Using Loran for Broadcast of Integrity Information for Modernized Global Navigation Satellite Systems (GNSS)

Sherman C. Lo, *Stanford University*
Benjamin B. Peterson, *Peterson Integrated Geopositioning*
Per K. Enge, *Stanford University*

BIOGRAPHY

Sherman C. Lo is a senior research associate at the Stanford University (SU) Global Positioning System (GPS) Laboratory. He is the Associate Investigator for the SU efforts on the Department of Transportation's technical evaluation of Loran. He is a coauthor of the Loran technical evaluation completed in March 2004.

Professor Per Enge is the Kleiner Perkins Mayfield, Sequoia Capital Professor in the School of Engineering. He directs the SU GPS laboratory and is actively involved in aviation navigation programs such as WAAS, LAAS and Loran with the US Federal Aviation Administration (FAA). He is the Director of the Stanford Center for Position Navigation and Time.

Benjamin Peterson is the founder of Peterson Integrated Geopositioning, LLC. He is active in various research and design efforts for enhanced Loran and modern Loran receivers. He was a captain in the United States Coast Guard and served head of the Engineering Department at the US Coast Guard Academy.

ABSTRACT

The United States (US) Federal Aviation Administration (FAA) has been examining the potential of using an enhanced Loran (*eLoran*) to provide back up for aviation. The 2004 FAA Loran technical evaluation report concludes that Loran with modernized equipment, new receiving equipment, and updated operating procedures, could meet aviation requirements for Required Navigation Performance 0.3 (RNP 0.3). Essentially, this means that *eLoran* can act as a stand alone navigation aid for aircraft enroute and landing applications. This is particularly important if GNSS is unavailable.

However, it is possible for Loran to play an even greater role in enhancing the safety and redundancy of an aircraft navigation service based primarily on GNSS. In particular, if *eLoran* can provide back up to space based augmentation system (SBAS) service, it could provide additional redundancy to the aviator. The limitation of the approach is the low bandwidth available on *eLoran*. Even with the use of newer Loran modulation techniques such as ninth and tenth pulse communications, the bandwidth is far below the 250 bps necessary for SBAS.

Still, *eLoran* bandwidth may be adequate to support *eLoran* functions and SBAS functions in a modernized GNSS environment. In this environment, dual frequency measurements, increased accuracy, and better ephemeris will be available to GNSS users. Additionally, some monitoring may be delegated to the receiver, allowing for a longer time to alarm (TTA). These factors have the effect of reducing the required bandwidth for SBAS. These reductions may make it feasible to support both RNP 0.3 and SBAS information with *eLoran*.

This paper will provide some of the preliminary analysis and design of a system that enables *eLoran* to support SBAS along with its existing functions. These designs are based on architectures being examined under the FAA GNSS Evolutionary Architecture Study (GEAS). The GEAS is exploring the feasibility of supporting 200 feet decision height worldwide with modernized SBAS (L5 SBAS). The desire is to develop feasible designs supporting the GEAS architecture. The goal is to do this with high performance and utility and without compromising with other *eLoran* functionality. The results of the analysis in the paper will show that *eLoran* can support both its primary applications of RNP, harbor entrance and approach (HEA), and timing and frequency as well as modernized SBAS. This can be accomplished in a manner that separates out the two functions allowing for flexibility and independent operation. However, there are some limits on update rate and TTA that can be supported. These limits are not overly restrictive and the paper will show these limits and how they were determined.

1.0 INTRODUCTION

Aviators and other navigators have always valued robustness and redundancy in their navigation aides. For aviation, this often means having two independent sources of navigation information. Even though the United States is moving towards using the Global Positioning System (GPS) as the primary means of navigation, ground infrastructure will still be retained to provide the redundancy. The need for such redundancy has been recognized by various sources including Volpe

National Transportation Safety Center (VNTSC) Report on GPS Vulnerability and presidential directive [1][2]. However, in providing redundancy, there must also be thought given to practicality and efficiency for the aviator will not want to carry too many expensive back up instruments. It would be ideal if one back up system could provide multiple modes of back up. Enhanced Loran (*eLoran*), as examined in the 2004 United States (US) Federal Aviation Administration (FAA) technical evaluation report is capable of providing stand alone back up to GNSS navigation and integrity for enroute and landing applications [3]. This is accomplished by having *eLoran* support performance up to Required Navigation Performance 0.3 (RNP 0.3), a form of non precision approach (NPA). The purpose of this paper is to examine the possibility of having *eLoran* also serve as a back up source of global navigation satellite systems (GNSS) integrity information derived from space based augmentation system (SBAS). This will enable *eLoran* to provide approach with vertical guidance to unaugmented GNSS users.

Loran is an attractive system for backing up GNSS. The properties of the Loran signal make it a good complement to GNSS. Additionally, its coverage and performance allows it to function as a backup to GNSS in many places and applications. Indeed, *eLoran*, the next generation of Loran, is being designed to support multiple modes of operation, including some of the most stringent position, navigation and timing (PNT) applications [4]. It will support aviation through RNP 0.3 for landing and RNP 1.0 for enroute. It will have the capability of supporting difficult maritime operations such as Harbor Entrance and Approach (HEA). For timing and frequency, *eLoran* will provide Stratum 1 frequency and highly synchronized (20 nanosec) time to UTC. As such, the US Department of Homeland Security (DHS) announced in February 2008 that *eLoran* would be implemented to provide "an independent national positioning, navigation and timing (PNT) system that complements the Global Positioning System (GPS) in the event of an outage or disruption in service [5]."

The broadcast of SBAS information using Loran was examined, prototyped and tested previously in 2001[6][7]. However, the 2001 design would likely preclude use of Loran for aviation due to jitter/interference created by modulation. Additionally, the data rate required for SBAS, 250 bps, is greatly in excess of what is being proposed for *eLoran*. While lower data rate versions of SBAS have been examined, these may provide only marginal benefits to the aviator while using up the entire bandwidth of *eLoran* [8][9]. However, looking towards the future, GNSS performance will improve with better accuracy and multiple frequencies. With these additions, it may be possible to develop a low bandwidth version of SBAS that can be broadcast on *eLoran*. Enabling *eLoran* to broadcast SBAS information makes it a two tiered back up to GNSS for aviation. It would back up a GNSS outage by providing aviation integrity for non precision approach. It would back up an outage in the SBAS geostationary satellite (GEO) by providing the integrity necessary to use GPS for precision approach (PA). This is seen in Table 1.

Scenario	GNSS & GEO	GNSS, No GEO	No GNSS, No GEO
Primary Navigation	GNSS	GNSS	Loran
Integrity	GEO SBAS	Loran SBAS	Loran
Operational Benefits	Enroute, PA	Enroute, PA	Enroute, NPA

Table 1. Using Loran to Back UP GNSS

This paper will examine different means of implementing SBAS on *eLoran* based future proposed architecture for SBAS. It will develop means of reducing data requirements in order to economically use the limit bandwidth available on Loran. It examines how to enable *eLoran* to broadcast these messages while not affecting its other function. This includes developing design that can separate the SBAS function from other functions. This allows service providers the ability to add the SBAS functionality as an option.

2.0 BACKGROUND

Before embarking on examining the design of SBAS information on Loran, it is important to begin with some background information. This section will first discuss SBAS both as it currently is implemented and where it is going in the future. This is useful for understanding the information required from the SBAS broadcast to provide integrity for GNSS. Similarly, Loran and its future evolution will also be discussed to understand the constraints on modifying Loran to carry SBAS information.

2.1 SBAS

An SBAS is an augmentation system based on using geostationary data links and a ground base monitoring infrastructure to improve the performance and safety of GNSS. This is achieved by using the ground network to generate and the geostationary satellite to provide differential corrections and confidence bounds for GNSS satellites. Corrections for clock (fast errors), ephemeris (long term errors), and ionosphere delay are transmitted as are accompanying bounds for the residual errors. Corrections for the ionosphere are important. Ionosphere delay is the largest errors on civil GNSS since these users currently only have access to one frequency and cannot estimate its value. The utility of SBAS has been recognized throughout the world. Current systems include the operational US Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), the Japanese MSAS, and the Indian GAGAN. Currently, these systems broadcast on GPS L1 (1575.42 MHz). Detailed information on using SBAS is provided in [10].

As GNSS evolves and improves, so will these SBAS systems. With the coming of modernized GNSS (GPS Block III, Galileo), a second civil frequency, L5 (1176.45 MHz) in the protected aeronautical radionavigation service (ARNS) band will be available to the aviator.

This allows users to remove ionosphere errors without the use of external corrections. Additionally, the modernized GNSS will provide more accurate clock and ephemeris information, further reducing the pseudorange error. SBAS will also transmit on L5 with a broadcast that will likely take advantage of these changes. While these changes are not expected to be completed and available until 2015-2020, the options for the future architecture of GNSS and SBAS need to be explored now so that they can be implemented. As a result, the US FAA has convened the GNSS Evolutionary Architecture Study (GEAS) to define and evaluate potential future implementations for safe navigation. A preliminary goal of the GEAS is to examine and develop architectures that allow an aircraft to get within two hundred feet of the ground (200 feet decision height (DH)) anywhere in the world.

2.2 GEAS ARCHITECTURES FOR SBAS

The GEAS is proposing several SBAS architectures that would enable approach with 200 feet decision height worldwide. These architectures assume the use of L5 on the geostationary satellite or even GPS Block III. Due to the improvements mentioned above (ionosphere, ephemeris), SBAS on L5 may only need to broadcast one maximum bias term and one bound on the statistical variation of random errors (such as the user differential range error (UDRE)) per satellite. The GEAS has proposed three different approaches with different dependencies for future L5 SBAS. Based on their relationship to previous integrity concepts, GEAS has termed them: 1) GPS integrity channel (GIC), 2) Relative RAIM (RRAIM) and Absolute RAIM (ARAIM). RAIM stands for receiver autonomous integrity monitoring. Specific details of these concepts are covered in [11].

GEAS DESIGN	GIC	RRAIM	ARAIM
Time to Alarm	10-30 sec	30 sec – 10 minutes	> 5 minutes
Benefits	Least dependent on constellation	Balance between ARAIM/RRAIM	Long TTA, Offloads monitoring to receiver

Table 2. Anticipated Time to Alarm for GEAS SBAS Designs

As result of the desire to provide global service, the GEAS believed that it may be necessary to support an increase in the time to alarm (TTA) from the current value of six seconds. This is accomplished by offloading the monitoring of fast changing errors to either the satellite or the user. In the case of ARAIM, the SBAS broadcast only needs to protect against very slowly varying hazards. This results in a TTA of five or more minutes. Even for GIC alterative, which is expected to have the lowest TTA, TTA will be 10 seconds or more. Table 2 shows each GEAS Approach with their respective TTA (estimated) and general benefits.

2.3 LORAN

Loran is a low frequency (LF), high power, terrestrial, pulsed, hyperbolic, horizontal navigation system operating between 90-110 kHz. Due to the nature of LF signals and the power of Loran transmissions, the signals have a long range. Users at distances of 800 km or more can receive these signals which makes then useful for a long-range navigation system. A map of worldwide Loran stations and coverage is seen in Figure 1. More details on Loran can be found in numerous papers and books [12]. In this section, basic details on Loran will be provided to help the user understand the rest of the paper.

Loran stations current operate in geographical groups of 3-5 stations known as chains. Within the chains, the broadcast of each station is spread in time using time division multiple access (TDMA) so that their signals do not interfere with each other. The chains are identified by the chain or group repetition interval, known as GRI, by which a station repeats its broadcast. Some stations broadcasting for two chains and such stations are called dual rated since they broadcast signals at both rates. As sometimes the broadcast for each rate overlaps, one rate will take precedence over the other. The order of precedence is set in the signal specification [13]. These overlaps are rare and predictable.

Figure 1. Worldwide Loran Coverage (Courtesy Megapulse)

2.4 ELORAN DATA BROADCAST

The design of *eLoran* incorporates a data channel as this is necessary to support its primary applications of NPA, HEA, and time/frequency. The Loran data channel is needed to broadcast aviation integrity warning, differential Loran corrections, and station identification messages so that *eLoran* can support the above functions. One version of the data channel modulates an additional pulse (the 9th pulse) to provide data. This concept and modulation is known as ninth pulse communication (NPC). It is capable of providing a minimum 18.75 bps of data after forward error correction. NPC can be extended onto a 10th pulse in most parts of the world including the United States [14]. This effectively doubles the data rate.

For the purposes of this paper, it is assumed that it will be necessary to carry the *eLoran* messages discussed above. Hence part of the bandwidth must be reserved for those messages. Additionally, it would be desirable to separate out the primary *eLoran* message channel from the SBAS channel. The term primary *eLoran* channel will be used in this paper to designate the channel carrying the *eLoran* message. The division gives the service provider an option on supplying SBAS information. This is important as the need for additional bandwidth is a major cost of providing the SBAS option. The separation allows service providers to minimize the number of modulated pulses they need to use if they choose not to exercise the option. Table 3 provides some possible options for utilizing the separate channels for the primary *eLoran* message and SBAS message. The first row indicates which types of stations are capable of providing the SBAS transmission. The worst case data capability of the station of the given type determines the pulses that can be modulated (row two). Row three indicates which modulated pulse will carry the nominal *eLoran* messages. Row four indicates the modulated pulses that will carry the SBAS messages. Row five provides the data rate available for SBAS. This data rate is the minimum data rate derived using the largest GRI. The last row indicates the percentage of the nominal bandwidth available in a station broadcasting on one rate being used for the SBAS message.

Stations providing SBAS	**All Stations**	**Dual Rated Only**	**Dual Rated Only**	**Dual Rated Only**
Modulated pulses	9th and 10th	9th	9th primary*, 9th & 10th secondary	9th and 10th
***eLoran* Message**	9th pulse	9th pulse primary	9th pulse primary	9th pulse primary
SBAS Message	10th pulse	9th pulse secondary	9th and 10th secondary	10th pulse primary 9th & 10th secondary
Available Data rate for SBAS	18.75 bps	18.75 bps	37.5 bps	56.25 bps
Percent of Nominal B	50% (1 pulse)	50% (1 pulse)	100% (2 pulses)	150% (3 pulses)

Table 3. Options for Implementing SBAS on a separate eLoran data channel

3.0 DATA REQUIREMENTS

The current L1 SBAS requires a data rate of 250 bps. However, the proposed options for using *eLoran* provide as little as 18.75 bps. This makes supplying SBAS information on *eLoran* difficult if not impossible. To enable *eLoran* to supply SBAS information, we will have to reduce the data requirements as much as possible. We use some of the underlying assumptions of the GEAS to achieve some reduction. From these assumptions, we can determine the underlying messages and information required. Additionally we can use other properties to further reduce the data requirements.

3.1 BASIC GEAS ASSUMPTIONS

As mentioned previously, there are two fundamental GEAS assumptions regarding civil GNSS users. First, they will use dual frequency receivers. Thus they can generate ionosphere free pseudoranges. Second, GNSS will have better ground infrastructure resulting in better clock and ephemeris estimates. A related assumption is that selective availability (S/A), the intentional dithering put on GPS to degrade the civilian signal, will no longer be an option on future satellites.

3.2 MESSAGE REQUIREMENTS

As a result of these assumptions, the basic broadcast may only need to provide bounds on the random error and maximum bias for each satellite. SBAS provides bounds on the random error through the user differential range error (UDRE). The UDRE is 3.29 times the random bound value at 1-σ. The paper will use the term bias to be synonymous with the bound on the maximum bias. Should differential corrections prove desirable or necessary, GNSS improvements will reduce the data rate required for these corrections. The improved clock/ephemeris estimation reduces its update rate while the absence of S/A reduces the data requirements from 12 to 9 bits per satellite.

However, achieving LPV with 200 feet decision height requires bounding performance to be improved. This improvement can be achieved by the use of clock ephemeris covariance matrix broadcast using message type 28 (MT 28). Due to the requirements of integrity, the broadcasted UDRE provided are quite large. This is because it has to cover the worst case user location in its coverage area. This user can have a UDRE that is an order of magnitude larger than the typical user. This has the negative effect of lowering system availability. As a result, SBAS has defined message type 28 (MT 28) which provides the clock-ephemeris covariance matrix which then allows the user to inflate the baseline UDRE bound as appropriate to their location. It is expected that the GEAS SBAS will want to maintain this feature as it increases availability. Hence, the broadcast of MT 28 may be potentially required.

Finally, the SBAS user needs to know which satellites are being corrected. A satellite mask is used to provide that information. The basic broadcast requirements for the future SBAS is given in Table 4.

Information	Message Type	Data Required (bits)	Current rate	Assumed GEAS required rate
Correction	2	9 per sat	6-12 sec	> 10 sec
Bias	N/A	4 per sat	N/A	Same as corrections
UDRE	2, 6	4 per sat	6-12 sec	> 10 sec
Bound Covariance	28	104 per sat	120 sec	120 sec
Satellite Mask	1	1 per sat	120 sec	120 sec

Table 4. Expected Required Broadcast Information for future SBAS

There is also broadcast information that is in the current SBAS that may be necessary in the future. These are primarily degradation parameters for degrading the corrections and bound over time. These may not be necessary due to the improvements in ground monitoring that results in better ephemeris estimates. Finally, it is desirable to have flexible quantization levels for the UDRE. A message defining these levels has been seen as desirable within the GEAS. These potential broadcasts for the future SBAS is given in Table 5.

Information	Message Type	Data Required (bits)	Current rate	Assumed GEAS required rate
Correction Degradation	7	4 per sat (+ 4 for all sat)	120 sec	> 120 sec
Degradation	10	66 total	N/A	> 120 sec

Parameters				
UDRE levels	New	N/A	N/A	120 sec

Table 5. Possible Additional Broadcast Information for future SBAS

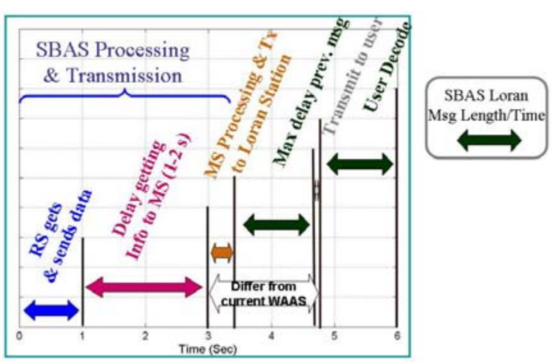
3.3 MESSAGE OVERHEAD

In addition to the basic SBAS information discussed above, there is overhead information that is necessary for every message. This message overhead includes information such as message identification. Other information may include cyclic redundancy check (CRC) to validate the bits in the message and preamble bits to synchronize messages. *eLoran* will use its error correction to provide CRC and synchronization. The *eLoran* data channel signal design is discussed in detail in [15]. As this overhead is constant for every message, longer messages allow one to amortized this "cost" over more data. This results in efficiency gains as less of the bandwidth is used for overhead. In this analysis, we assume that the overhead is 5 bits and only contains message identification.

3.3 MESSAGE LENGTH & TIME TO ALARM

The amortization of the message overhead over longer messages allows for a higher percentage of the bandwidth to be used for data. This comes at the expense of time of alarm as longer messages result in longer time to alarms. The relationship of minimum achievable TTA to message time for SBAS on *eLoran* is seen in Figure 2. This shows the worst case where the alarm message arrives just as a message is being transmitted. Thus it has to wait for one entire message time (i.e. maximum delay of the previous message) before being transmitted. From the figure, we derive the relationship between minimum achievable TTA and message time. The assumption is that while the GEAS goal is worldwide coverage, the Loran transmitter is only responsible for its local area and thus only needs GNSS observations from a smaller area. As such the data transmission delay from reference station to master is only two seconds. It would be larger if the reference station is half way around the world from the master.

Time to Alarm (TTA) ~ 3.5 sec + 2 * (message time)



Master Station (MS) Processing & distribution to Loran Station time ~ 0.3 seconds
Reference Station (RS) Processes measurements for 1 second

Figure 2. SBAS on eLoran Timeline

3.5 QUEUEING

From previous analysis of WAAS and modified WAAS usage, bandwidth utilization should not exceed 80-95 percent for the system to be feasible [9]. Some margin must be retained since the information being transmitted does not come at a constant rate. This means that there may be times when the short term bandwidth required will be greater than average level. This data cannot be delayed significantly as SBAS information have required update times and must be transmitted in a timely manner. As a result, a SBAS messaging system that uses more than 95 percent of bandwidth is not feasible since there will be periods of time where it cannot transmit all the required data. For this analysis, we decided to conservatively use 80 percent bandwidth as our threshold.

4.0 REDUCING DATA REQUIREMENTS

4.1 USING LORAN PROPERTIES

The basic reduction in data bandwidth due to future improvements may not be enough to allow *eLoran* to broadcast the modernized SBAS message. Data reduction can be achieved if we limit ourselves to protecting only the users capable of receiving the Loran data broadcast. The coverage area is significantly smaller than an SBAS geostationary satellite. As a result, fewer satellite corrections are required and some vectors, such as the MT 28 covariance matrix, can be projected into a scalar form with only a small reduction in performance.

4.2 REDUCED SATELLITE SET

While a SBAS such as WAAS generally transmits corrections for every satellite in the GPS constellation, any given user needs only a subset of these corrections. The number of satellites necessary to service all users of a data link depends on the coverage area of that link. Since the coverage area determines the number of satellites visible to any user, it has a direct relationship to the number of satellite corrections that need to be sent. The decision is based on the analyses of the number of satellites visible to a coverage area and how the set of visible satellites changes.

A satellite visibility model is used to determine the number of satellites visible within a given radius of a central point, i.e., the Loran transmitter. This circle defines the coverage area of the data link. Only satellites visible from within the coverage area need to be corrected. Since the results depend on both the GNSS constellation used and the central point selected, many different central locations within the coterminous United States (CONUS) along with two different Global Positioning System (GPS) constellations (optimal 24 from Appendix B of [10] and the 28 satellite from August 2000) are tested. Figure 3 shows the number of satellites for which corrections must be provided to ensure that any user covered by the data link has corrections for all satellites visible. The central point used is located in Columbus, Ohio. The number is plotted as a function of the coverage radius. Simulations of one and two days were conducted and the minimum, maximum and average number of satellites is given for both constellations. Assuming the maximum coverage radius of the Loran data channel is about 1000 km, this means only 12-16 satellites need to be corrected to cover the maximum of the two constellations examined. In this paper, we will study two cases: 15 and 20 satellites. This is supposed to represent two cases: one GNSS constellation (i.e. GPS or Galileo) and two constellations (i.e. GPS and Galileo) are used. The one drawback of such an implementation is the need to more regularly change satellite masks than in nominal SBAS where changes are infrequent. The same model is used to determine how often a new mask needs to be calculated and broadcast. Analysis indicates that the mask should change roughly every hour [8][9].

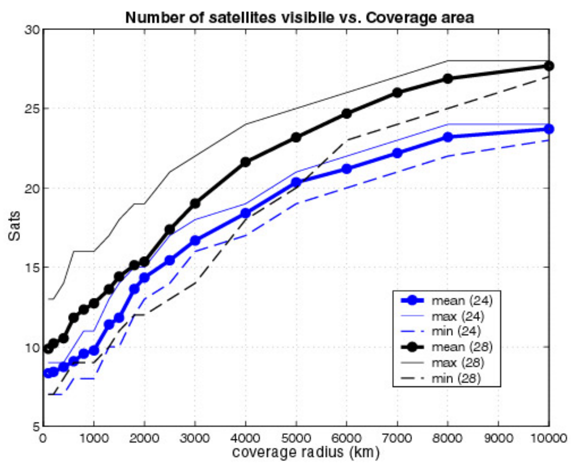


Figure 3. Visible Satellites vs. Coverage Radius

4.3 PROJECTION OF MT 28

While the update rate of MT 28 is not high, the large amount of data necessary for it makes it one of the largest users of bandwidth. If MT 28 is determined to be necessary for modernized SBAS, support of this message may be infeasible in many designs. A plan for reducing the data required for the MT 28 message information is required to broadcast that information on *eLoran*. One way is to provide a scalar projection of the matrix for the Loran coverage area. However, this will result in performance degradation to some users. We need to quantify the degradation to determine its magnitude and whether it is acceptable.

An analysis of the degradation due to scalar projection of MT 28 was conducted using the Matlab Availability Algorithm Simulation Tool (MAAST) [16]. MAAST simulates SBAS performance. For these tests, we compared the ratio of a normalized minimum and maximum value of the random error bound or UDRE termed dUDRE. The ideal minimum dUDRE is 1. The Loran transmitter will broadcast the maximum value as it covers all users. Hence, the ratio will provide a sense of the performance degradation suffered by a user who would have used the minimum value.

Several simulations were performed at various locations. The simulation was conducted over a 12 hour, the orbital period of the GPS satellite. The current WAAS monitor network is used as a baseline and various Loran coverage radius (600-1000 km) were used. Results using GPS is shown. The results using a GPS+Galileo constellation were similar or no different.

Figure 4 shows the maximum dUDRE at a given hour over the 12 hour period for three locations. The coverage radius is 1000 km. One location is within the center (Dana, IN) and two locations are at the fringe (Seneca, NY and Middletown, CA) of the WAAS network. The minimum dUDRE is one for all times and cases and so the maximum dUDRE is also the ratio of the best to worst dUDRE. As expected, the dUDRE ratio is lower near the center of the network as the observability is better there and hence there is a less variation between the best and worst user. Table 6 shows the dUDRE ratio for these three locations for different coverage radii.

Another analysis is to determine the degradation experience by using the scalar projection. The distribution of the dUDRE over the 12 hour period is seen in Figure 5 for Dana, IN. It shows that about half the users have dUDRE values less than 1.5. This implies that these users will have to increase inflate their UDRE by a factor of roughly two to three when compared to using the full MT 28 covariance matrix.

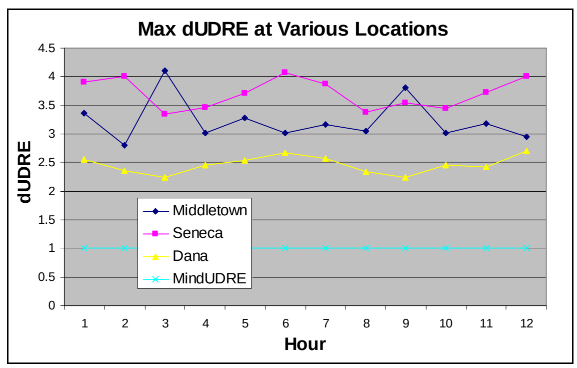


Figure 4. Maximum dUDRE at Dana, IN, Seneca, NY and Middletown, CA (1000 km radius coverage)

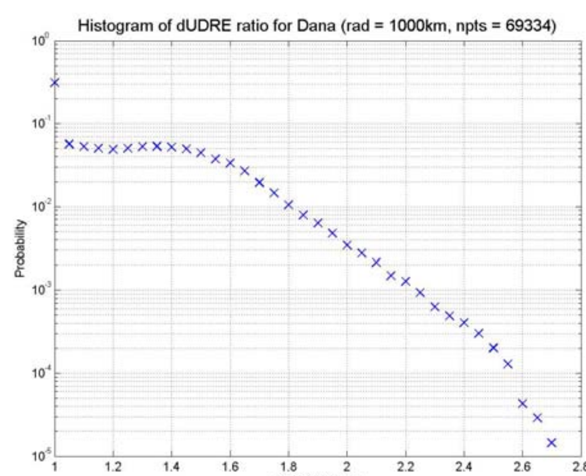


Figure 5. Probability Distribution of dUDRE for all users in coverage area (12 hr period)

Coverage radius	Dana, IN	Seneca, NY	Middletown, CA
600 km	2.18	3.33	3.18
	1.72	2.82	2.36
800 km	2.71	3.33	3.44
	2.25	2.82	2.46
1000 km	2.71	4.07	4.10
	2.25	3.35	2.80

Table 6. Maximum and Minimum of Max dUDRE at three locations

5.0 ANALYSIS OF DATA USE

Determining feasibility means analyzing the data bandwidth requirements of broadcasting the information discussed previously. First, the analysis also needs to consider some practical aspects of the broadcast such as message overhead. This affects the efficiency of our usage of the bandwidth. Next, we examine data bandwidth usage for some of the scenarios mentioned earlier using baseline values for required update rate. Finally, we look at some variations and sensitivities to update rate.

5.1 BASELINE ANALYSIS

The first question we ask is whether the bandwidth is adequate given the highest (most frequent) expected update rates for the information discussed previously. This means updating the basic information at the rates mentioned in Table 4. For this analysis, we only focus on transmitting the basic required information mentioned in Table 4. This represents our baseline design. Some of the less critical information is not considered due to their lower criticality and data requirement. As a result, they may be transmitted on the *eLoran* channel.

The three data options (50%, 100%, 150%) discussed in section 2.4 will be assessed. These options are the basis for the scenarios examined. The scenarios combine the data option with different levels of MT 28 information. We examine three different levels of MT 28 information (none, scalar, full). This is because the full MT 28 covariance matrix requires significant bandwidth and it is not clear whether the information is needed. The basic scenarios examined are presented in Table 7. Not all scenarios are examined in each analysis for two reasons. First, being feasible for one scenario could mean that the option is feasible for other scenarios. For example, if the 100% full MT 28 is feasible then the 100% option is feasible for the no and scalar MT 28 scenarios. Additionally, the no MT 28 and scalar MT 28 scenarios are reasonably close in data requirement.

Scenario Name	Data Rate (bps)	MT 28 (bits per sat)
50% No MT 28	18.75 bps	0
50% Scalar MT 28	18.75 bps	5
100% No MT 28	37.5 bps	0
100% Scalar MT 28	37.5 bps	5
100% (Full) MT 28	37.5 bps	104
150% Scalar MT 28	56.25 bps	5
150% (Full) MT 28	56.25 bps	104

Table 7. Basic Scenarios Examined

Figure 6 and Figure 7 show the bandwidth requirement, assuming 20 satellites, for the scenarios described in Table 7 as a function of message length and time to alarm. An additional scenario of 150% with scalar MT 28 is shown in Figure 6 as this is the only scenario that is feasible using the nominal conditions of Table 4. The equivalent 15 satellite performances are seen in Figure 8 and Figure 9. For the 15 satellite, many more scenarios are feasible. Only the 100% (with MT 28) and 50% scenarios are not feasible.

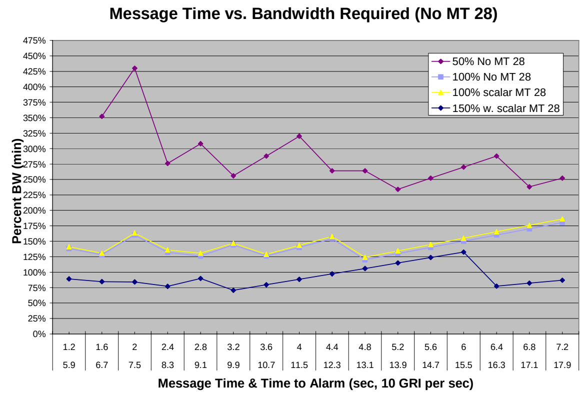


Figure 6. Bandwidth usage for scenarios with no or scalar MT 28 information (20 sats)

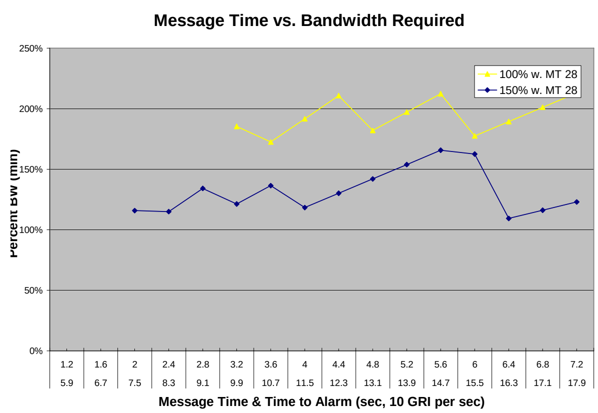


Figure 7. Bandwidth usage for scenarios with full MT 28 matrix (20 sats)

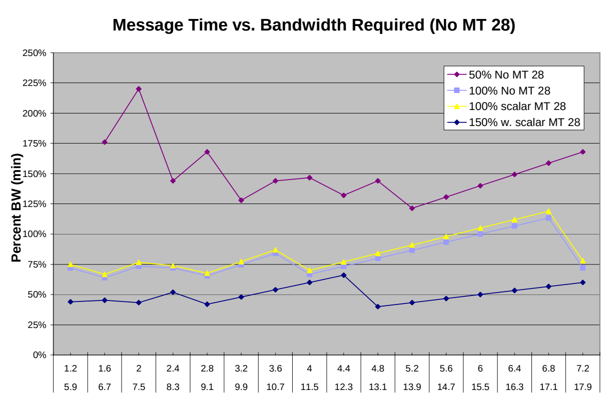


Figure 8. Bandwidth usage for scenarios with no or scalar MT 28 information (15 sats)

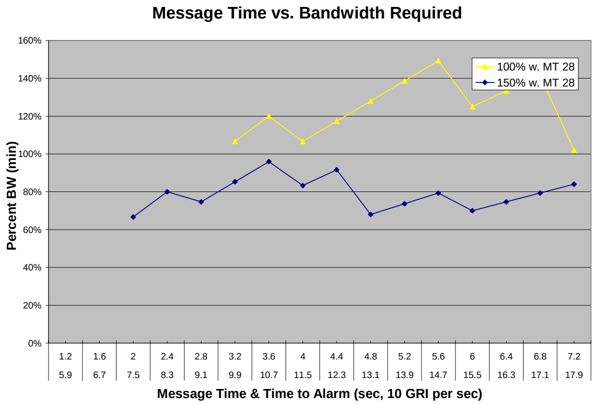


Figure 9. Bandwidth usage for scenarios with full MT 28 matrix (15 sats)

5.2 BASELINE SBAS DESIGN RESULTS

For the nominal update rate case, the results show only one implementation to be feasible. This option requires 150% bandwidth meaning only dual rated stations capable of supporting both 9th and 10th pulse can provide the capability. This limits the number of stations capable of supporting the SBAS message. Additionally, if the full MT 28 information is necessary, no alternative is feasible.

If the corrections update interval is increased to 30 seconds, several more options are available. The 150% bandwidth can now support full MT 28 while a 100% bandwidth option can support scalar MT 28 corrections. In fact, these options are feasible even if the corrections update rate is 15 seconds. This means dual rate stations capable of supporting both 9th and 10th pulse on one of its rate will be capable of supporting the SBAS message. This slightly increases the number of stations capable of providing SBAS information.

Table 8 shows the result of the baseline analysis. It makes a conservative assumption in that for a design to be feasible, the design can only use at most 80% of the bandwidth available. If a design is feasible for 15 satellite correction set, "15" will be indicated. The same is true for a 20 satellite set. Notice that 150% option can support all designs for 15 satellites and nearly all for 20 satellites. The 100% option can support most 15 satellite designs with the exception of having the full message type 28. It can also support some 20 satellite designs. The 50% option cannot support any design in the baseline analysis.

Scenario (80% pass)	50% (1 pulse)	100% (2 pulse)	150% (3 pulse)
Nominal No MT 28	x/x	15/x	15/20
Nominal Scalar MT28	x/x	15/x	15/20
Nominal Full MT28	x/x	x/x	15/x
30 sec corrections No MT 28	x/x	15/20	15/20
30 sec Scalar MT28	x/x	15/20	15/20
30 sec Full MT28	x/x	x/x	15/x

Table 8. Summary of Feasibility (Uses 80% or less of BW) of Each Scenario for Different Data Requirements

5.3 REDUCING UPDATE RATE

The basic feasibility analysis results demonstrate some options that can provide SBAS on *eLoran*. However, it is somewhat disappointing as the most desirable option (50% bandwidth) cannot reasonably support the any baseline SBAS design. Fortunately, we have additional design possibilities. The update rates used in the analysis represents a baseline value. The actual update time will likely be longer. Longer update times reduces the required bandwidth as fewer messages need be transmitted over a period of time. The next analysis is to examine the feasibility with respect to changes in the required update time/rate.

Figure 10 and Figure 11 show the bandwidth requirement for the scenarios described previously. The only change is that the corrections and bias update time is increased to 30 seconds. This is a reasonable assumption under GEAS as remaining errors will generally have long decorrelation times. From Figure 10, we see that 50% bandwidth still does not work for the update rates assumed in the analysis. The 100% bandwidth option can provide the required bandwidth if scalar MT 28 information is used. The results from Figure 11 shows that full MT 28 cannot be supported by 100% bandwidth and supporting full MT 28 requires 150% bandwidth.

We can also examine the benefits of having a slower UDRE update rate. First, we examine the 50% bandwidth option. Now it is assumed that scalar MT 28 is necessary which adds another data requirement. However, the update rates for the corrections, bias bounds, and UDRE will be changed. Let us fix the update rate for the corrections and bias bounds to be 45 seconds. Figure 12 shows the bandwidth usage for various UDRE update rates. As seen, the 50% bandwidth option is feasible even at 15 second updates for UDRE. This is merely a 5 second increase of the UDRE update interval. Given the future SBAS assumptions, this increase can likely be supported.

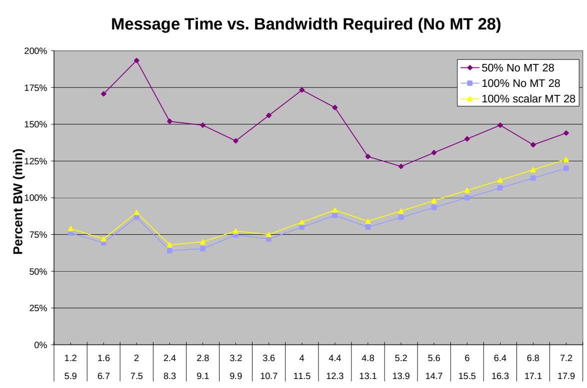


Figure 10. Bandwidth usage for scenarios with no or scalar MT 28 information (30 second corrections/bias update)

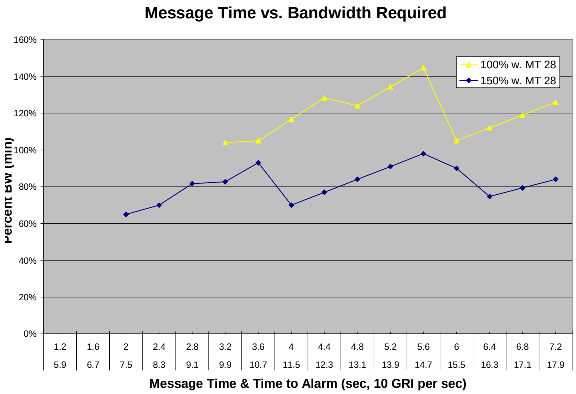


Figure 11. Bandwidth usage for scenarios with full MT 28 matrix (30 second corrections/bias update)

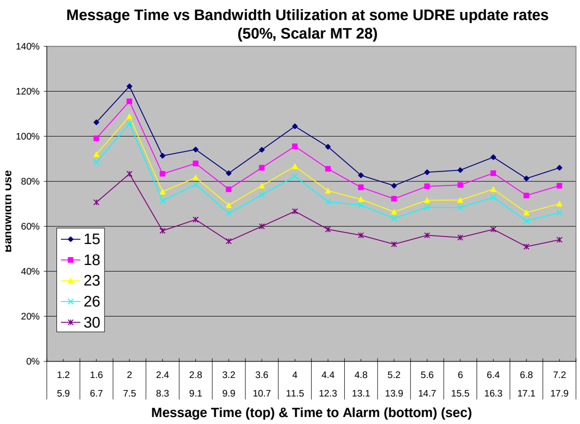


Figure 12. Bandwidth usage for 50% bandwidth scenario with scalar MT 28 information (different update rates for UDRE)

Next, we examine the 100% bandwidth option and try to determine the minimum update time so that it can support full MT 28 information. Again, fix the update rate for the corrections and biases to be 45 seconds. Figure 13 shows the bandwidth usage for various UDRE update rates. From the analysis, it seems like this option starts being feasible at 25-30 second updates for UDRE.

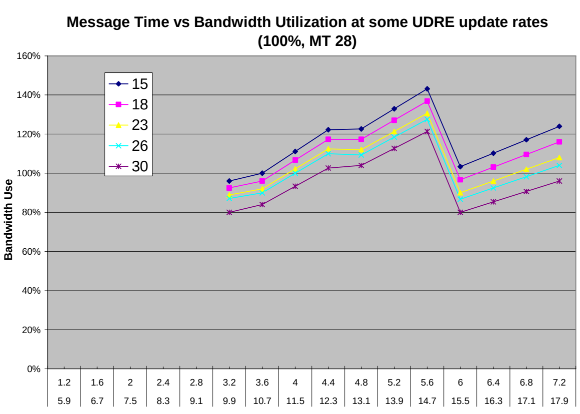


Figure 13. Bandwidth usage for 100% bandwidth scenario with full MT 28 information (different update rates for UDRE)

5.4 RESULTS FOR REDUCED UPDATE RATE

If the corrections update interval is increased to 45 seconds and the UDRE update interval is increased slightly to 15 seconds, the 50% bandwidth option become available. This is important as the 50% option essentially means all stations worldwide can support SBAS on *eLoran*. This can be accomplished by having a station use both 9th and 10th pulse. If a station can only support 9th pulse but is dual rated, it can provide SBAS on its secondary rate. This option also results in the lowest amount of Loran to Loran interference known as crossrate interference.

Table 9 summarizes the results of the analysis on reducing bandwidth by between reducing UDRE, correction, and or bias update rates. The table shows UDRE message (first term) and UDRE update rate (second term) in seconds for each design. Note that the UDRE message rate is than the update rate because UDRE values are also contained in the corrections message. Some scenarios are not examined because 1) the 100% can already support scalar MT28 and 2) the 50% can never support full MT 28. Thus the table shows that with a 45 second update for corrections and bias bounds, the 50% option can support UDRE update rates of 10 and 15 seconds for 15 and 20 satellites. From the table, we see that with a slight reduction in update rates, the 50% option support 15 and 20 satellite designs with scalar MT 28 and the 100% option can support full MT 28 for both satellite designs.

Scenario (80% pass)	Sats	50% (1 pulse)	100% (2 pulse)
45 sec corrections scalar MT 28	15	13/10	N/A
	20	22.5/15	
45 sec corrections full MT 28	15	N/A	18/12.9
	20		60/30

Table 9. Minimum UDRE update rates (message/UDRE update) for feasible 50% and 100% BW Scenarios assuming 45 sec update on corrections

6.0 CONCLUSIONS

As the GPS and other GNSS has become integral to the critical infrastructure in many safety and economic activities, it has become increasingly necessary to determine an efficient means of retaining most of the safety or economic benefits derived from these systems the event that they are unavailable. The goal of this paper was to determine the feasibility of *eLoran* to provide SBAS redundancy in addition to supporting stand alone aviation, maritime and timing back up to GNSS.

Preliminary analysis shows that *eLoran* does have the capability of providing redundancy to future SBAS. All options can provide SBAS information. Additionally, all options can provide some form of MT 28 information. The most desirable option uses only one modulated pulse and supportable by all stations. It is feasible depending on the update requirements on future SBAS corrections and bounds. If these update rates are not at their maximum (once every 10 seconds), this options are available. Reducing update rate requirements also allows two modulated pulse (100%) options to support full MT 28. The update reduction is not thought to be a constraint as it is anticipated, depending on the future architecture used, that the rates will indeed be lower. This makes several attractive versions of implementing SBAS on *eLoran* feasible.

The analysis performed in this study also has some implications for GPS III. The minimum data rate analysis supports the belief that 25 bps is capable of supporting SBAS integrity messages on GPS III. The largest driver of the data bandwidth in this case many be the MT 28 message information. Should bandwidth be an issue, work should be done to examine more efficient means of conveying the information such as parametric modeling.

7.0 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Federal Aviation Administration and Mitchell Narins under Cooperative Agreement 2000-G-028. They also acknowledge the inputs of Dr. Todd Walter of Stanford University for his insights into the GEAS architectures. The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the United States Federal Aviation Administration or Department of Transportation or any other person or organization.

8.0 REFERENCES

[1] “Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System,” John A. Volpe National Transportation System Center, August 20, 2001.

[2] Presidential Decision Directive, “U.S. Space-Based Positioning, Navigation, and Timing Policy”, December 15, 2004

[3] FAA report to FAA Vice President for Technical Operations Navigation Services Directorate, “Loran’s Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications,” March 2004.

[4] International Loran Association, “Enhanced Loran (*eLoran*) Definition Document,” Revision 1.0, January 2007. http://www.loran.org/news/

[5] Press Office, U.S. Department of Homeland Security, “Statement from DHS Press Secretary Laura Keehner on the Adoption of National Backup System to GPS,” February 7, 2008.

[6] Peterson. B. B., et al., "High Speed Loran-C Data Communications – 2001 Update", in Proceedings of the 2nd International Symposium on Integration of LORAN-C/Eurofix and EGNOS/Galileo, 2001, Bonn, Germany, pp. 135-155.

[7] Lo, Sherman, Peterson B., Enge, P. and Swaszek, P., “Loran Data Modulation: Extensions and Examples”, IEEE Transactions on Aerospace and Electronic Systems.

[8] Lo, Sherman and Enge, Per, "Broadcasting Data from an SBAS Reference Network over Low Rate Broadcast Channels", Proceedings of the International Symposium on Integration of LORAN-C/Eurofix and EGNOS/Galileo, March 2000, Bonn, Germany, pp. 199-209

[9] Lo, Sherman, “Broadcasting GPS Integrity Information Using Loran-C,” Ph.D. Dissertation, Stanford University, July 2002.

[10] RTCA Special Committee-159, “Minimum Operation Performance Standards for Airborne Equipment Using Global Positioning System/Wide Area Augmentation System,” RTCA/DO- 229D, December 2006.

[11] Walter, Todd, Blanch, Juan, Enge, Per, Pervan, Boris, and Gratton, L., “Future Architectures to Provide Aviation Integrity” Proceedings of the Institute of Navigation National Technical Meeting, San Diego, CA, 2008

[12] Forssell, Borje, Radionavigation Systems, Prentice Hall, Englewood Cliffs, NJ 1991.

[13] Specification of the Transmitted LORAN-C Signal, COMDTINST M15662.4A, Commandant, USCG, May 1994.

[14] Peterson, Benjamin, “Feasibility of Increasing Loran Data Capacity using a Modulated Tenth Pulse”, Proceedings of the International Loran Association 36th Annual Meeting, Orlando, FL, October 2007

[15] Carroll, K., Peterson, B. B., et al., "Differential Loran-C,” in Proceedings of GNSS 2004 – The European Navigation Conference, Rotterdam, The Netherlands, May 2004.

[16] Jan, Shau-Shiun., Chan, Wyatt, Walter, Todd, and Enge, Per, “Matlab Simulation Toolset for SBAS Availability Analysis”, Proceedings of Institute of Navigation-GPS, Salt Lake City, UT, 2001