Broadcasting Data from an SBAS Reference Network over Low Rate Broadcast Channels

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BIOGRAPHY

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ABSTRACT

Space Based Augmentation Systems (SBAS) have been developed principally to augment GPS for aviation and other safety of life applications. An SBAS reference network generates corrections and integrity information that are broadcasted primarily using geostationary satellites. However, SBAS information may also be transmitted on other data links so that the user has an auxiliary means of receiving the data. Existing systems are potential alternate data links for information generated by an SBAS such as the Wide Area Augmentation System (WAAS). However, some of these systems have very low data rates. This paper will discuss the usage of low rate data channel, such as LORAN-C, to provide an auxiliary data link for Space based Global Navigation Satellite System (GNSS) Augmentation System integrity and correction messages. It will detail the design decisions made in creating message systems with data rate lower than the WAAS data rate. Simulated performance of these systems will also be shown.

1. INTRODUCTION

Several Space Based Augmentation Systems (SBAS) are currently being developed and fielded. An SBAS will use geostationary satellite data links to broadcast information that can provide increased accuracy and safety to users of the Global Positioning System (GPS). The information provided by an SBAS may also be broadcasted on another data link. This paper will outline how SBAS information, specifically those generated by the Wide Area Augmentation System (WAAS), can be transmitted on data channels with data rates that are below the WAAS data rate. LORAN will be examined as a case study of the system.

1.1 SPACED BASED AUGMENTATION SYSTEMS

SBAS will increase the performance of the basic GPS navigation system by providing differential corrections, confidence bounds, and additional ranging signals. An SBAS uses a ground reference network to calculate an inverse GPS solution. The inverse solution involves the SBAS master station using measurements from the reference network to derive the location and clock bias of the GPS satellites. From that information, corrections to GPS ephemeris and GPS clock and selective availability (S/A) errors are derived. These corrections are sent to the user in two formats. Long term corrections are sent to correct for satellite ephemeris errors while fast corrections correct for satellite clock errors including S/A. The use of dual frequency receivers at the reference stations permits the calculation of ionospheric corrections. While generating the corrections, the SBAS master station also determines confidence bounds for the corrections and monitors the health of the GPS satellites. The SBAS master station then packages the information for broadcast.

The SBAS master station decides which set of corrections or information should be transmitted and packages the data using predefined message types. WAAS messages are set and defined by the WAAS Minimum Operation Performance Standards (MOPS) [1]. For the purposes of this paper, WAAS will be used as our model SBAS. The message is 250 bits in length and is transmitted once per second giving a required WAAS data rate of 250 bits per second (bps). The overall transmission rate is 500 bps since a 1/2 rate convolutional coding is employed for forward error correction (FEC). The message is uplinked to WAAS geostationary satellites where the signal is then retransmitted back to earth at the GPS L1 frequency (1575.42 MHz). The signal is modulated with both data and a spread spectrum pseudorandom signal. The WAAS spread spectrum code and the GPS coarse/acquisition (C/A) codes are from the same family of Gold codes. More information on the WAAS messaging system is given in [2]. The WAAS geostationary signal provides the wide area correction, correction confidences, and an additional GPS-like ranging signal.

WAAS corrections and confidence bounds for GPS satellites provide several enhancements to stand alone GPS. The enhancement can be broken down into four areas: accuracy, integrity, availability, and continuity. A detailed discussion of these features is included in Appendix A.

Since the WAAS geostationary data link is at GPS L1, synchronized to GPS time, and modulated in the same manner as GPS satellites, the augmentation provides users with an additional GPS-like ranging signal. Another benefit of the similarity is that receiver manufacturers should not have to make significant changes to the design of GPS receivers in order to support WAAS. However, because the signal is very similar to GPS, it is susceptible to the same threats as the GPS constellation.

1.2 ALTERNATE DATA LINKS

Alternate data links for WAAS messages can supplement the geostationary broadcast of WAAS in many ways. L1 interference, temporary outages of geostationary satellites, line of sight obstructions can all pose problems to the geostationary signal. Furthermore, geostationary satellites are not able to provide coverage to some areas such as Northern Alaska. Since WAAS is designed to provide increased protection for safety of life applications, another means of obtaining the WAAS corrections would complement and enhance the services provided by WAAS. An alternate data link that provides GPS integrity messages can increase the safety of WAAS/GPS, especially if the data link has failure modes that are independent of WAAS/GPS failure modes.

Many data links have features that are suitable for an alternate data link for WAAS. If the data link can provide 250 bps data rate with a high probability of receiving and decoding a message correctly, then one can transmit the same WAAS message as the geostationary satellite. If the data link cannot provide a reliable 250 bps data rate, it may still be useful as an alternate data link if it can provide reliable communications at a lower data rate. A sub 250 bps data link can generally only carry a subset of the information transmitted by WAAS. The performance using the data link will be degraded when compared to the performance using the original WAAS signal. The degradation is the result of two factors. First, users are provided with a reduced set of corrections. Also, additional time latency in the system makes information less pertinent. LORAN is one such low data rate channels. Since LORAN broadcasts in a reserved radio-navigation band and is subject to failure modes that are different from GPS/WAAS, it often considered as a system that can augment GPS.

There have been many proposals to use LORAN to augment or supplement GPS (For example [3][4][5]). LORAN has been used for navigation for decades and it can be modified to carry a low rate data broadcast. Eurofix has demonstrated the ability to send RTCM (Radio Technical Commission for Maritime Services) Type 9 Differential GPS corrections on LORAN. While the Eurofix corrections are adequate for many users, they are not suitable for safety of life applications where integrity is essential. This paper will present means by which WAAS information can be broadcasted using low bandwidth data channels such as LORAN.

This paper also attempts to determine the level of performance that can be achieved from low data rate WAAS schemes - schemes for broadcasting WAAS information on channels with data rates less than 250 bps. One must determine which subset of WAAS message or information should be sent. The LORAN communication channel will be used as a case study to examine the implementation of the concepts developed in the paper. A graphical measure will be used to show WAAS performance and to measure the performance of the LORAN GPS Integrity Channel (LOGIC) in lossless and binomial message loss channels. For more details on the graphical display of the performance metrics, see Appendix B Triangle Charts.

2. TWO CASE STUDIES USING LORAN

We present two case studies where LORAN communication channels are used as an alternate data link for WAAS. One will involve using LORAN as a low 35 bps rate communications channel and one will involve using LORAN as a 167 bps communication channel. The following section will describe the means by which data can be modulated onto LORAN to achieve these two data bandwidths.

2.1 LORAN COMMUNICATIONS

In order to use LORAN-C as an alternate data link, we need to examine the data transmission capabilities of LORAN-C. Eurofix has demonstrated the capability of LORAN-C to carry a small amount of data with minimal impact on current LORAN users. Eurofix uses Pulse Position Modulation (PPM) where the LORAN pulse is time advanced/delayed [6]. Balanced modulation, whereby an equal number of delay and advanced signals are used per Group Repetition Interval (GRI), is employed to mitigate receiver phase offsets. Hence there are 141 unique balanced sequences per GRI since only six of the eight pulses are modulated. Under Eurofix, LORAN-C is encoded to have a transmission rate of about 70 bps for worst case GRI. Assuming that half the symbols are used for error correction, the result leads to a data rate of roughly 35 bps. The actual data carried is lowered by the overhead required for error correction and error detection.

2.2 ADVANCED LORAN MODULATION

Higher data rates on LORAN may be possible. There are schemes that are able to increase the raw transmission rate to about 350 bps. Again, the data rate will be lower due to the use of error correction and detection coding. The details and analysis of these schemes are presented in [7].

One method to increase the data capacity on LORAN signals is to combine a variety of basic modulation schemes. Three basic schemes have been examined. The schemes can coexist and can be combined to form a hybrid signal design. The first scheme is aforementioned Pulse Position Modulation (PPM).

The second scheme is Intrapulse Frequency Modulation (IFM) whereby modulation is encrypted within the pulse by a slow frequency shift in the signal. The gradual change in frequency will result in a phase shift of up to 90 degrees in 100 microseconds. The gradual change insures that the frequency content of the transmission remains between 90-110 kHz. A three level (per pulse) system may use 90,0,-90 degrees as its levels while a five level system may involve 90, 45, 0, -45, -90 degrees as its levels. The change should occur after the sixth zero crossing to reduce the effects of the coding scheme on the navigation performance of LORAN.

The third method is Supernumary LORAN whereby additional pulses are inserted in between the current pulses. Reference [8] demonstrates how the pulses can be added without affecting current LORAN-C users. The additional pulses can be modulated using PPM and IFM. So a hybrid scheme that has 16 pulses per GRI can be created. Data is modulated onto the pulses using PPM and IFM. This results in the preferred hybrid scheme seen in Table 4. It is assumed that the data rate is half the transmission rate (i.e., the code rate is 1/2).

One cost of employing these schemes is increased noise due to sky wave interference. Table 1 shows that increased data rates on LORAN are achievable though this will entail additional costs. However, the increased data rate allows for more flexibility in designing the LOGIC messages and a more useful LOGIC signal.

Scheme	Data Rate (bps)	Transmitter Costs	Receiver Costs	SNR (for P(error) < 1e-3)
Pulse Position Modulation	35	Additional logic	Additional processing for PPM	17.1 dB
Intrapulse Frequency Modulation	47.5 to 55	Additional logic for half cycle generators	3 matched filters and processing	26 dB
Preferred Hybrid (with Supernumary)	180	All of the above & 2x Transmission power	All of the above & ability to receive supernumary	26 dB

Table 1. Data Schemes on LORAN [5]

2.3 MESSAGE AND SYSTEM DESIGN

Since the data rate is less than the data rate of WAAS, one has to eliminate either some of the overhead of WAAS or some of the information contained in WAAS. The overhead includes information such as message type, issue of data (IOD), preamble (for acquisition and synchronization), and cyclic redundancy check (CRC). The overhead cannot be easily removed. A 24 bit CRC should still be maintained to retain a probability of undetected error $\leq 2^{-24}$ or 5.96×10^{-8} (for all channel bit error probabilities $\leq .5$). The majority of the reduction in bandwidth must come from elimination of some WAAS information. Table 4 shows a rough break down of the percentage of times a certain type of message is sent.

There are many message types used by WAAS. Corrections to the user pseudorange include fast corrections and long-term corrections that correct for satellite errors, and ionospheric corrections that correct for ionospheric delay. The user differential range error (UDRE) message provides information that allows the user to derive a bound on the errors corrected by the satellite corrections. The fast correction mask defines which satellites are included in the satellite correction and UDRE messages. Without the mask, the user would not be able to process the fast correction and UDREs. The mask typically does not change very often and when it is changed, the mask message is repeated several times to allow all users to acquire the new mask. The ionospheric grid mask defines the operating area of the ionospheric corrections. Other messages include information such as degradation parameters for the fast corrections and UDRE that helps the user propagate the errors and bounds through time. Of course, there are other messages sent. For more details, reference Appendix A of the WAAS MOPS [1].

In creating a system for sending WAAS based integrity messages using low data rate channels, one must first determine what is the minimal amount of information necessary for the desired application. For WAAS messages, the fast corrections and UDREs are necessary components. The fast corrections provide much of the range corrections while the UDREs are necessary to provide integrity. Ionospheric corrections are necessary to achieve protection levels (confidence bounds) that will allow Category I (CAT I) and Instrument Approach with Vertical Guidance (IPV) approaches. For more details concerning these approach standards, see Appendix A. Long term corrections are necessary too but it may be possible to incorporate the offset introduced by the satellite ephemeris error into the user error bound. Other WAAS parameters such as those used in Type 7 and 10 messages are also necessary.

Correction	**Message type**	**Percent of All Messages Sent**
Fast Corrections	2-4	50.0%
Fast Corrections (GLONASS)	5	1.7%
UDRE Update	6	16.7%
Fast Degradation	7	0.8%
Long Term Corr	25	10.8%
Iono Corr	26	2.3%
Geo Nav	9	0.8%
Iono Grid Mask	18	0.3%
Fast Corr Mask	1	1.7%
UDRE Degrade	10	0.8%
WAAS Service	27	0.3%
Weight Fac	7	0.8%
Geo Almanac	17	0.3%
UTC/WAAS	12	0.3%

Table 2. WAAS Message bandwidth usage

The determination of the utility and necessity of each piece of information sent by WAAS was used to reduce bandwidth. Some messages can be eliminated without much loss. The messages relating to the geostationary satellite do not need to be sent because the alternate data link is only necessary when the signal from the geostationary satellite cannot be received. Further reductions are more difficult but necessary.

The fast corrections and UDRE messages represent about 70 percent of the message sent on WAAS and hence 70 percent of the bandwidth used. To further reduce the bandwidth used, one needs to reduce the amount of bandwidth used by fast corrections and UDRE. One method is to send the same information using fewer bits. Rate distortion theory indicates that it is possible to transmit the information using a lower data rate. However, research has shown this design to be less resistant to message loss.

Another method is to reduce the satellite set for which corrections are being sent. Figure 1 shows the number of GPS satellites visible at a 2 degree mask angle from within the coverage area of LORAN chain 9940 (seen in Figure 3). The 2 degree elevation angle was chosen to provide an overestimate of the number satellites needed. A 24 satellite GPS constellation is assumed and the coverage area is defined to be a rectangular area whose bounds are 1300 kilometers (~800 miles) to the east of the eastern most point in the chain, west of the western most point of the chain, and so on. The result indicates that LOGIC needs to send corrections for at most 60 percent of the satellites in the GPS constellation corrections in order to maintain full coverage of all satellites available to users in the coverage area. The simulation also indicates that generally less than three new satellites enter into view every hour. That means that a fast correction mask can be changed once per hour without many visible satellites not being corrected. Though this is higher than the rate at which WAAS changes its mask, it is an acceptable rate for our purposes. The scheme is referred to as the selective satellite scheme.

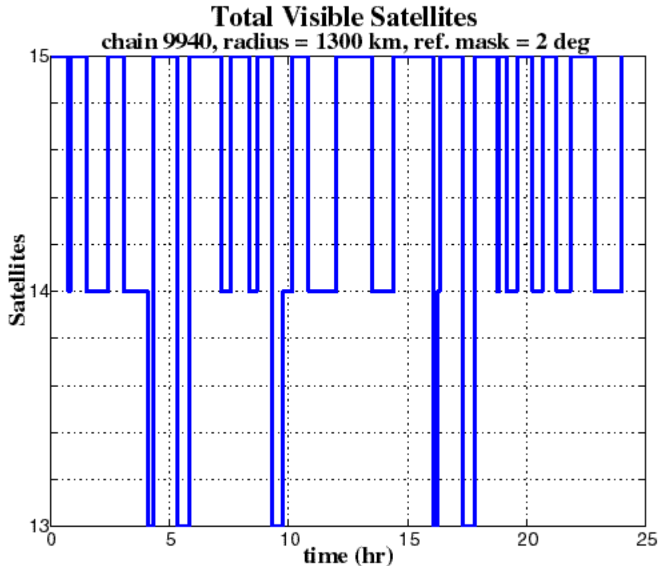

Figure 1. Satellite Visible to Chain 9940 Coverage Area (1300 km extension)

One final means of reducing bandwidth is to re-value, truncate, or requantize the various corrections, UDREs, and WAAS parameters to lower resolution. Lower resolution will result in using fewer bits per correction at the expense of reduced accuracy and the need for larger error bounds.

The information needs to be sized to fit on the data portion of the messages. The creation of new message types will be necessary to place the repackaged and/or requantized WAAS information. Since the LOGIC messages may not be sent at the same rate as WAAS and since LOGIC messages do not necessarily have a one to one correspondence to a WAAS message, there needs to be a decision algorithm which determines which LOGIC message to send. It is possible that a WAAS message may generate enough information to merit more than one LOGIC message. It is also possible that with LOGIC transmitting messages at a slower rate than WAAS, the LOGIC ground station may decoded two WAAS messages while only being able to transmit one message. This generates a situation where LOGIC has to decide which of several messages to send. Hence a message decision algorithm is a necessary part of the LOGIC design. A basic system diagram of the LOGIC system is shown in Figure 2.

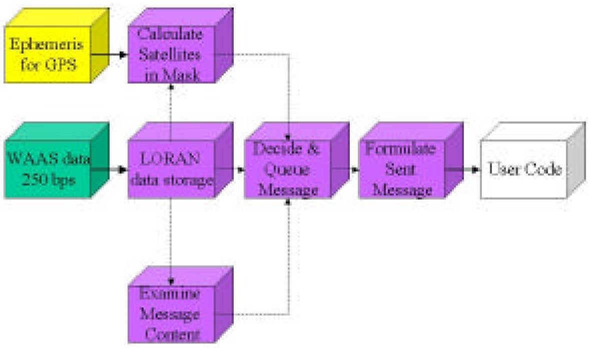

Figure 2. LOGIC System Diagram

GPS satellite measurements taken from the National Satellite Test Bed (NSTB) from June 24 to June 27, 1998 was used to analyze of the message schemes. From the data, the Stanford WAAS Test bed Master Station (TMS) generated the WAAS correction used and additional code was written to simulate the transmission of the data to the Middletown LORAN station, the processing done by the station, and the transmission to the user. The data link between the WAAS TMS and the LORAN station is presumed to be lossless and to have one second of time latency. As seen in Figure 3. Coverage Area, the Middletown station is part of the LORAN 9940 chain - a chain that covers the U.S. West Coast. Using the station location, the LOGIC code determines which satellites it is going to correct and then it decides which message to send. The NSTB data contains measurements from the GPS satellites in view at various stations in the test bed. Figure 3 shows the approximate coverage area of the 9940 chain and the NSTB reference stations (designated by stars) for which a LOGIC and a WAAS solution are calculated. Denver is also examined, even though it is outside the coverage area, to test the robustness of the system.

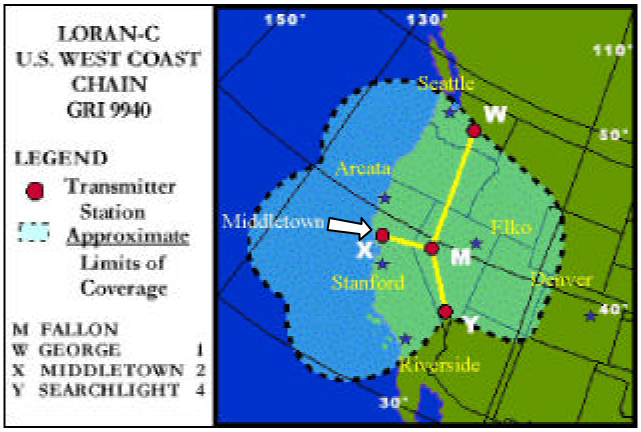

Figure 3. Coverage Area & Test Set Up

2.4 LOW DATA RATE LOGIC

For low data rate LOGIC, it is assumed that the data rate is 35 bps - roughly approximating the Eurofix data rate. In the design of the message, a 24 bit CRC was included to maintain a similar probability of undetected error. A longer message would amortize the cost of using a 24 bit CRC over several seconds hence increasing the ratio information to message bits. However, there is a constraint on the length of a message. ICAO GNSS Standards and Recommended Practices (SARPS) also specify that for either Non-Precision Approach (NPA) or IPV, there is a 10 second time to alert. Figure 4 shows a time line for the transmission of a WAAS based message over an alternate data link. The conclusion of the analysis is that any message that is roughly over 2 seconds in length would fail the time to alert requirement. These two constraints drive the choice of the message length/time to 2 second.

With 30 of the 70 bits of the message being used for framing, overhead and CRC, there is very little capacity left for data. Corrections were provided for the top twelve GPS satellites in the coverage area of a LORAN station. Furthermore the corrections and other parameters such as UDRE were requantized. In addition, the projected errors from satellite ephemeris were incorporated into the UDRE bound thus eliminating the need of transmitting the long-term corrections. These techniques allow the transmission of a WAAS based integrity message on a low bandwidth channel with the cost of degraded accuracy and larger accuracy bounds.

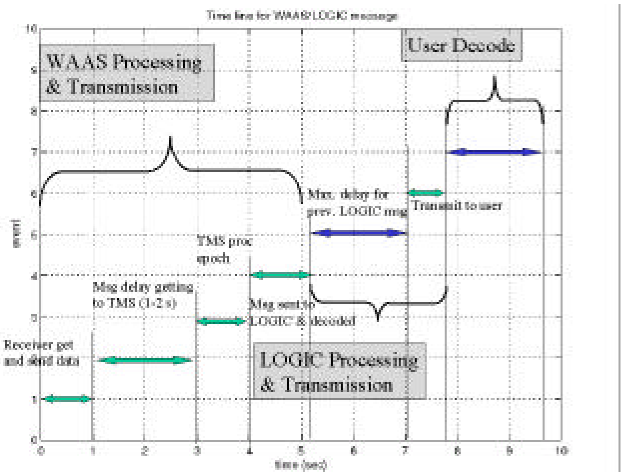

Figure 4. LOGIC Time Line

Tests were conducted with an a priori message decisions and a real time decision algorithm. One has to be careful with the decision algorithm design since there is more data than can be sent and so it is possible that more critical messages are precluded by less important data. If one uses a queue, one has to make sure to eliminate messages that are no longer relevant (timed out) otherwise the queue will exceed any bounds set on it. An a priori decision algorithm was used to derive the results below. The real time decision algorithms did not perform significantly better than the a priori method and were more complicated to design and implement. Under the a priori scheme, a two fast correction messages and a UDRE message are sent every 6 seconds. Each fast correction message provides corrections for 6 satellites. Occasionally a mask, degradation parameters, and other messages are sent in place of one of the fast correction messages. Hence, the update time for fast corrections is more than 6 seconds on average and the update time for the UDREs is exactly 6 seconds. The WAAS MOPS requires that UDREs be updated every 6 seconds so the scheme is compliant with respect to that requirement.

The performance in the absence of message loss can be seen in Figure 5. Figure 5 shows the Horizontal Protection Level (HPL) triangle chart of a user at Seattle, Washington using corrections generated at the Middletown LORAN station. The Stanford TMS used actual measurements to generate the WAAS corrections. These corrections were passed to the LOGIC code that generated the LOGIC corrections and simulated the data link. The position solutions were generated from actual measurements taken at Seattle and the low data rate LOGIC corrections. Similar performance can be seen in Stanford and Riverside, California as well as Denver, Colorado. Note that the protection levels achieved using the 70 bit message is only capable of achieving NPA performance and not capable of achieving IPV, its more stringent counterpart.

However, one cannot assume that the data link is perfect and in fact the WAAS MOPS dictates a structure that accounts for lost messages. Tests were performed with a simulated lossy channel. Current tests utilize a binomial error model. Results show that the protection levels are not changed very much. The large protection levels are due mostly to degraded corrections and UDREs and because ionospheric corrections are not sent. Even with a 20 percent message loss channel, the low data rate LOGIC system achieved better than 99.999% availability for NPA. Since WAAS was designed to provide high availability for CAT I approaches and since NPA has much less stringent requirements than CAT I or even IPV, it is not surprising that this LOGIC system achieves NPA with such high availability. The difference between LOGIC with low message loss rates (less than 1%) and high message loss rates (between 1% and 20%) shows up more in accuracy rather than availability for NPA.

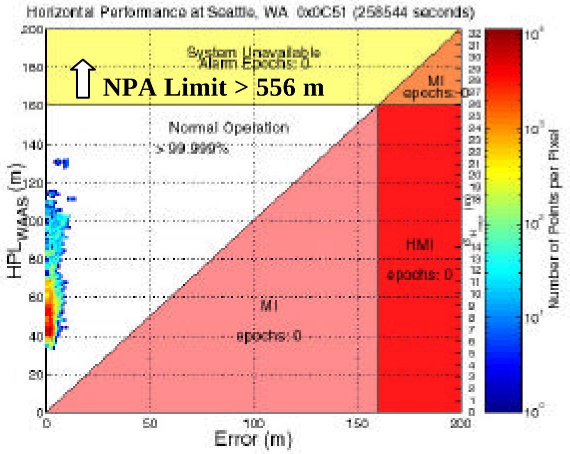

Figure 5. Low Data Rate LOGIC Horizontal Protection Level - Seattle (No Message Loss)

2.5 HIGH DATA RATE LORAN

A higher data rate was also tested to determine if an increase in bandwidth could result in increased capabilities. A 167 bps data rate channel was tested. The data rate is slightly lower than the highest data rate achieved with the advanced LORAN modulation scheme described in an earlier section. The data rate was also selected because it allows for the transmission of a 250 bit message every 1.5 seconds or 2/3 the message rate of WAAS.

Since the data rate is reasonably close to that of WAAS, there is a temptation to send a 250 bit message that utilizes as much of the current WAAS message types as possible for more compatibility with a full WAAS system. The compatibility allows for simpler software since one can utilize the same decoding and correction algorithms as used by WAAS. It may also allow for easier certification since it only introduces some new message types rather than completely repackage the correction into a different format. Hence if the basic WAAS message structure is used, costs can be lowered and the overall system, from both user and transmitting equipment, could be simplified.

If a WAAS-like message is used, the system will transmit messages at a lower rate than WAAS and so there must be some data that must be eliminated. Again, a selective satellite algorithm to choose the top 19 satellites to send corrections. Furthermore some messages can be combined. Eliminating some messages and only sending corrections for a subset of GPS satellites allows this LOGIC scheme to transmit the required WAAS derived information using lower message rate than WAAS. In fact, this LOGIC system transmits the required WAAS information at the rate required by the WAAS MOPS. The time to alert of the high bandwidth LOGIC will meet the 10 second time to alarm requirements of IPV but it will not meet the requirements of CAT I. CAT I requires a six second time to alert. Going back to Figure 4, WAAS will alert a user generally 4-5 seconds. However, with the additional system latency, LOGIC will take at least 6-7 seconds to alert a user and hence cannot be considered for use on Category I approaches. Since this high rate LOGIC system is designed to meet IPV specifications, it shall be denoted as LOGIC-IPV.

Correction	**LOGIC Message type**	**Usage as Percent of full WAAS bandwidth**
Fast Corrections	2	16.7%
UDRE Update	6	16.7%
Fast Degradation, UDRE Degradation, Weight Fac	New LOGIC type	0.8%
Mixed Corr	24	16.7%
Iono Corr	26	2.3%
Iono Grid Mask	18	0.3%
Fast Corr Mask	1	1.7%
TOTAL		55.2%

Figure 6. LOGIC-IPV Bandwidth Usage as a Percentage of Full WAAS

The LOGIC-IPV system sends one to two less fast correction messages whenever a full set of fast corrections is broadcasted. In addition, fewer long-term corrections are sent and some WAAS messages (Type 7 and 10) are combined into one LOGIC message. Analysis shows that LOGIC only uses about 55.2% of the messages carried by a 250 bps full WAAS system even though it has a bandwidth equal to 66.7% of WAAS. That means, over a long period of time, the channel can transmit the LOGIC subset of WAAS information. However, there will be short periods of time where WAAS will generate more LOGIC messages than can be transmitted by the LOGIC channel. A decision algorithm was created to queue and prioritize such information. For example, fast correction messages and UDRE messages, which have fast de-correlation times, are given higher priority than long term corrections. Over the long run, the LOGIC message queue will become empty however there will be times where the queue will contain several messages. From the data runs, we gathered rough statistics on the average and maximum delays of various messages. Note that the delay includes an additional second latency to account for the reception and decoding of the WAAS message by the LOGIC processor. High priority information such as fast corrections and UDREs are generally not delayed more than 3 seconds from the time it is decided that these messages are to be sent. However since a LOGIC-IPV fast correction message is repackaged from perhaps two or more WAAS fast correction messages, individual fast corrections may experience more delay. The maximum possible delay will be the amount of time it takes for WAAS to send a complete set of fast corrections plus a second or two for latency and processing. This should be around 10 seconds. LOGIC will time propagate the fast correction and the UDRE to account for delay.

Message	Average Delay (sec)	Maximum Delay (sec)
Fast Correction Mask	3.7429	56
Fast Degradation Parameters	3.9576	92
Iono Grid Mask	3.7143	31
Iono Correction	3.3038	65
All Messages	3.1780	92

Table 3. LOGIC-IPV Message Delay time

Again, we present results from both lossless and lossy transmission cases. The performance of the system in the coverage area is adequate to meet IPV specifications, which specifies both vertical and horizontal performance. Only the vertical performance results are shown since the horizontal specifications were easily met.

The Vertical Protection Level Charts (Figure 7, Figure 8) show that the performance is worse than WAAS. Accuracy is slightly worse while error confidence bounds (protection level) are higher. The result is expected since the WAAS MOPS specify the rapid manner by which confidence bounds degrade with time. Figure 9 shows that LOGIC-IPV significantly degrades when the message loss rate is above 1 percent - a result that is similar to the performance of WAAS. For lower loss rates, the system has greater than 99.99% availability for IPV for all test locations in the coverage area.

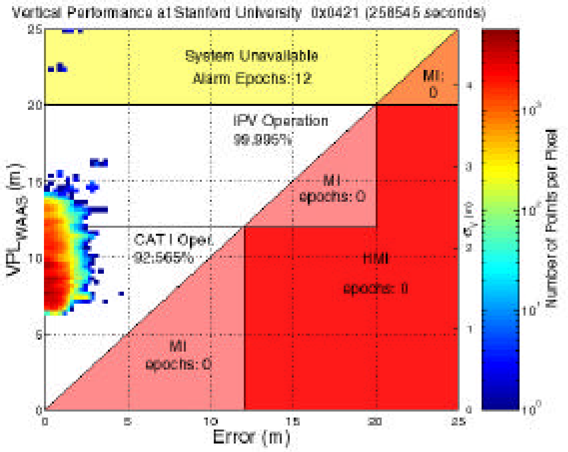

Figure 7. Vertical Protection Level Chart LOGIC-IPV performance on June 24-27, 1998 - No message loss

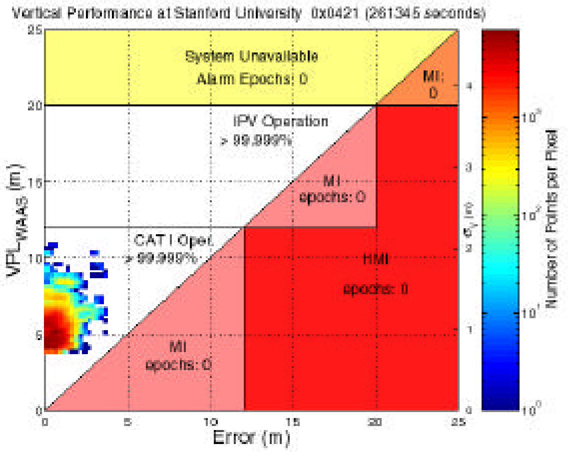

Figure 8. Vertical Protection Level Chart WAAS performance on June 24-27, 1998 - No message loss

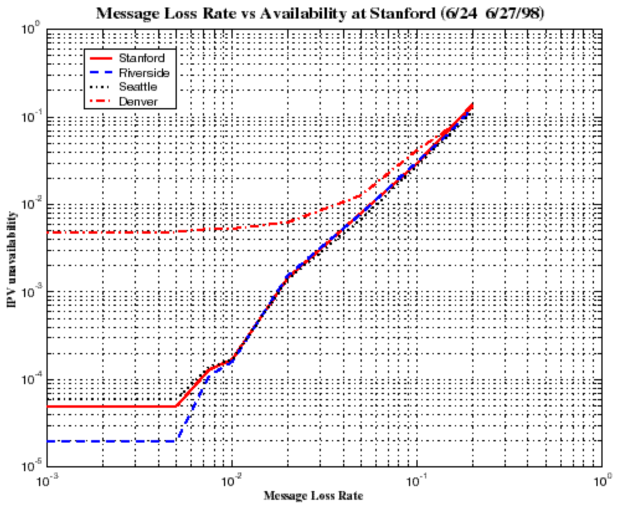

Figure 9. LOGIC Performance with Message Loss

3. CONCLUSION

The case studies of different sub 250 bps WAAS derived integrity messages demonstrate that there is some utility in the transmission of a reduced and truncated set of corrections. These corrections can act as back up for users in safety of life applications or they can be used as differential corrections systems for users without the need for the high integrity specified by safety of life applications. A low bandwidth LOGIC can provide aviation with an alternative data link that can still enable NPA. A167 bps LOGIC system can provide aviation with an additional means of receiving information necessary to conduct enroute and landing operations down to IPV. Using LORAN to transmit the message mitigates line of sight problems. This makes the system feasible for land and sea applications as well as aviation. The ability to place the message on LORAN increases the utility of LORAN and adds another advantage to a combined GPS/LORAN navigation system. The schemes are general and not limited to LORAN. They can be used on any data channel. For example, another possible transmission channel is a FM subcarrier channel such as the Radio Data System (RDS) or a VHF datalink such as VHF Data Broadcast (VDB).

Table 4 shows the basic results of analysis of the two LOGIC schemes. The disadvantages listed are relative to its counterpart LOGIC scheme.

Bandwidth	**35 bps**	**167 bps**
Performance	NPA	IPV
Advantage	Data rate achieved and demonstrated	Very compatible with WAAS, Achieve IPV
Disadvantage	Requires completely new message structure for WAAS information	Additional changes at LORAN station needed for modulation scheme, More potential interference, More expensive user equipment
Additional Costs	LOGIC Station/Processing, Eurofix Modulation at LORAN station, Code Certification, New LORAN User equipment	LOGIC Station/Processing, Advanced LORAN Modulation at LORAN station, Code Certification, New LORAN User equipment

Table 4. LOGIC Results

Furthermore, other intermediate data rates also merit investigation. Studies are being conducted to determine the requirements necessary for other landing operations. It is hoped that approximate minimum data rates limits necessary for each of these operations will be established.

4. APPENDIX A: SBAS & ACCURACY, INTEGRITY, AVAILABILITY, AND CONTINUITY

Accuracy can be viewed as how close the position solution is to the true position. Increased accuracy is provided by the correction messages and the additional ranging signal. As mentioned before, WAAS corrections for accuracy come in three forms - fast corrections, long term corrections, and ionospheric corrections. Requirements on accuracy for various aviation applications can be seen on Table 6.

Integrity is a more nebulous concept. In the case of WAAS and other GPS integrity channels, one can interpret it as a measure of the reliability position solution and the user derived error bound on the solution. A measure of performance for integrity is to examine how often the actual position error is bounded by the user derived error bound calculated using the user differential range error (UDRE) transmitted by WAAS. Using the UDRE for each satellite used in the position solution, the user calculates a horizontal and vertical protection level (HPL, VPL respectively) that provides a bound on the horizontal and vertical position errors. In aviation landing applications, the VPL and HPL specify a protection level such that there is 99.99999 % (seven nines) or better chance that the position error is bounded by the HPL and VPL level prescribed by the integrity message. In addition, WAAS provides integrity by alerting users of bad or malfunctioning satellites.

Availability can be viewed as being the percentage of time a GPS position solution is calculated and usable for a specified application. Availability is application specific. A WAAS solution may be available for one type of aircraft landing approach however it may not simultaneously be available for a more stringent type of approach. This may be because the integrity bounds (such as VPL) exceed the maximum allowable error for the more stringent application. That means there is a appreciable chance that the position error may exceed the maximum allowable error. For aviation, one uses alert limits to demarcate whether a solution is available for use. An alert limit is a limit for error above which the position solution is no longer available for use in the specified application even though a solution may be available. The alert limits for a specific application defines the maximum allowable position error for that application. Table 5 shows the ICAO GNSS SARP signal in space performance requirements for various typical aviation operations. For instrument approaches with vertical guidance (IPV), the requirement is that protection bound on vertical error (VPL) must be below the vertical alert limit for IPV approaches (around 20 meters) to use be considered usable for IPV. There is a similar requirement for horizontal errors with a horizontal alert limit of 556 m (.3 nautical miles). For non-precision approaches (NPA), the horizontal alert limit is also set at 556 m with no limits on vertical accuracy.

Typical operation	Horizontal alert limit	Vertical alert limit	Associated RNP types
En-route	4 NM	N / A	20 to 10
En-route	2 NM	N / A	5 to 2
En-route, Terminal	1 NM	N / A	1
NPA	.3 NM	N / A	.5 to .3
IPV	.3 NM	22.8 m	.3 / 125
Category I precision approach	40.0 m	20.0 to 10.0 m	.03 / 50 to .02 / 40

Table 5. ICAO GNSS SARPS

For example, in figure 10, the vertical protection level for the solution is smaller than the vertical alert limit for IPV approach but larger than the vertical alert limit for CAT I approach. This means that the position solution is available for use on IPV but not CAT I.

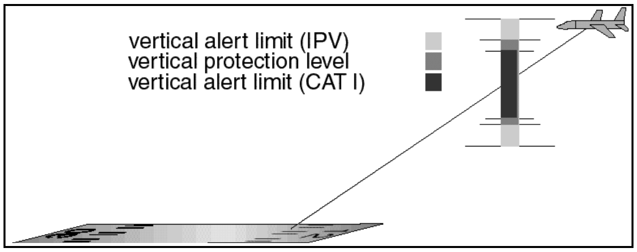

Figure 10. Example of Availability

Continuity is amount of time between periods where a GPS solution is unavailable. Again, continuity is also driven by application. Both availability and continuity is increased by WAAS by the addition of geostationary ranging signals. Again, requirements on continuity for various aviation applications can be seen on Table 6.

The services provided by SBAS are meant to make such systems suitable to safety of life applications. For an application such as aircraft landing, one needs reasonably accurate position solutions since large position errors are not tolerable. Furthermore, the system should be available almost at the time since even an outage of a few seconds could result in the aircraft's position changing by half a mile or more. Integrity requires that users are aware of malfunctioning satellites or other problems without much delay. As seen in Table 6, the ICAO GNSS SARPS specify requirements on accuracy, integrity, continuity, and availability [9]. It also specifies time to alert, which is the maximum allowable time between the detection of a GPS fault by the master station and the user reception of a message flagging that fault. WAAS is designed to meet the specifications for en-route operations and landings up to Category I precision approach.

Typical operation(s)	Accuracy Lateral 95%	Accuracy Vertical 95%	Integrity	Time to alert	Continuity	Availability
En-route	2.0 NM	N / A	1-10^{-7} / h	5 min	1-10^{-4} / h to 1-10^{-8} / h	.99 to .99999
En-route, Terminal	.4 NM	N / A	1-10^{-7} / h	15 s	1-10^{-4} / h to 1-10^{-8} / h	.99 to .99999
Initial approach, Non-precision approach (NPA), Departure	220 m	N / A	1-10^{-7} / h	10 s	1-10^{-4} / h to 1-10^{-8} / h	.99 to .99999
Instrument approach with vertical guidance (IPV)	220 m	9.1 m	1-2x10^{-7} per approach	10 s	1-8x10^{-6} / h in any 15 s	.99 to .99999
Category I precision approach	16.0 m	7.7 m to 4.0 m	1-2x10^{-7} per approach	6 s	1-8x10^{-6} / h in any 15 s	.99 to .99999

Table 6. ICAO GNSS SARPS Performance Requirements

5. APPENDIX B: READING TRIANGLE CHARTS

Stanford University has developed the triangle chart to help visualize the performance of an integrity message. The chart helps quantify three of the services described in Appendix A (availability, integrity, accuracy). It is a two dimensional histogram with true error and protection level (confidence bound) as the axis. Figure 11 shows a typical WAAS Vertical Protection Level (VPL) chart. The vertical axis displays the vertical protection level while the horizontal axis measures the true error. The line at 20 meters defines the vertical alert limit for IPV. Any solution with a vertical protection level above the vertical alert limit is considered unavailable for use in IPV and hence the system is unavailable for IPV use when this occurs. Any solution below the 45 degree line represents misleading information (MI) because the protection level did not bound the actual error, i.e. the actual error was greater than the protection level. This should only occur in less than .00001 % of all solutions. Any solution that is below the 45 degree line with protection level below the alert limit while the error is above the alert limit is considered to be a case of hazardously misleading information (HMI). HMI occurs when the system, by virtue of the protection level, permits the use of a position solution while in actuality the error in the position solution is beyond the alert limit.

The availability of the system for IPV can be determined by examining the percentage of points that lie within the GOOD (or REALLY GOOD) regions. These regions designate when a solution is available for use for IPV and CAT I operations respectively. Of course, for CAT I operations, we only examine the points within the REALLY GOOD region.

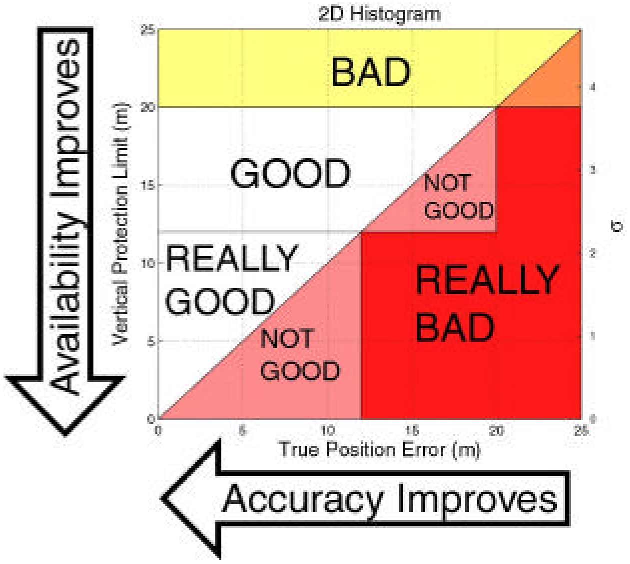

Figure 11. Sample VPL Triangle Chart

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