level SBAS interoperation with information exchange can further enlarge GLS service volume, especially in the overlaying region, as shown in Figure 5.6.

Put together, Figure 5.7 shows that more than 90% of the combined network (Scenario 2.4) service volume with a 99.9% GLS availability can be achieved via simple switching by the user receiver (Scenario 2.2.a). Benefit evaluation for different network configurations will be further investigated in the next chapter.

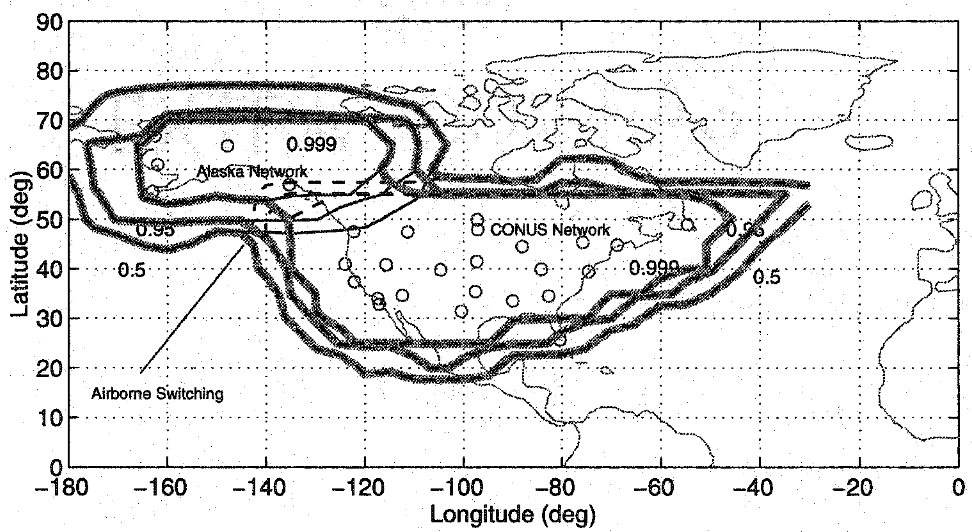

Figure 5.5: GLS availability of nominal operating NSTB CONUS and Alaska subnetworks. Dashed lines shows the achievable user performance by switching between two subnetworks for better services.

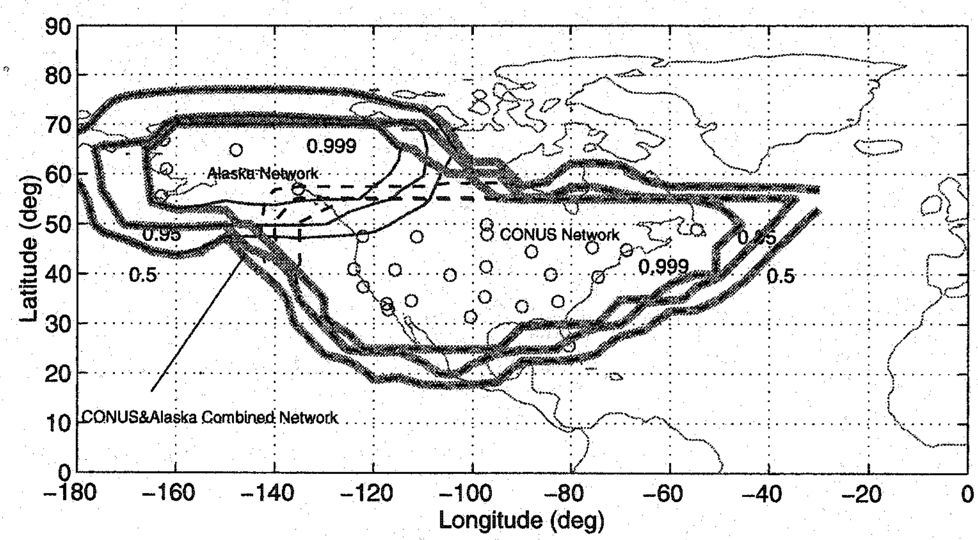

Figure 5.6: GLS availability of nominal operating NSTB with combined CONUS and Alaska network.

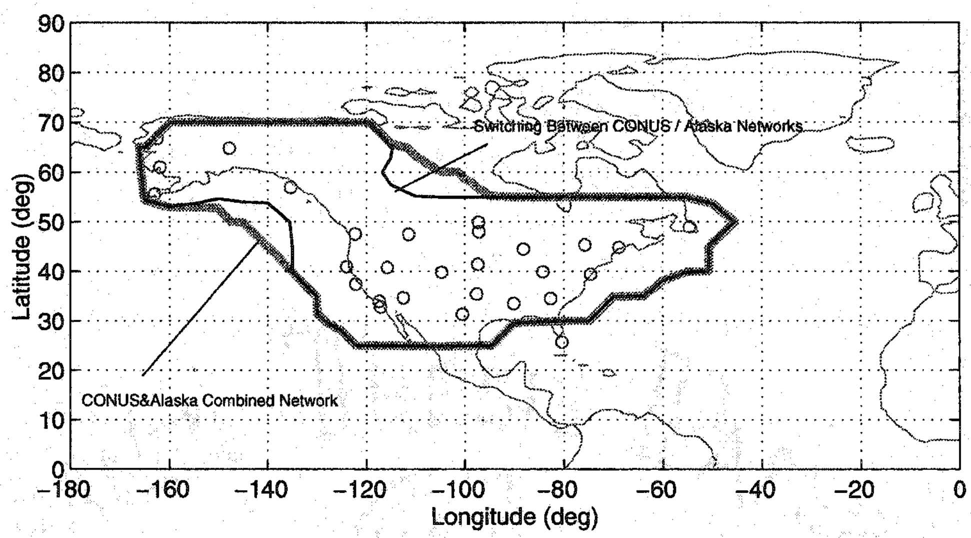

Figure 5.7: Comparisons of achievable GLS availability between the CONUS & Alaska combined networks and a simple switching by the user equipment.

Chapter 6

Interoperability Tests

The previous chapter demonstrated coverage and availability improvements due to cooperative efforts among regional subnetworks using the service volume model analysis framework. A recent Interoperability Working Group (IWG) meeting proposed a joint international test plan with cooperation between the National Satellite Test Bed (NSTB) and the EGNOS System Test Bed (ESTB) to quantitatively evaluate scenarios for interoperation [DWE+00]. These interoperability tests have been conducted independently by the European GMV S.A. Global Navigation Satellite Systems (GNSS) division, located in Madrid, Spain, and by the Stanford University WAAS Laboratory based on the same real data sets collected from ESTB and NSTB. Conclusions are drawn based on the results from both investigations. The agreement of the major conclusions in each study successfully consolidates the understanding of characteristics relating to interoperability among SBASs.

This investigation mainly consists of off-line static tests using the EGNOS system and National Satellite test beds. Figure 6.1 shows the geographic distribution of these two prototype networks and the interoperability area. The interoperability area is defined as an intermediate region between the EGNOS and WAAS networks, with latitude from 0° to $70°N$ and longitude from $85°W$ to $10°E$. To evaluate the system performance in each scenario, independent monitoring stations located between these two SBASs are selected from the global International GPS Service (IGS) network. The intermediate regions of interest are also illustrated in Figure 6.1. Note that only

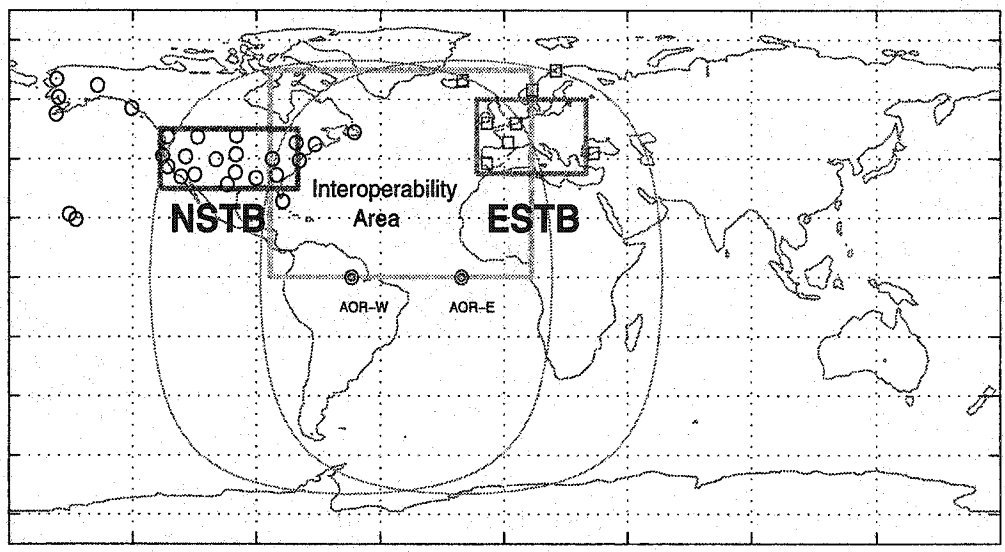

Figure 6.1: EGNOS and WAAS prototype test beds, ESTB and NSTB, network distribution and interoperability area of interest. Note that INMARSAT AOR-W and AOR-E provide sufficient coverage over the interoperability area (the intermediate regions between ESTB and NSTB networks) and will be assumed as the communication data links for broadcasting SBAS messages.

AOR-W and AOR-E satellites are considered here because they provide sufficient coverage over the entire interoperability region. The primary goal of these joint tests is to demonstrate the interoperability benefits between EGNOS and WAAS using the ESTB and NSTB. Evaluations will also focus on justification of the optimal interoperation strategies in terms of complexity, performance and practicality. In addition, core algorithms associated with these candidate scenarios are validated. The accurate and consistent synchronization algorithm NCVTT is crucial for LNAV/VNAV or the Non-Precision Approach with Vertical Guidance (NPV-I) operation mode. Furthermore, UDRE spatial degradation characteristics and a possible design for Message Type 27 is analyzed from the interoperability point of view. Conclusions based on these tests and analyses illustrate a promising future for achievable service levels in the intermediate regions between EGNOS and WAAS.

6.1 Interoperability Test Platform

6.1.1 National Satellite Test Bed (NSTB)

As described previously, the US National Satellite Test Bed (NSTB) is a research and development prototype that has been used to demonstrate various technical features of the FAA's WAAS concept. The NSTB currently has 18 reference stations in CONUS, three in Southern Canada, five in Alaska, two in Hawaii and one in Iceland. The present network of the NSTB provides a complete tool to conduct independent analysis of WAAS algorithms and a host of other related activities. Through the NSTB, the FAA will ensure the success of the WAAS and a future seamless GNSS.

6.1.2 EGNOS System Test Bed (ESTB)

In support of EGNOS system development, European Space Agency (ESA) has developed a real time prototype, called the EGNOS System Test Bed (ESTB)[NG99]. The ESTB is based on a network of eight reference stations spread over Europe that collect real time data from GPS, GLONASS and Atlantic Ocean Region East (AOR-E) satellites. These data are transmitted to a central processing center where differential corrections and integrity information are computed, and corresponding formatted messages are forwarded for uplink to the AOR-E or Indian Ocean Region (IOR) satellites. Several test users in Europe will then receive and process the EGNOS messages.

6.1.3 International GPS Service (IGS)

The International GPS Service global system has an international network of nearly 200 continuously operating dual-frequency GPS stations, more than a dozen regional and operational data centers, three global data centers, seven analysis centers and a number of associate or regional analysis centers. The Central Bureau for the service is located at the Jet Propulsion Laboratory, which maintains the Central Bureau Information System (CBIS) and ensures access to IGS products and information. An international Governing Board oversees all aspects of the IGS.

The IGS was formally recognized in 1993 by the International Association of Geodesy (IAG) and began routine operations on January 1, 1994, providing GPS orbits, tracking data, and other data products in support of geodetic and geophysical research. In particular, since January 1994, the IGS has made available to its user community the IGS official orbit of each GPS satellite based on contributions from the seven current IGS Analysis Centers. The IGS also supports a variety of governmental and commercial activities and develops international GPS data standards and specifications. Right now, the IGS global system of satellite tracking stations, data centers, and analysis centers has been successfully putting high-quality GPS data and data products on line in near real time to meet the objectives of a wide range of scientific and engineering applications and studies for years.

6.2 Interoperability Test Configuration

6.2.1 Real Data Characteristics

These tests have been based on the analysis of a full day of data, as the GPS constellation repeats about every 24 hours. In particular, data collected from August 24 to 28, 1999 have been analyzed. The conclusions presented here mainly focus on results from the 27th of August 1999. The conclusions are in agreement with the GMV S.A. study based mainly on the data collected August 28th, 1999 [NG99].

Nominal Reference Station Networks

The eight ESTB stations are shown in Figure 6.2. These ESTB stations are used as though they were the nominal EGNOS stations. Data from these stations are at a 1 second sample rate. A full day of data was available for most of the stations except Scilly (which was sampled irregularly at a much lower rate and had a total of about 50 minutes of data available).

The 21 stations of the NSTB used in this analysis are given in Figure 6.3. These stations are used as the nominal active reference stations in the tests. The data rate is also 1 Hz, and about 24 hours of data was available from these stations.

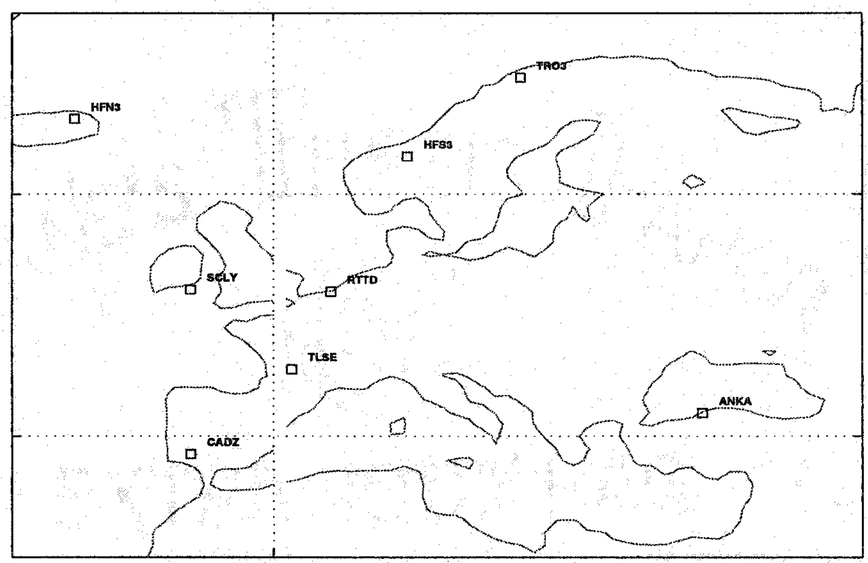

Figure 6.2: Eight ESTB reference stations used in the tests: Ankara (anka), Cadiz (cadz), Hofn (hfn3), Honefoss (hfs3), Rotterdam (rttd), Scilly (scly), Toulouse (tlse), and Tromso (tro3).

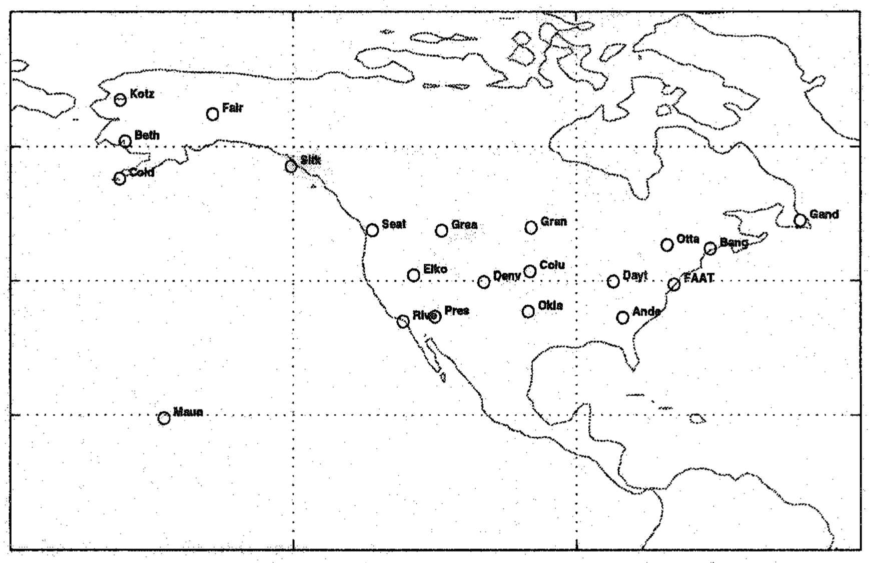

Figure 6.3: 21 NSTB reference stations used in the tests: Atlantic City, Anderson, Riverside, Seattle, Dayton, Prescott, Bangor, Greenwood, Columbus, Denver, Grand Forks, Elko, Oklahama City, Mauna Loa, Ottawa, Gander, Sitka, Fairbanks, Bethel, Kotzebue, and Cold Bay.

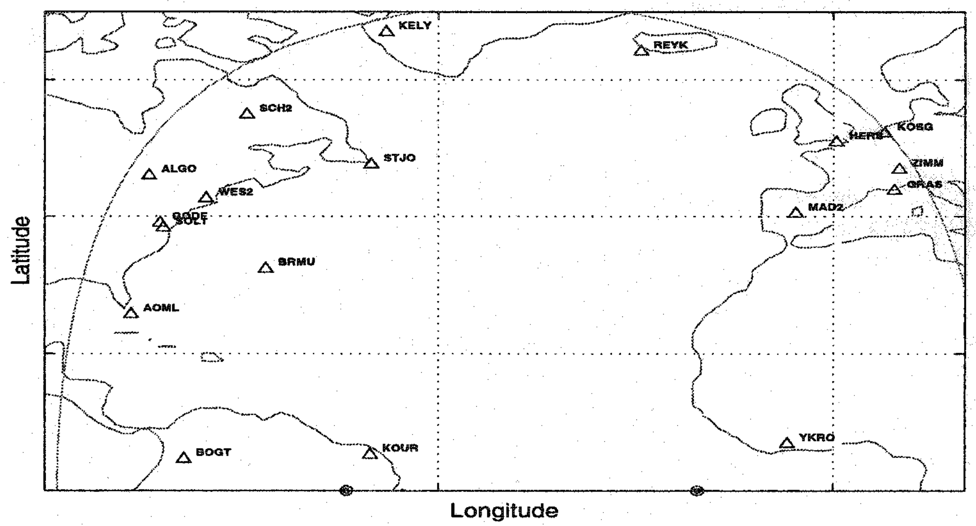

Figure 6.4: 18 static IGS reference stations used as independent monitoring users in the tests: Algonquin Park (algo), Key Biscayne-Miami (aoml), Bogota (bogt), Bermuda (brmu), Greenbelt (gode), Caussols (gras), Hailsham (hers), Kangerlussuaq (kely), Kootwijk (kosg), Kourou (kour), Robledo (mad2), Reykjavik (reyk), Schefferville (sch2), Solomons Island (sol1), St. John's (stjo), Westford (wes2), Yamoussoukro (ykro) and Zimmerwald (zimm).

Static Monitoring Stations

The IGS networks have been used as static independent monitoring stations. Eighteen IGS stations were selected and are presented in Figure 6.4. The sample period is 30 seconds with about 2800 samples per day available from most stations.

6.2.2 Test Configuration

The performance evaluations here mainly focused on the LNAV and LNAV/VNAV operation modes. Specifically, both modes share the same horizontal alert limit (HAL) of 556 meters, while LNAV/VNAV also has a vertical alert limit (VAL) of 50 meters.

The user position fix is based on the standard weighted navigation algorithm, and the Klobuchar single frequency ionospheric model is used when necessary for the LNAV mode. For the LNAV/VNAV operation, the vertical guidance protection level

(VPL) is calculated using the same concept as the VPL equation for the GLS mode defined in the RTCA MOPS [RTC98].

The Stanford University National Satellite Test Bed Master Station (TMS) central processing algorithm is used in the master stations for the SIS generation during the tests. The Stanford algorithm [EWP+96] is a major prototype candidate for the Phase II WAAS development. SIS of EGNOS and WAAS networks is assumed to be broadcast from AOR-E and AOR-W, respectively. Because ranging from these satellites was not available, they were considered as data links only.

6.2.3 Test Scenarios

Interoperability Benefits and Reference Scenarios

The following specific scenarios were used to quantitatively determine the relative benefits of interoperability:

- Reference stand-alone scenario: EGNOS with ESTB stations working alone.
- Reference stand-alone scenario: WAAS with NSTB stations working alone.
- Benchmark Scenario 2.4: Combined EGNOS and WAAS networks with ESTB and NSTB networks working together, using all reference stations to feed a centralized master station and SIS, as a single SBAS system. This is a special case of the generic extended network, Scenario 2.4.

Among these reference scenarios, the stand-alone scenarios present the baseline SBAS performance, while Benchmark Scenario 2.4 illustrates the optimal solution and the upper bound on performance from the interoperability point of view. Therefore, Benchmark Scenario 2.4 will be used as a limiting case against which the other scenarios are judged.

Airborne Scenarios

- Scenario 2.2.a: Switch between the available services. The airborne receiver has access to SIS from both EGNOS and WAAS, and navigation solutions are computed independently based on information from each. Service availability depends on the selection of the SBAS with a higher availability (lower HPL and VPL).

- Scenario 2.2.d: User estimates the time offset between the EGNOS and WAAS networks, then corrections are mixed to form the user position fix. The airborne receivers combine all information from both networks at the correction level to maximize the achievable availability. The algorithm detail was described in Section 4.4. Specifically, after applying ANCVTT process, all the information available is used in the navigation solutions as if it were from a single SBAS. The fully degraded clock and ephemeris corrections are combined for commonly viewed satellites by both WAAS and ENGOS. The fully degraded ionospheric corrections for the commonly monitored line-of-sight signals are combined as well.

For Scenario 2.2.d, information fusion is conducted at the correction level to maximize service availability. Within this context, compensation for the time offset between EGNOS and WAAS is critical for the LNAV/VNAV operation mode. There are several methods available for achieving this goal, such as actively synchronizing each master clock to a certain level of accuracy to the GPS or UTC time standard, or having time offset information estimated by master stations and broadcast to the user in Message Type 12, or using a network common view time transfer algorithm for airborne receivers to estimate and compensate the time offset on the fly. For most of these strategies, the accuracy and simplicity of these methods are all feasible solutions for the LNAV operation mode. Among these candidates, detailed analyses and tests based on the real data demonstrated that the airborne receiver network common view time transfer algorithm provides a satisfactory performance.

Extended Network Scenarios

- Scenario 2.4: WAAS with NSTB stations alone plus one additional ESTB station at Cadiz.

- Scenario 2.4: WAAS with NSTB stations alone plus two additional ESTB stations at Cadiz and Hofn.
- Scenario 2.4: WAAS with NSTB stations alone plus three additional ESTB stations at Cadiz, Hofn and Honefoss.

The stand-alone network plus additional remote reference stations to expand service coverage is of interest from the interoperability point of view in case only a single SBAS is available or airborne receivers would prefer to use Scenario 2.2.a (switching between services) for the sake of simplicity.

6.3 Evaluation Criteria

In this section, the tests results will be presented and analyzed in detail. The performance comparison of different scenarios are evaluated based on the key criteria, including accuracy, integrity and availability. It is noticed that among these key performance parameters, availability is the most comprehensive and of greatest interest. There are no integrity failures observed in the current test and system accuracy is extremely good for all cases. Therefore, conclusions are based mainly on the availability results of the different scenarios.

6.4 Interoperability Scenarios

6.4.1 Interoperability Benefits

The accuracy performance comparisons among the major reference scenarios are shown in Figure 6.5, where NSTB stand-alone and ESTB stand-alone systems, together with combined NSTB and ESTB network results are contrasted. This comparison illustrates the achievable accuracy benefits. The central bar represents the performance upper bound through complete or optimal interoperability. It is observed that the combined networks (Benchmark Scenario 2.4), capitalizing on the strengths of each system, perform consistently well for all users within the coverage area.

It is also noticed that the benefit of combined networks over switching between the two can only be appreciated by the users within the intermediate regions, since each stand-alone SBAS works equally well within its own service volume. Therefore, it is worthwhile to point out that the benefits due to data combination are not very impressive given these test results.

Further comparisons using availability analysis based on the real data will reveal in greater detail the regions that would benefit most from interoperability. Figure 6.5 also shows that at some stations, the accuracy of Scenario 2.4 looks even worse than stand-alone solutions. This observation reminds us that accuracy alone is not a complete or sufficient criteria. Since accuracy is based on the available navigation solutions, the number of samples used to conclude the 95% accuracy for each scenario is different. For example, in Bermuda, where neither NSTB or ESTB was available some of the time, Scenario 2.4 was available. Although Scenario 2.4 could provide sufficient corrections for the user to calculate a position fix by employing the combined NSTB and ESTB networks, the solution error could be relatively large due to the poor geometory. As a result, the 95th percentile of Scenario 2.4 navigation errors became larger than that of NSTB alone scenario.

As we see, Scenario 2.4 supports higher availability than the stand-alone solutions. Nevertheless, a key observation from these test results is that the SBAS system can work extremely well even for users far away from the active networks. For example, both the horizontal and vertical errors are rather small, as shown in Figure 6.5, even if an airplane keeps using WAAS when it is flying in Europe, or a user in the US navigates with EGNOS alone. The accuracy performance is extremely good, even for the stand-alone baseline system. It is not of concern for any of the different scenarios.

The availability performance for these three scenarios is presented in Figure 6.6. It is still valid to draw the conclusion from the results shown here that the most significant benefits of data combination go to the users in the intermediate regions. The availability of a stand alone system drops to zero very quickly as users move away from the active networks. This is especially true for the LNAV/VNAV operation mode and is mainly due to the very limited coverage of ionospheric corrections. The

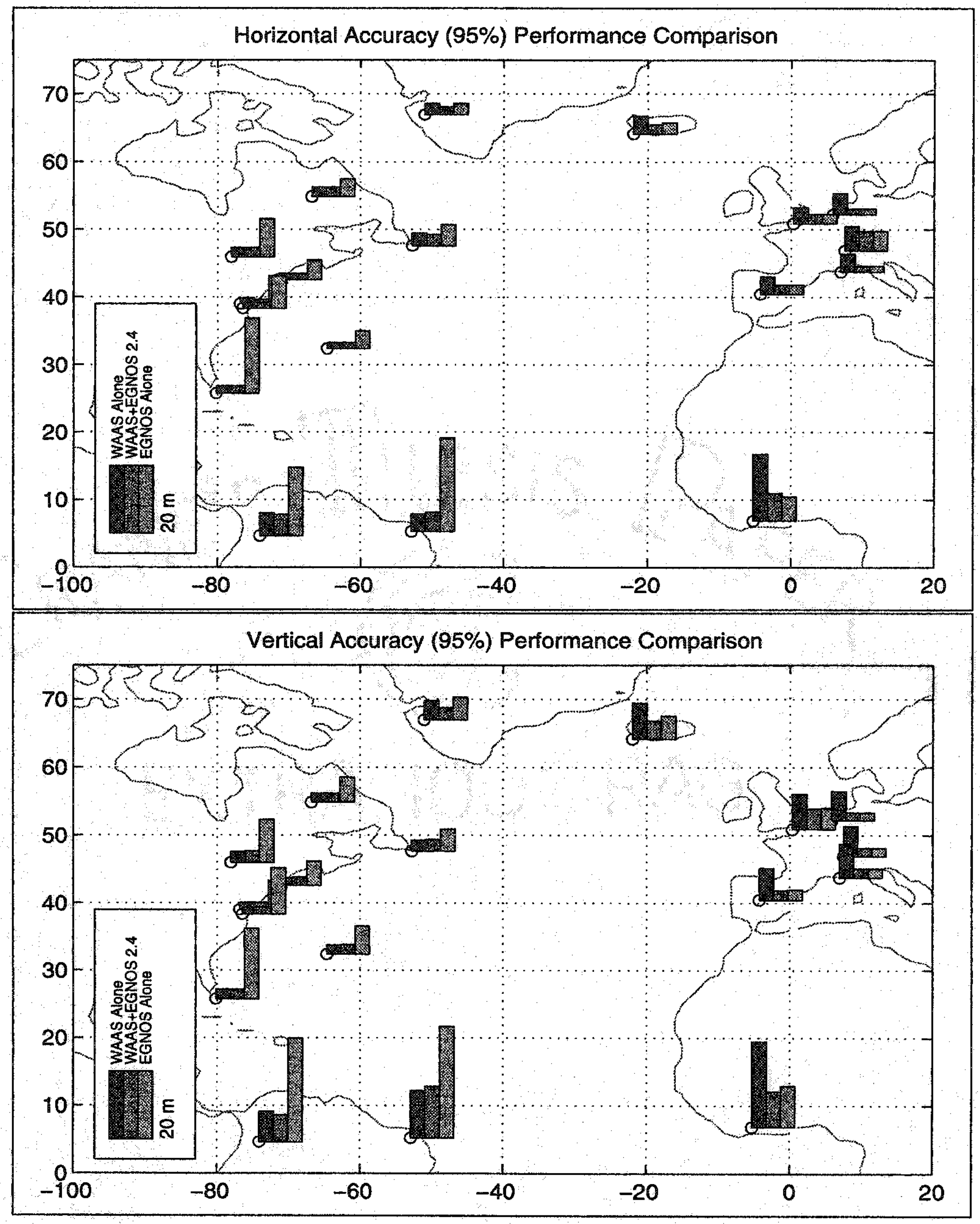

Figure 6.5: Comparison of horizontal (top) and vertical (bottom) 95 percentile accuracy performance of IGS static monitoring stations under different reference scenarios. The three types of bars represent different scenarios using different darknesses: NSTB stand-alone case, combined ESTB and NSTB network Benchmark Scenario 2.4, and ESTB stand-alone situation. A reference scale of 20 meters is shown at the bottom left corner of each plot. Note that a shorter bar represents better accuracy (smaller position error envelope) than that of a taller one.

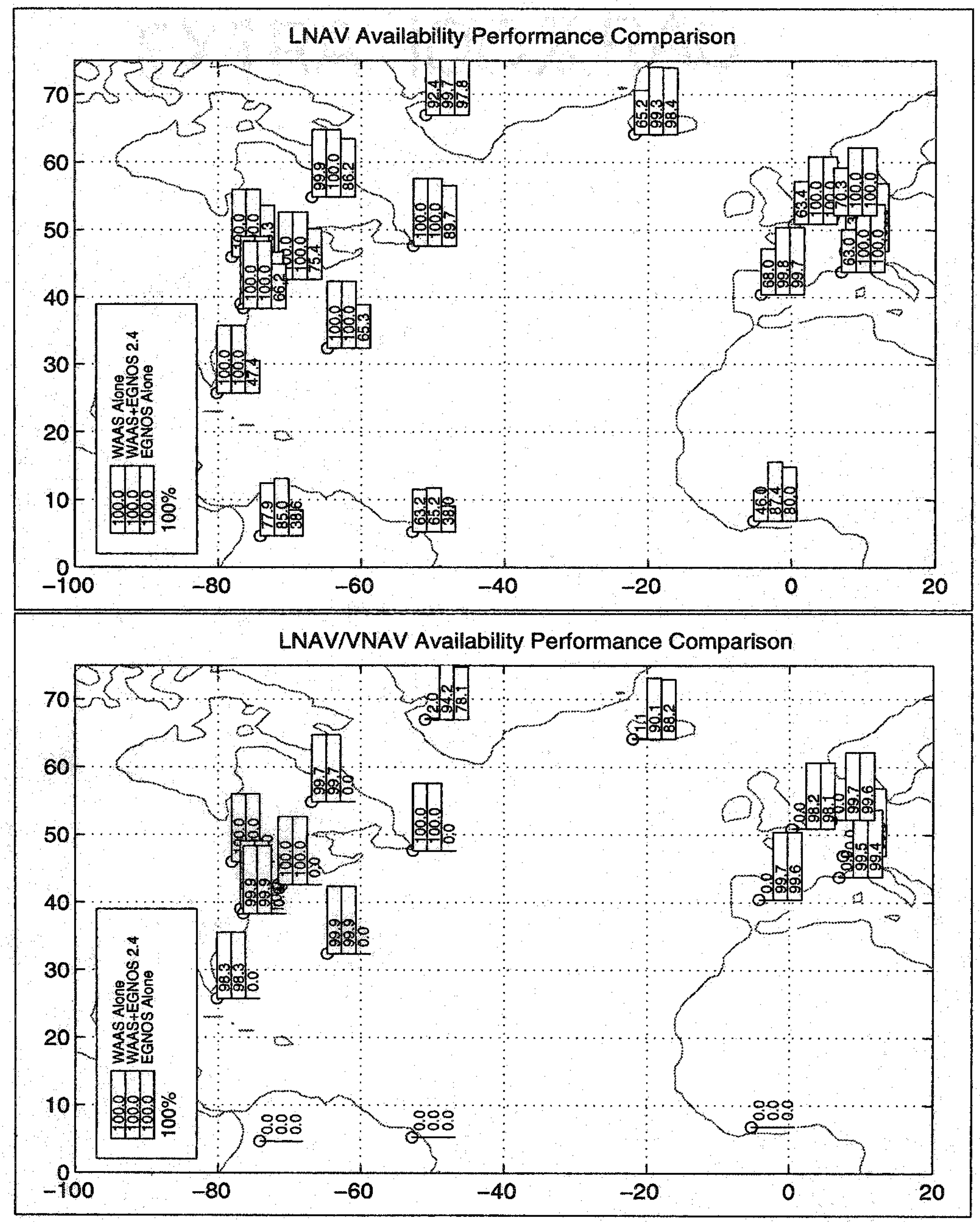

Figure 6.6: Comparison of LNAV (top) and LNAV/VNAV (bottom) availability performance of IGS static monitoring stations under different reference scenarios. A group of three bars at each reference station represents availability level under different reference scenarios: NSTB stand-alone, ESTB and NSTB combined Scenario 2.4, and ESTB stand-alone situation. A reference scale of 100% availability is shown at the bottom left corner of each plot. Note that a taller bar represents higher availability than that of a shorter one.

confidence on ionospheric corrections goes down faster than that on satellite corrections spatially. This, combined with the stringent requirement of the LNAV/VNAV mode on vertical guidance, makes the biggest difference between the availability of LNAV and that of LNAV/VNAV.

Put together, interoperability can effectively combine the strengths of both stand alone networks. It is not surprising to notice that the benchmark scenario of combined NSTB and ESTB networks performs best among the alternatives. However, there are very few cases when Benchmark Scenario 2.4 is much better than both NSTB alone and ESTB alone scenarios for either the LNAV or LNAV/VNAV approach. Therefore, further investigation of the benefits from data combination by a central master station in Benchmark Scenario 2.4 over other interoperability scenarios is of great interest.

6.4.2 Airborne Scenarios

The availability performance comparison between the scenarios of airborne switching (2.2.a) and airborne combining (2.2.d) are illustrated in Figure 6.7. The results of Reference Scenario 2.4 using ESTB and NSTB combined networks are also presented in the plot as the optimal theoretical benchmark for comparisons. As we concluded before, the benefits of optimal data combination only become visible for the users in the intermediate regions. Therefore, the performance comparisons presented in the figure only include those five IGS stations that fall into the regions of interest. It is also noticed that both airborne Scenarios 2.2.a and 2.2.d perform very well in terms of availability, and close to the optimal Benchmark Scenario 2.4. The results show that a simple switching algorithm used by the user between adjacent SBASs yields at least 95% of the benefits achievable with a much more expensive and complicated optimal solution. Further improvement by airborne combining can increase the service utility to more than 98% of optimal. Time offset compensation is recommended to maximize the service utility for this case. Test results regarding the candidate network distribution designs under Benchmark Scenario 2.4 illustrate that a few additional remote reference stations can effectively improve the stand-alone system overall performance and achieve desired interoperability for the intermediate regions. Specifically, for the

LNAV operation mode, the geometry of the active reference network is the most critical factor for service availability and coverage, while the network density and IGP selection rules are of greater importance for the LNAV/VNAV mode. No integrity failures were experienced at any of the stations for any of the scenarios.

Note that the simple switching scenario yields better results than one SBAS alone at a given location in the intermediate regions. This is because the airborne receiver listens to the SIS of both SBASs and conducts navigation solutions based on information from each SBAS independently. Service quality is based on the selection of the SBAS with a higher availability. Therefore, the switch occurs at different locations at different times due to satellite constellation changes.

Given that airborne switching Scenario 2.2.a can avoid explicit time offset estimation by switching between independently available SBAS services, it is of interest due to its simplicity. The airborne combining Scenario 2.2.d uses the network common view time transfer method to actively compensate the time offset between two SBASs, which enables a mixture of satellite constellations in navigation solutions to enhance overall availability. Therefore, it is not a surprise to notice that Scenario 2.2.d consistently outperforms 2.2.a, and performs close to the Benchmark Scenario 2.4. However, the differences are not significant enough to warrant anything other than the simple switch (2.2.a). A possible exception to this result exists for users in Greenland.

6.4.3 Extended Network Scenarios

The test results within this group are contrasted for justifying the cost effective network distribution design. The major candidates shown here include these scenarios: WAAS with NSTB network plus one additional reference station from ESTB at Cadiz, WAAS plus two additional ESTB stations at Cadiz and Hofn, and WAAS plus three additional ESTB stations at Cadiz, Hofn and Honefess.

For a fair comparison, the baseline WAAS stand alone scenario and the combined ESTB and NSTB network scenario are listed for reference in Figure 6.8. It is noticed that for both the LNAV and LNAV/VNAV operation modes, a few additional remote

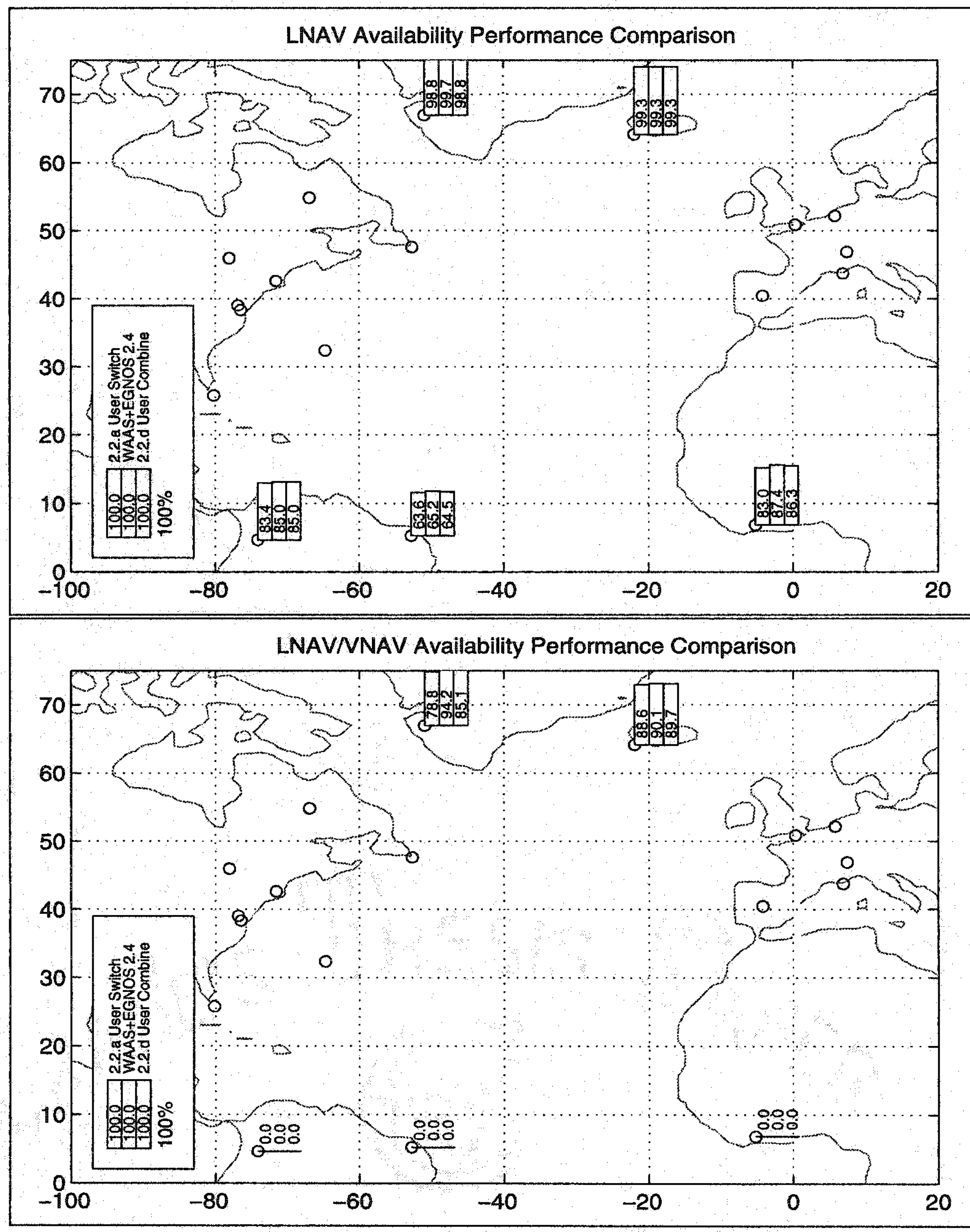

Figure 6.7: Comparison of LNAV (top) and LNAV/VNAV (bottom) availability performance of IGS static monitoring stations under Scenarios 2.2 and 2.4. Notice that only those stations are included where the extended network Scenario 2.4 outperforms any one of the stand alone SBASs. A group of three bars at each reference station represents availability level under different scenarios: airborne switching (2.2.a), combined ESTB and NSTB Benchmark Scenario 2.4, and airborne combining of information from both SBASs (2.2.d).

reference stations can have a large impact on availability for the users far away from the nominal active networks. It is easy to appreciate the availability benefit due to the network geometry with a wider spread of reference stations for the LNAV operation mode. A higher density network becomes necessary to expand the coverage of valid ionospheric corrections when the LNAV/VNAV service level is desired at certain regions. This service is a strong function of IGP selection rules and reference station placement. For this test we used the Stanford TMS rule requiring one ionospheric measurement within 1700 kilometers of the IGP to broadcast a correction [Wal98]. This is considerably less stringent than the WAAS Phase I rule [ABP+97]. LNAV/VNAV results will differ greatly depending on what rule is employed.

6.5 Further Evaluations

6.5.1 Far Field Interoperability

Based on previous analysis and test results, we have a comprehensive understanding about interoperability and its characteristics between the two most significant SBAS candidates: WAAS and EGNOS. There remains strong interest in extending the knowledge to the case of interoperability between two far apart SBASs, for example, the mutual impact between MSAS and EGNOS, or MSAS and WAAS. Considering that the real data resource is currently limited to the WAAS and EGNOS prototype systems, justifying interoperability between MSAS and WAAS or MSAS and EGNOS needs to rely on certain approximations.

Therefore, we selected a subset from the NSTB network, the WAAS prototype system. It consists of the Pacific coast NSTB (NSTB/PC) stations in Alaska and Hawaii, and a few west coast reference stations. This subset is treated as one independent SBAS prototype system in the following tests. A second independent SBAS is still based on the EGNOS test bed network. It is a reasonable test system in the sense that the spherical distance between these two currently far apart SBAS networks is similar to that between MSAS and EGNOS, as well as MSAS and WAAS. The time zone difference between these three systems is always approximately less than eight

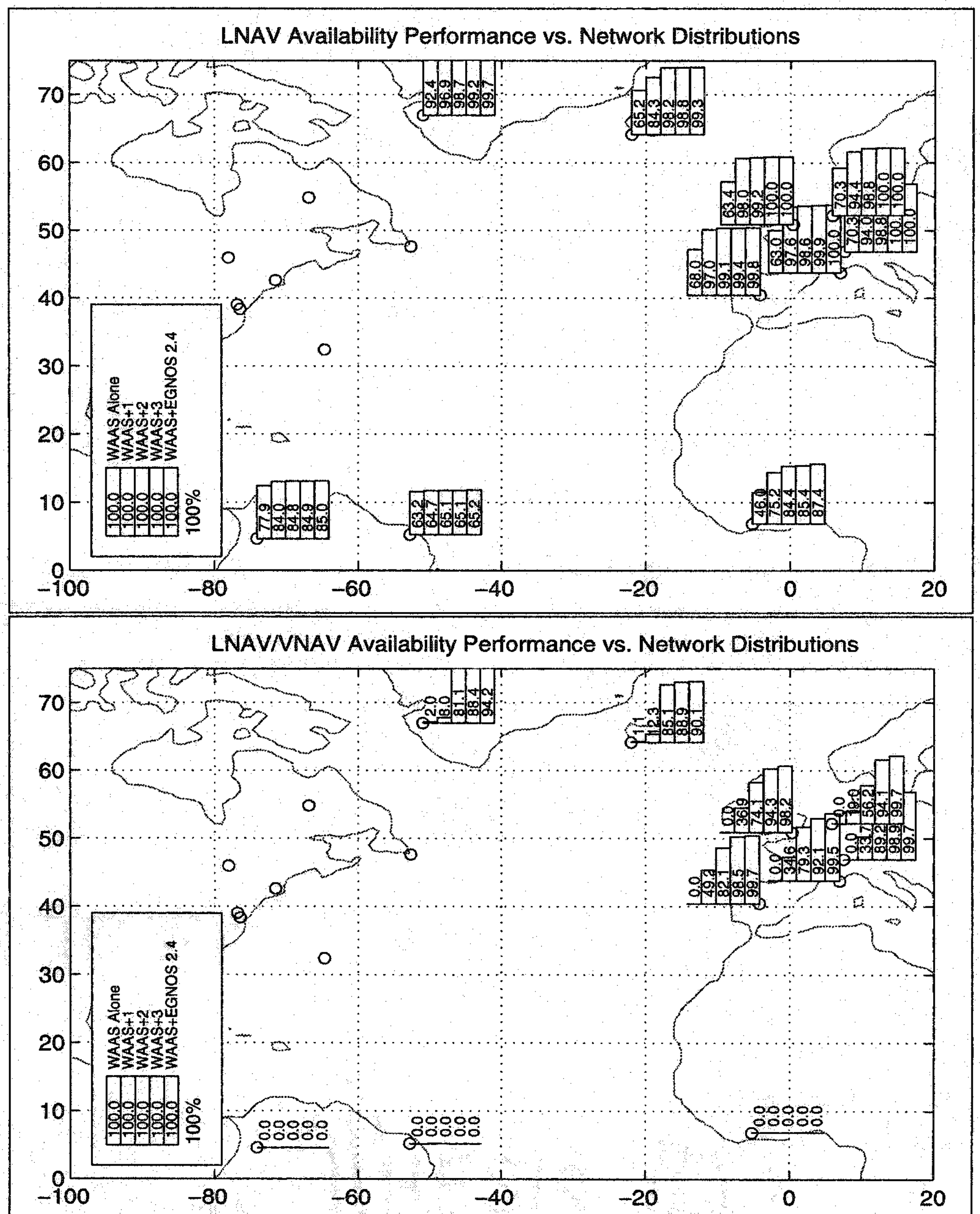

Figure 6.8: Comparison of LNAV (top) and LNAV/VNAV (bottom) availability performance of IGS static monitoring stations under Scenario 2.4 regarding the distribution of a SBAS reference network. Notice that stations included are only those that weren't provided full coverage by WAAS alone. A group of five bars at each related reference station represents availability level under different scenarios: WAAS working alone, WAAS plus one EGNOS reference station (Cadiz), WAAS plus two EGNOS reference stations (Cadiz and Hofn), WAAS plus three EGNOS stations (Cadiz, Hofn and Honefoss), and Benchmark Scenario 2.4 with combined WAAS and EGNOS networks.

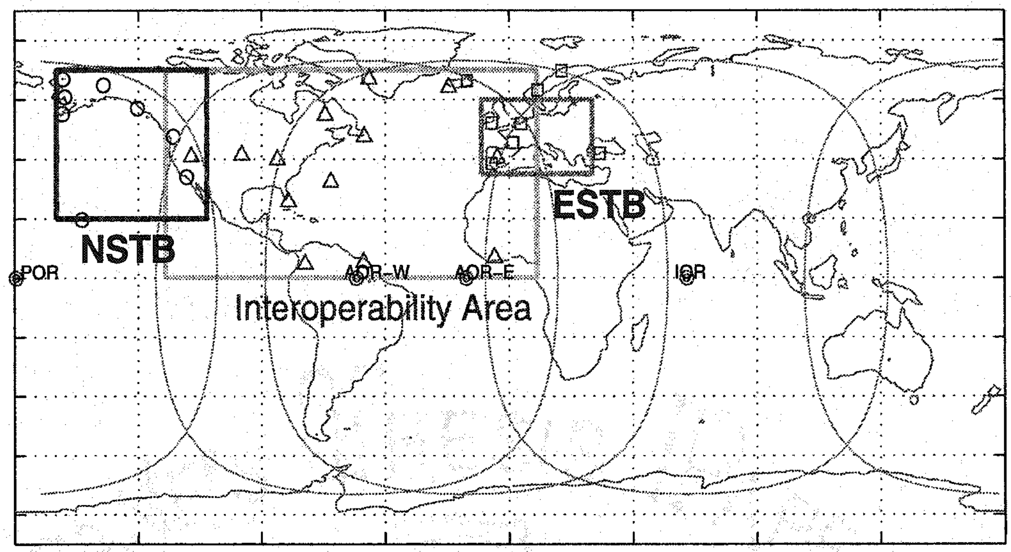

Figure 6.9: The test platform for far field interoperability tests using the NSTB and ESTB networks. Several NSTB reference stations are used as passive monitoring stations to evaluate performance of each scenario. The circles stand for the Pacific coast NSTB (NSTB/PC) network reference stations forming a wide area augmentation system, including five Alaska stations, as well as stations in Mauna Loa, Seattle and Riverside. The rectangles stand for the ESTB reference stations, the same as those in the previous tests. The triangles stand for the passive monitoring static reference stations, including several IGS stations and three NSTB stations, including Elko, Columbus and Dayton.

hours. The SBAS networks used in current tests is shown in Figure 6.9. Note that the distance between the two networks is similar to that between EGNOS and MSAS. Therefore, the results from the tests should be applicable to far field interoperability issues. As shown in the plot, the interoperability region is enlarged to cover the whole intermediate field of greatest interest from the global aviation transition point of view.

Here, we assume the communication satellite AOR-W will relay the information from both networks, which makes the signal-in-space information available for the users in the intermediate region. We also conducted the same test scenarios as we

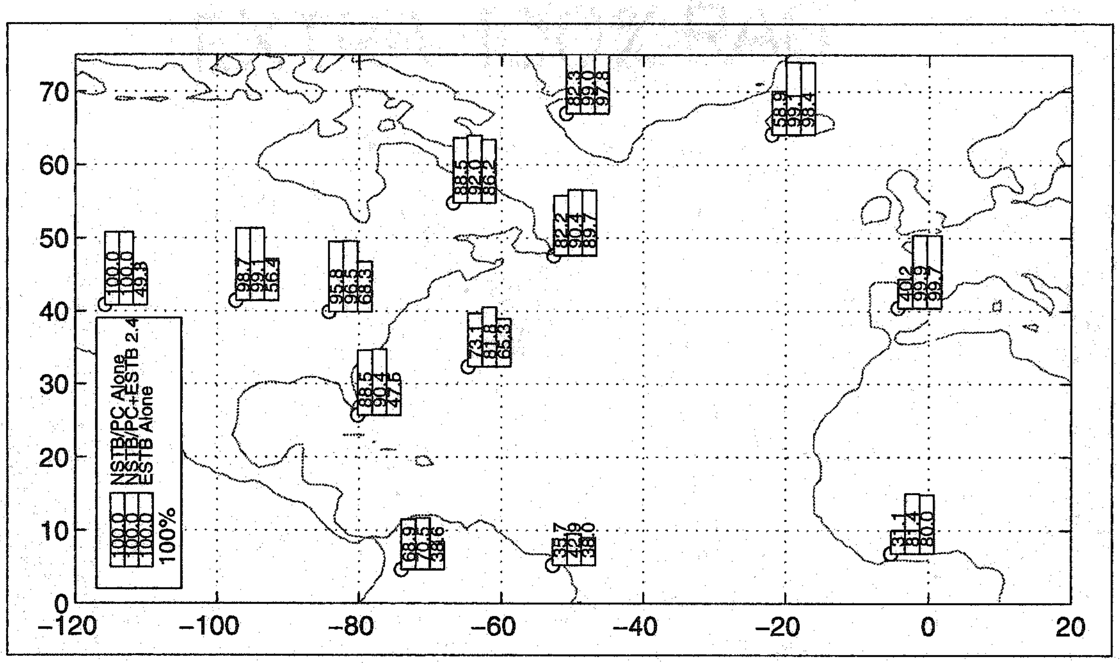

Figure 6.10: Availability Performance of Far Field Interoperability Scenarios. Comparison of LNAV operation mode availability performance of intermediate region static monitoring stations under different far field interoperability scenarios. The SBAS networks are far apart, as shown in Figure 6.9. This plot shows the comparison results between Benchmark Scenario 2.4 and two stand-alone networks' performance.

did for the original NSTB and ESTB configurations. The comparison results are still based on the performance at several similar IGS reference stations plus a few NSTB reference stations in order to establish the point.

The test results are condensed into LNAV-only availability performance comparison plots, as shown in Figures 6.10 and 6.11. It is noticed that the satellite observability of two far apart networks can still help each other in monitoring high orbit navigation satellites and generating integrity information and corrections. This enables the benefit of interoperability of multiple SBASs. Note that the switch occurs at different locations at different times due to satellite constellation changes. Therefore, even simple switching yields better results than one SBAS alone at a given location in the intermediate regions. For example, in Bermuda, where NSTB/PC was unavailable some of the time, ESTB was available. The simple switch algorithm takes

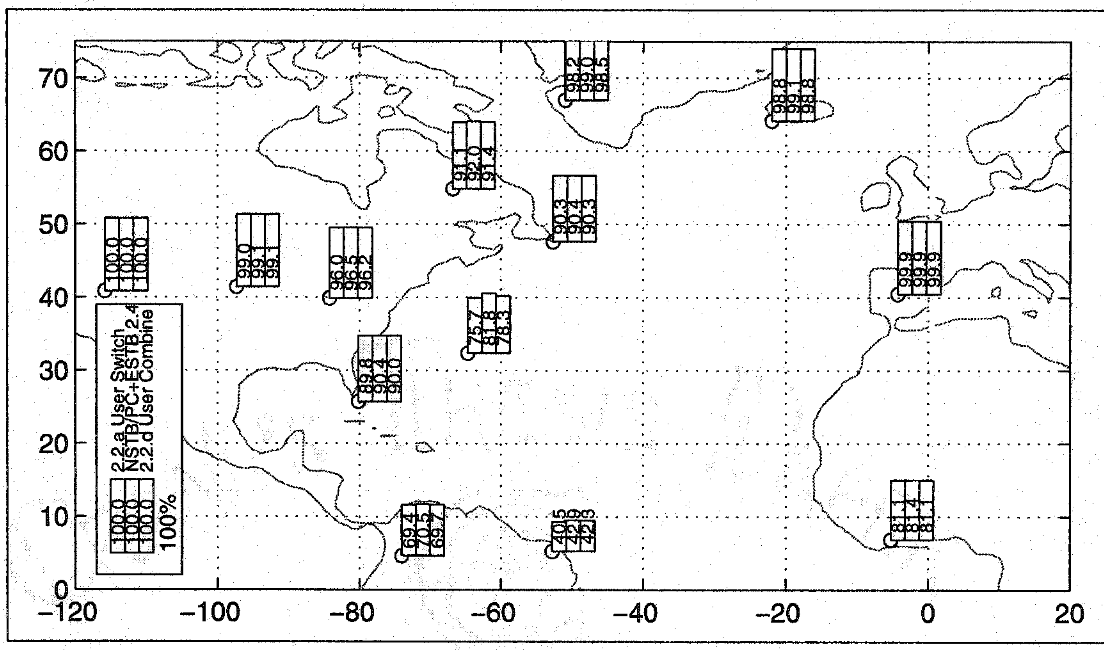

Figure 6.11: Availability Performance of Far Field Interoperability Scenarios. Comparison of LNAV operation mode availability performance of intermediate region static monitoring stations under different far field interoperability scenarios. The SBAS networks are far apart, as shown in Figure 6.9. This plot shows the comparison results between Benchmark Scenario 2.4 and the airborne scenarios, including a switching (2.2.a) and a combining (2.2.d) scenario.

advantage of this situation and improves the NSTB/PC availability from 73.1% to 75.7% by occasionally switching to ESTB for the LNAV/VNAV approach.

However, the test results also show that when two SBAS networks are too far apart, the LNAV/VNAV approach availability in the intermediate region will not gain much from interoperability. Most of the intermediate region reference stations cannot conduct LNAV/VNAV level operation using SBAS services. This is due to the fact that ionospheric corrections from the SBAS signal-in-space are necessary to achieve the required level of performance. Far apart SBASs cannot help each other because the distance between available ionospheric grid points does not give enough information to support vertical guidance with high availability.

6.5.2 Near Field Interoperability

Complementary to far field interoperability, there is also a near field issue when two SBASs are close to each other. Neighborhood parallel development of SBASs is being considered in Asia, and cooperation or integration of wide area systems could occur for Canada, the US, Mexico and other nearby countries [ADM].

To evaluate the different scenarios' applicability for near field interoperability issues, we conducted another test based on the real data collected from the National Satellite Test Bed. As shown in Figure 6.12, we partitioned the NSTB network into three subsets: the West coast network (WCN), the East coast network (ECN), and the intermediate region network. In the test, WCN and ECN are treated as two independently developed wide area augmentation systems, while the intermediate region reference stations are used to monitor the system performance under different scenarios. The test results are evaluated based on the same criteria used in the previous tests. Here, we will draw conclusions based on the LNAV/VNAV operation mode availability results.

Similar to the results we obtained previously, it is observed that each individual network performs well inside each nominal coverage area, while service availability degrades very quickly when the users move away from the nominal service volume for the GLS or LNAV/VNAV operation modes. This is mainly due to the ionosphere

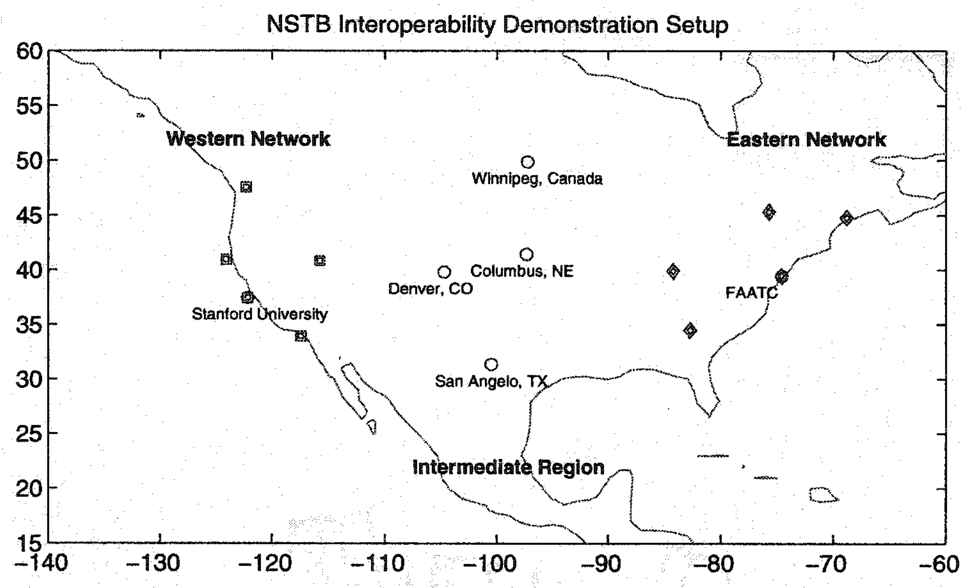

Figure 6.12: Setup of NSTB interoperability tests: western, eastern subnetworks, and intermediate region monitoring station distributions. Notice that the squares stand for the western network stations, the diamonds stand for the eastern network, and the circles represent the intermediate region independent monitoring stations.

coverage limitation of individual networks. To illustrate the interoperability benefit for the near field scenarios, we will show the vertical performance comparisons between different interoperability scenarios at a typical intermediate region location using triangle plots. A good candidate station is located in Winnipeg, Canada, as shown in Figure 6.12. This station is centered in the middle of two independent networks that best illustrate interoperability impacts in the current setup. The results of five scenarios are shown together in Figure 6.13 using the triangle plot, including western network stand alone, eastern network stand alone, airborne switching Scenario 2.2.a, airborne combining Scenario 2.2.d, and combined network Benchmark Scenario 2.4.

Each individual network performs reasonably well, but the availability is low due to spatial degradation when the user is away from the service volume of each sub-network. The user switching algorithm (2.2.a) improves the availability performance up to 99.9% compared to 95% for the eastern network alone in the operation mode with a Vertical Alert Limit (VAL) at 22.5 meters [DWEP99]. The user combining scenario (2.2.d) performs even better. Benchmark Scenario 2.4 achieves the best performance through combined networks.

For Precision Approach Category I, Scenario 2.4 is substantially better than the others. The results encourage Mexico's participation in the operational WAAS through Mexican reference stations. This will improve availability of WAAS service over the southern portion of the U.S., and facilitate an eventual transition to an operational WAAS capability in Mexican airspace, as was the case with Canada [ADM].

6.6 Conclusions

This chapter demonstrated the interoperability between WAAS and EGNOS using the ESTB and NSTB. The mutual benefits of interoperability between these two systems are characterized and validated using real data sets. Several major interoperation scenarios, including airborne switching (2.2.a) and airborne combining (2.2.d), as well as several alternatives for expanding the network coverage geometry by using a few additional remote reference stations, do in fact improve system availability in the intermediate regions of interest for both the LNAV and LNAV/VNAV operation

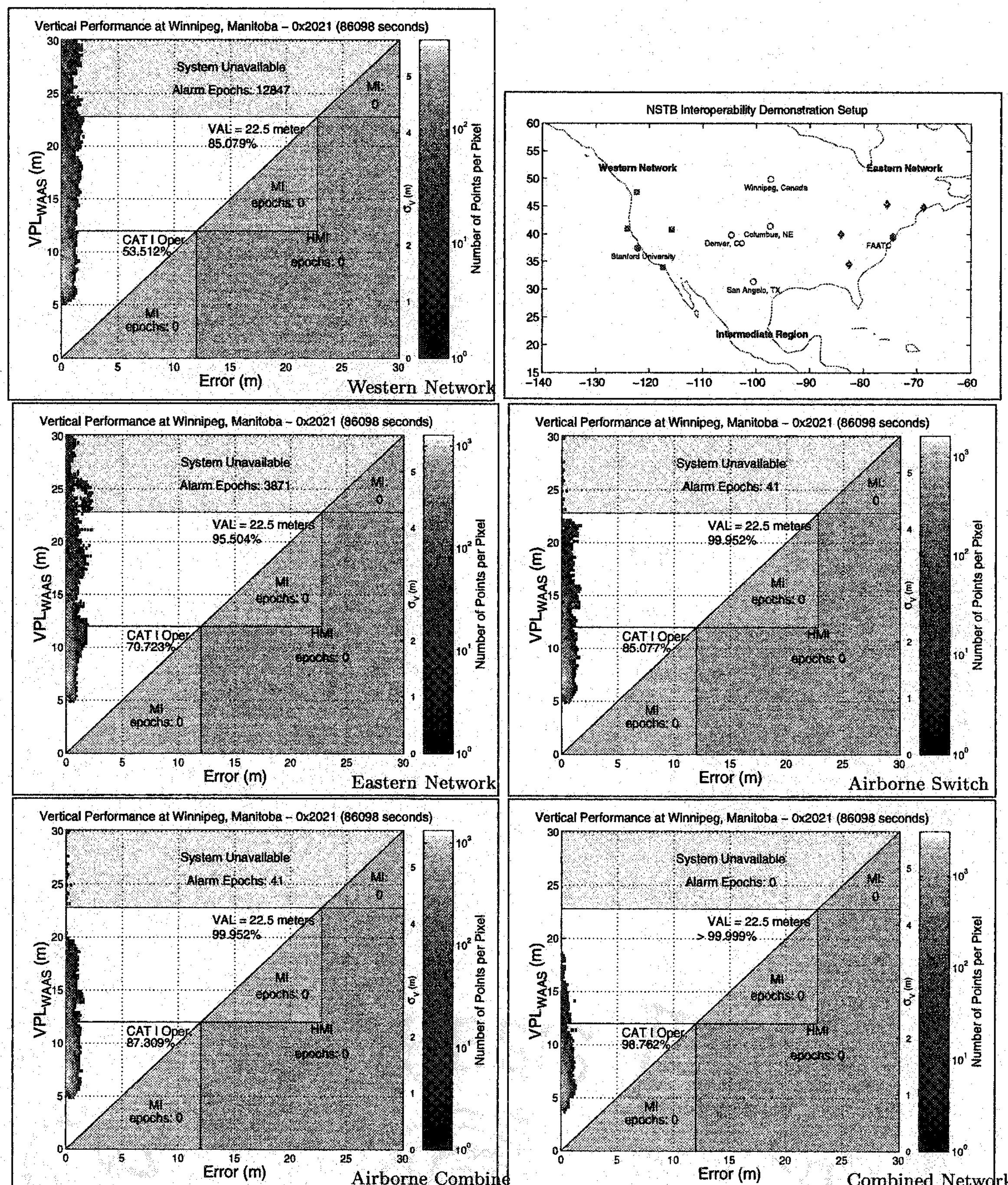

Figure 6.13: Vertical performance comparisons of near field interoperability scenarios. The vertical performance of the monitoring station in Winnipeg, Canada, is presented using a triangle plots to illustrate the detailed impact of different scenarios on the near field interoperability.

modes. It is demonstrated that the intermediate regions reap the most benefits from some kind of data combination.

For the LNAV operation mode, the network geometry of the active reference stations is the most critical factor for service availability and coverage, while the network density and IGP selection rules are of more importance for the LNAV/VNAV mode. For far field SBAS interoperability, the LNAV operation mode benefits most from coordination and cooperation between SBASs. SBAS service providers with middle range separations can potentially benefit from interoperability to improve service availability from the LNAV to LNAV/VNAV operation modes. For near field SBAS interoperability, operation modes with vertical guidance from LNAV/VNAV to GLS are of greatest interest.

Among the major interoperability candidate scenarios, the optimal method of maximizing the total utility of multiple SBASs is by directly linking all the ground reference stations together and combining the information using a central master station. This, however, requires the addition of extensive communication links and would be expensive. Nevertheless, a few remote reference stations can still be added to each stand-alone SBAS to effectively expand its service coverage at a reasonable cost. For near field, Scenario 2.4 has the advantage for Precision Approach Category I. The results encourage Mexico's participation in the operational WAAS through Mexican reference stations, as was the case with Canada.

Other compromises include a simple switch between SBASs and combining information from multiple SBASs in the user equipment. The primary conclusion is that a simple switching algorithm by the user between adjacent SBASs yields at least 95% of the benefits achievable with a much more expensive and complicated optimal solution. Further improvement can be achieved by combining information from multiple SBASs in the user equipment, which can increase the service utility to more than 98% of optimal. However, time offset compensation is recommended to maximize the service utility for the airborne combining scenarios. For Scenario 2.2.d, the network common view time transfer (NCVTT) method is recommended for a high quality clock synchronization between SBASs.

Therefore, a simple switch by the airborne equipment is the most effective choice for achieving the desired interoperability. Other more elaborate scenarios generally do not improve performance significantly and add significant infrastructure costs, or algorithm complexity. Therefore, the airborne switching approach is highly recommended and should be adopted as the interoperability standard.

Chapter 7

Conclusions

The FAA pioneered the introduction of GPS augmentation systems to revolutionize the National Airspace System (NAS), which directly led to the worldwide acceptance and development of SBASs. Before this research began, most SBAS research and development focused mainly on individual implementation and enhancement. A perfect global navigation system is always a demanding desire and challenging issue for international aviation. While the SBAS system effectively expands service coverage, interoperability becomes the ultimate answer to a seamless worldwide service solution. This dissertation demonstrates the potential benefits and optimal strategies of SBAS interoperability.

7.1 Results and Contributions

This research has demonstrated the potential benefits and optimal information fusion strategies from multiple SBASs to achieve a perfect global navigation system, from the analysis framework to real data demonstrations.

Starting from the definition of various types of interoperability, I analyzed the key issues associated with SBAS interoperability both vertically and horizontally. In order to evaluate interoperability issues effectively, I developed a basic interoperability analysis framework based on the information fusion theory, combining both linear estimation theory and statistical hypothesis testing theory together with a service volume model analysis tool. Based on this framework, I quantified interoperability benefits using real data analysis.

Integrity and its spatial degradation are some of the most important challenges of the current SBASs and their interoperability. I developed a generic integrity analysis framework based on probabilistic risk assessment and service volume model analysis for investigating the SBAS signal-in-space integrity and its spatial degradation. The results demonstrated the robustness and high integrity of SBAS navigation services. They also verified that integrity spatial degradation is of major concern in this realm.

The realization of interoperability relies on the key interoperability algorithms. I derived the network common view time transfer algorithm and demonstrated its effectiveness using real data analysis. This basic algorithm enables the direct information fusion among SBASs to achieve the desired level of interoperability efficiently via the airborne equipment. However, the algorithm is generic and valid for centralized network clock synchronization as well.

I also conducted a joint international test between the prototype networks of WAAS and EGNOS, demonstrated the interoperability of WAAS and EGNOS, and quantified the benefits of international coordination and cooperation efforts. Airborne algorithms were also tested and justified based on the real data collected from the NSTB and ESTB. The results demonstrate the excellent performance of airborne algorithms and their efficiency.

This research investigated many possible answers for the SBAS interoperability issues. The *optimal* solution is a scenario based on trade-offs between many complicated implementation considerations. If system availability is used as the metric, then the optimal method of maximizing the total utility of multiple SBASs is to link all the ground reference stations directly together and to combine the information using a central master station. This, however, requires the addition of extensive communication links and can be expensive. Nevertheless, a few remote reference stations can still be added to each stand-alone SBAS to expand service coverage effectively at a reasonable cost. Another compromise is a simple switch between SBASs in the user equipment. This delivers performance at a level of at least 95% of optimal for LNAV operation mode. Further improvement can be achieved by combining information from multiple SBASs in the user equipment, which increases the service utility to more than 98% of optimal.

This research clearly shows that a simple switch by the airborne equipment is the most effective choice for achieving the desired interoperability. Other more elaborate scenarios generally do not yield much benefit and entail significant costs in infrastructure or, at a minimum, greater algorithm complexity. Therefore, the airborne switching approach is highly recommended and should be adopted as the interoperability standard.

7.2 Recommendations for Future Research

Over the course of this research, numerous issues arose which deserve further investigation.

System Integrity First of all, integrity becomes the most important factor and issue that SBAS must achieve, especially with regard to the orbit and clock related spatial degradation effects on interoperability. A more comprehensive analysis of satellite failure modes and error models will pinpoint the uncertainties and increase our confidence in the integrity monitoring of the navigation satellites. Message Type 27 and Message Type 28 [WHE01] related analysis, and the UDRE spatial degradation study will also be beneficial for SBAS interoperability and global aviation services.

Meanwhile, the potentially correlated error modes require further investigation and independent alternative integrity monitoring strategies to further enhance SBAS redundancy, robustness and availability, which will further improve future civil navigation ability.

Ionospheric activity monitoring and prediction remains a major concern for service availability. Further research in this area is required.

Another critical topic is the potential threat introduced by the so-called *evil waveform* [PAE00]. This threat arises due to the malfunction of satellite navigation signals causing non-common mode errors for receivers from different manufacture sources, which could potentially cause undetected integrity threats if no sufficient monitoring strategies are conducted. A greater understanding of the impact of this threat and effective detection methods will potentially ease this concern.

Future Perspective May 1, 2000 is a historical day in GPS history as on that day its operational constellation became fully available for service. The turning off of SA marks the inevitable coming of satellite navigation civil applications. It is revolutionary in every aspect. It will also have a deep impact on the interoperability of SBASs. Future operational SBASs will continue to focus on integrity and ionospheric monitoring issues. The bandwidth constraints are greatly reduced due to the dramatic reduction of fast varying clock errors. SBAS has more freedom in improving and fine tuning the service quality for a wider area of coverage and a higher degree of service quality.

In the future, multiple civil frequencies available to the public will further improve navigation service quality. It would provide additional improvements on calibrating ionospheric error and multipath [DWEP98b]. Furthermore, multiple frequencies will also increase the system availability in case of unintentional interference.

Appendix A

Glossary Of Terms

A/S Anti-Spoofing (encrypion of P code to Y code)

C/A code Coarse/Acquisition code (1.023 MHz)

CONUS Conterminous US

CVTT Common View Time Transfer

DA Decision Altitude

DGPS Differential GPS

DOD Department of Defense

EGNOS European Geostationary Navigation Overlay System

ESTB EGNOS System Test Bed

FAA Federal Aviation Administration

FDI Fault Detection and Isolation

GBAS Ground Based Augmentation System

GIC GPS Integrity Channel

GIVE Grid Ionospheric Vertical Error

GLS GNSS Landing System

GNSS Global Navigation Satellite System

GNSSP GNSS Panel

GPS Global Positioning Sytem

GUS Ground Uplink System

HAL Horizontal Alert Limit

HMI Hazardously Misleading Information

HPL Horizontal Protection Limit

ICAO International Civil Aviation Organization

IFB Interfrequency Bias

IGP Ionospheric Grid Point

IGS International GPS Service

ILS Instrument Landing System

IWG Interoperability Working Group

L1 First L-band GPS frequency at 1575.42 MHz

L2 Second L-band GPS frequency at 1227.60 MHz

LAAS Local Area Augmentation System

LNAV Lateral Navigation

LNAV/VNAV Lateral/Vertical Navigation

LOS Line-Of-Sight

MCS Master Control Station

MDA Minimum Descent Altitude

MI Misleading Information

MSAS Japanese MTSAT-Satellite Augmentation System

NAS National Airspace System

NCVTT Network CVTT

NPA Non-Precision Approach

NPV-I Non-Precision Approach with Vertical Guidance

NSTB National Satellite Test Bed

OCS Operational Control Segment

P code Precise code

PA Precision Approach

PIM Parameterized Ionospheric Model

PMF Probability Mass Function

PRN Pseudo Random Noise

RAIM Receiver Autonomous Integrity Monitoring

RNAV Area Navigation

RNP Required Navigation Performance

SA Selective Availability

SBAS Satellite Based Augmentation System

SID Sudden Ionospheric Disturbance

SIS Signal-In-Space

SPS Standard GPS Positioning Service

SSN Sun Spot Number

SV Space Vehicle

SVM Sevice Volume Model

TEC Total Electron Content

TID Traveling Ionospheric Disturbance

TMS Test Bed Master Station

UDRE User Differential Range Error

UMP Uniform Most Powerful

USNO US Naval Observatory

UTC Coordinated Universal Time

VAL Vertical Alert Limit

VHF Very High Frequency

VPL Vertical Protection Limit

WAAS Wide Area Augmentation System

WADGPS Wide Area DGPS

WMS Wide Area Master Station

WNT WAAS Network Time

WRS Wide Area Reference Station

Y code Precise code (P code) after encryption

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