WAAS Performance in the 2001 Alaska Flight Trials of the High Speed Loran Data Channel

Sherman C. Lo, Dennis Akos, Sharon Houck, Per Ludvig Normark, Per Enge
Department of Aeronautics and Astronautics, Stanford University

Abstract: The Wide Area Augmentation System (WAAS) enables the Global Positioning System (GPS) to provide the performance and integrity necessary for en route flight and many landing procedures. Currently, WAAS employs two geostationary satellites to provide coverage to the United States. However, operational WAAS will require a redundant broadcast of WAAS throughout the US. Additional geostationary satellites will be used to provide some redundancy. Loran can serve as a cost-effective additional broadcast channel for WAAS. While additional geostationary satellites are still necessary, Loran can further augment broadcast of the WAAS message particularly in terrain, urban canyons or high latitudes. Using Loran has some appealing features. First, Loran can be modified to attain the capacity to support the WAAS message. Second, it could also provide a reversionary positioning capability in case the GPS/WAAS signal is lost due to radio frequency interference (RFI). Loran can be particularly helpful in Alaska, where terrain combined with high latitudes could block the signal from the geostationary satellite that appears low in the Alaskan sky.

In 2001, an experimental system was developed to modify the Loran pulse to carry data at a rate sufficient to transmit WAAS. Trials of the system demonstrated its efficacy in transmitting the WAAS data rate using existing Loran transmitters. In August, flight trials were conducted to further evaluate the system using the operational Tok, Alaska Loran station.

This paper describes the flight and ground tests of the reception of WAAS from Loran and the geostationary satellite. Data was collected over two days from a surveyed static site in Anchorage and two aircraft. The performances of each data link and an integrated solution are presented. The analyses clarify some of the advantages and disadvantages of both systems in Alaska airspace. The results show that Loran does provide utility as a back up data link for WAAS.

BACKGROUND

The Global Positioning System (GPS), augmented by systems such as the Wide Area and Local Area Augmentation Systems (WAAS, LAAS), will become the primary means of aircraft navigation. WAAS increases the performance of the basic GPS navigation system by providing differential corrections, confidence bounds, and additional ranging signals. It uses a geographically diverse ground reference network to calculate differential corrections and error confidences for various GPS pseudorange errors. These WAAS corrections and confidences are applicable over a large area such as the United States. They enable GPS to provide the performance and safety for necessary for en route flight and many landing procedures. Accuracy levels of 1-2 meters in the horizontal and vertical direction are achievable using WAAS.

WAAS transmits one 250-bit message every second. A half rate convolutional error correcting code is used resulting in a transmission rate of 500 symbols per second. Two geostationary satellites are currently being used to broadcast the WAAS message. Geostationary satellites are attractive due to their capability to cover large areas. Also the data link is at GPS L1 frequency (1575.42 MHz) and can provide an additional GPS ranging signal. However, since geostationary satellites are used, it is possible to lose the WAAS signal, especially at high latitudes such as Alaska. Thus it is desirable to have a redundant data link for WAAS since it can provide additional redundancy in the system, increased coverage and additional radio frequency interference (RFI) rejection. One candidate is Loran.

Loran is a terrestrial navigation system whose origins date to the Second World War. It became operational in 1958 and has played a significant role in maritime navigation. Hence the system is operated and maintained by the United States Coast Guard (USCG). Loran is a hyperbolic positioning system and operated in groups known as chains. These chains are uniquely identified by the interval between sets of transmitted pulses. This interval is known as the group repetition interval (GRI) and usually expressed as a multiple of ten microseconds, i.e., GRI 7960 = 79600 microseconds. The power of Loran transmissions allows users at distances of 800 km or more to receive these signals. Furthermore, since the signal is low frequency (LF), reception is not dependent on line of sight. These properties make it useful for a long-range terrestrial navigation system.

The 1996 Federal Radionavigation Plan (FRP) stated that Loran-C would be terminated in 2000. However, 1999 FRP stated that the United States would continue operating Loran for the short term while evaluating "the long term need for continuation of the Loran-C radionavigation system." The Federal Aviation Administration (FAA), following up the 1999 FRP and a Congressional directive, initiated a program to assess the utility and role of Loran in the future. The program not only addresses the current capabilities of Loran-C, but also examines the potential of new technology and techniques when applied to Loran. The four major areas of development are:

- Loran H-field antenna suitable for aircraft
- Digital signal processing (DSP) Loran receiver with all in view capabilities

- Enhanced Loran communications capability for GPS integrity
- Hybrid GPS/Loran receiver architecture

The goal of the first two tasks is to allow aviation to use stand alone Loran for lateral navigation (LNAV). The third task develops a Loran data channel that can provide WAAS information to aviation users and is the focus of this paper. The fourth task integrates the results of the first three areas to create a highly reliable receiver architecture for aviation.

Work on developing Loran to transmit WAAS information has been on going since 1999 [1]. Many modulation techniques were examined with the final decision being to use interpulse frequency modulation (IFM). These modulation techniques are discussed in [2].

By 2001, a prototype system capable of broadcasting the full 250 bit WAAS message on Loran was developed. The effort involved considerable equipment development including a Loran data channel (LDC) modulator and a new Loran communications receiver capable of receiving the LDC signal at high speeds. Also a new H-field antenna was built. Flight tests were conducted in May and June 2001 using the Wildwood, NJ Loran station. Wildwood is the home of the U.S. Coast Guard (USCG) Loran Support Unit (LSU). The Wildwood station is not an operational station and well suited for use for experimental efforts. After the successes in May and June, the next phase of development was to implement this system on an operational Loran station. It was decided to use the Tok, AK station since the high latitude regions of Alaska are areas of concern for WAAS.

This paper presents some results from the August 2001 Alaska flight trials of the Enhanced Loran data channel. These trials are part of the ongoing efforts in developing a capability of transmitting WAAS to users using Loran.

ALASKAN FLIGHT TRIALS

The Alaska flight trials were conducted on August 23-24, 2001. Two aircraft – a Ohio University Beechcraft King Air and a FAA Technical Center Convair 550 – were operated from Merrill Field in Anchorage. Both aircraft were equiped with a Loran receiver, GPS/WAAS Novatel OEM 4 receiver and data collection unit along with an H-field antenna. Technical issues with the H-field antenna on the King Air led to the use of an E-field antenna on the second day.

The August 23 tests involved the Convair flying a roundtrip from Anchorage to Prudhoe Bay and the King Air flying a roundtrip from Anchorage to Juneau. Both Juneau and Prudhoe Bay represent theoretical limits of the LDC transmission from Tok. On the 24th, the King Air flew from Anchorage to Homer, then head Northwest before returning back to Anchorage. The LDC signal is expected to have a high symbol error rate at Homer due to interference from the Loran station at Narrow Cape. The Convair flew a high altitude course from Anchorage to Juneau and back. A map of Alaska indicating these areas is presented in Figure 1.

In addition to the flight test, a static site in Merrill field was also operated. The static site was previously surveyed allowing for a truth reference. It also collected GPS/WAAS and Loran data for future analysis. A preliminary test was conducted on August 17 to verify that the LDC transmission from Tok was operating within desired parameters. Static data was logged during this test.

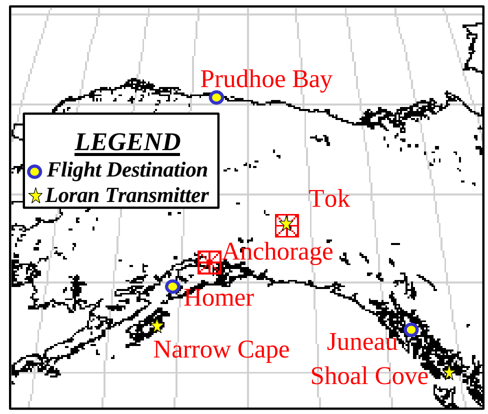

Figure 1 Alaska Flight Test

TRANSMITTER SET UP

The Loran transmitter at Tok, Alaska was used to provide the LDC signal. This is the first operational Loran station to transmit the signal and the use of this station required taking the entire 7960 chain of line. Tok serves as the master station for this chain. However, Tok is an attractive option since it provides reasonable signals to areas of interest – Fairbanks, Anchorage and Juneau. Furthermore, its equipment is compatible with the LDC modulator developed by Peterson Integrated Geopositioning (PIG).

The geostationary satellite broadcast of WAAS was used to provide the WAAS message to the LDC modulator. A Novatel OEM 4 GPS/WAAS receiver and a GPS patch antenna were used to receive the broadcast. Since Tok is located at 63 N, the geostationary satellite is at a very low elevation in the sky (approximately 12 degrees). The set up of the GPS antenna used to receive the WAAS signal is critical. The antenna was originally positioned on the roof of the Tok Loran station as seen in Figure 2. This set up resulted in a carrier to noise ratio (C/No) of 33 dB-Hz, which is barely acceptable. Next, the antenna was placed on the ground pointed towards the estimated location of the geostationary satellite. A higher-grade cable was also used. The changes provided significant gain with the result being a C/No of 45 dB-Hz. This became the final configuration and is seen in Figure 2.

The LDC modulator takes the WAAS message output from the OEM 4 receiver and uses Reed-Solomon (R-S) error correcting code to provide forward error correction for the LDC. The modulator then takes the symbols and determines the set of waveforms that form the desired symbols. These waveforms are then used to drive the Loran transmitter. The station was operated at a GRI of 48300 microseconds. At this rate, one 250 bit WAAS message could be transmitted every second. The data transmission rate actually is slightly greater than 250 bps resulting in enough extra bandwidth to send an additional message every 29 to 30 messages. Since the additional bandwidth is not needed, it was decided just to repeat the previous message. A more detailed description of the design is given in [3].

The set up used adds latency to the system since the modulator has to wait for the entire WAAS message to be received from the geostationary satellite before applying Reed-Solomon, determining the waveform and transmitting those waveforms. Connecting the Loran station to WAAS master station (WMS) generating the messages with a high speed landline can eliminate the latency. This eliminates the delay incurred from using the geostationary satellite. However, the method used is more practical, cost effective and more than adequate for evaluation. It can be used to evaluate the landline design since the latency can be removed in post processing.

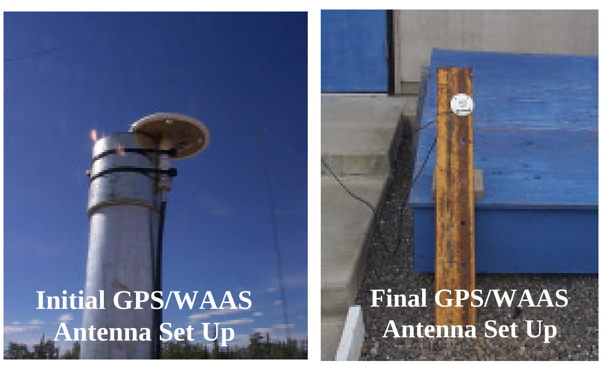

Figure 2 Initial & Final GPS/WAAS Antenna Set Up

DATA COLLECTION

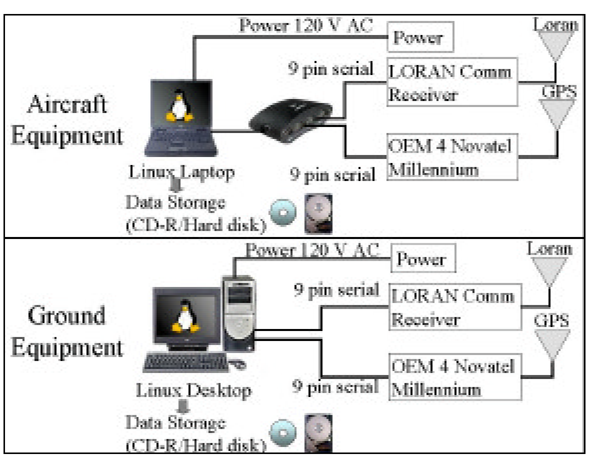

Figure 3 Set Up of WAAS User and Data Collection Equipment

Four data collection units were built for the flight trials - one ground unit and three portable units. Each unit consists of a Loran communications receiver, a Novatel OEM 4 Millenium GPS/WAAS receiver and a Linux based data processing and collection computer. The Loran communications receiver is an Intel based personal computer operating under Windows that is capable of receiving the LDC signal. It outputs the forward error correction (FEC) decoded WAAS messages to the data collection computer. It also stores raw LDC observables in its hard disk. Additional details on the receiver architecture are provided in [4]. The Novatel OEM 4 receiver, while not a certified aviation receiver, is capable of receiving both the GPS and WAAS signals. It is capable of outputting a WAAS solution though only raw GPS observables and the decoded WAAS messages are used. The data collection computer operates a modified version of the Stanford WAAS user code and it takes outputs from both the Loran and the Novatel receivers and processes a WAAS solution either using the WAAS messages received from either source. It stores data from both receivers. Four distinct binary files are generated.

- The Novatel OEM 4 GPS binary messages. Included are GPS observables and GPS messages
- WAAS Message from the geostationary satellite. This is from the Novatel receiver
- WAAS message from the LDC receiver.
- Timing file that tracks the relative order and time of arrival of each message in the above three files.

The formats of the first three files are shown in Figure 4.

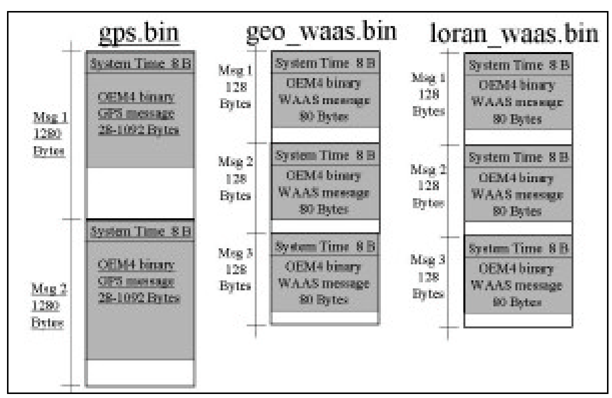

Figure 4 Data File Format from Data Collection Computers

The ground unit operated a version of the code capable of supporting real time data visualization and analysis. The portable units operate on laptops and use a slimmed down version of the code that supports data collection. It also generates the WAAS solution but is not capable of real time data analysis.

STATIC TEST RESULTS

The static ground site, located at Merrill Field, provides a reference location for monitoring the LDC and geostationary signals. It also provides a truth reference since the location had been surveyed. The geostationary satellite is at roughly 15 degrees in elevation and the WAAS signal received from the geostationary satellite was very reliable. No losses were seen. The performance of the geostationary WAAS (GEO WAAS) broadcast is seen in Figure 5 which presents the vertical protection level (VPL) chart for the system. The chart helps quantify availability, integrity, and accuracy. It is a two dimensional histogram with true error and vertical protection level as the vertical and horizontal axes, respectively. The VPL represents a 99.99999% confidence bound on vertical error and is calculated by a user from the data transmitted by WAAS. Any solution below the 45-degree line is defined to constitute hazardously misleading information (HMI) because the protection level did not bound the actual error, i.e., the actual error was greater than the protection level. This should occur with a probability of less than one in ten million or 10^{-7}.

Approach with vertical guidance (APV), formerly known as GLS, is a precision approach that requires a VPL of 20 meters or less. This limit for the VPL is known as the vertical alarm limit (VAL). Any solution with a VPL above the 20 meters VAL is considered unavailable for use in APV. Hence the system is unavailable for APV use when this occurs. Lateral navigation/ vertical navigation (LNAV/VNAV) is a precision approach with a VAL of 50 meters. The goal of phase I WAAS is to achieve LNAV/VNAV with 99.9% availability. While both approaches also have horizontal requirement, the vertical requirement is more difficult to meet. As a result, the horizontal protection level (HPL) chart is not presented.

Figure 5 shows that the availability of the system for GLS or APV approaches is almost 95% while the availability for LNAV/VNAV approaches is greater than 99.999%. Just as important is that integrity is maintained with all points above the 45-degree line.

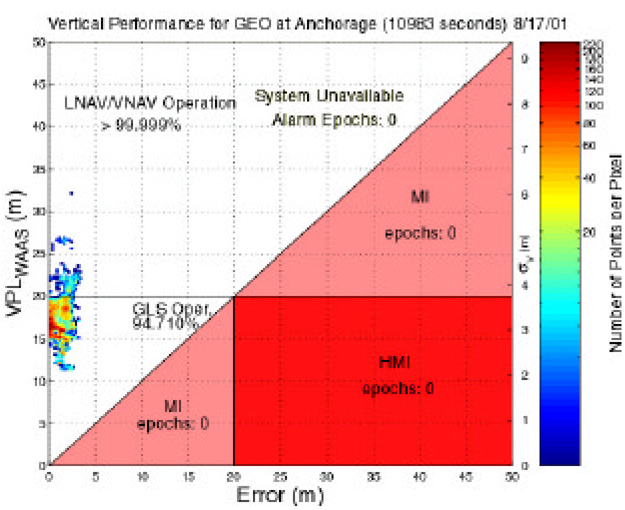

Figure 5 VPL using GEO WAAS (Anchorage, 8/17/01)

A modified grid ionosphere vertical error (GIVE) algorithm was used. The GIVE is number calculated by WAAS that provides an estimate of the error on the ionosphere delay. It is a 3.29 σ or 99.9% error bound. The modified algorithm simulates the performance that would be achieved using the design specified in the new GIVE algorithm description document (ADD). Thses changes will be implemented in operational WAAS in 2002. The change made for the flight trials allows the current broadcast ionosphere corrections to be used by setting a nominal large value of the GIVE for Alaska. Otherwise, the broadcast GIVE at that time would not allow the use of the ionosphere corrections resulting in significant performance degradation.

The LDC WAAS signal performed nearly as well. The few missing messages on the LDC resulted from Tok station not broadcasting them. The Tok transmitter did not have those messages because the GPS/WAAS antenna was occasionally blocked. As seen from Figure 2, the GPS/WAAS antenna is placed close to the ground and so the geostationary signal can be easily obscure by walking personnel. This issue was rectified for the August 23-24 test with the use of traffic cones. Tests were also conducted for various transmission power levels. Excluding instances where the transmitter was below the nominal power, the static LDC receiver received every WAAS message transmitted by Tok.

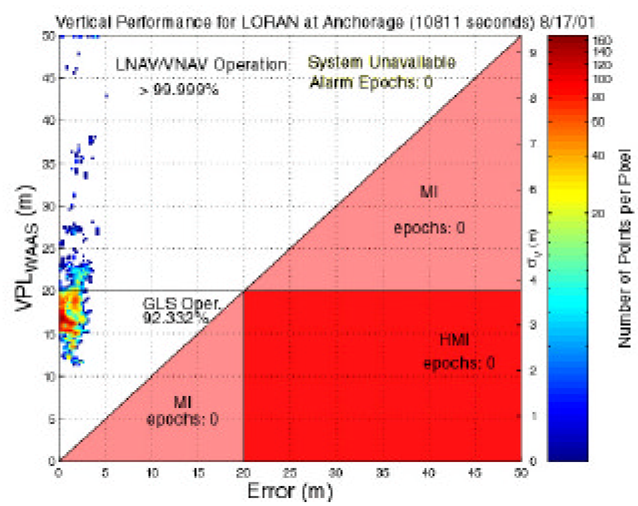

Figure 6 VPL using LDC WAAS (Anchorage, 8/17/01)

As mentioned previously, a big difference between LDC WAAS and GEO WAAS is latency. The WAAS message must be received by Loran station Tok, and then transmitted again by the station. This process incurs a delay on the message versus one received directly from the geostationary satellite and is seen in Figure 6. The sawtooth pattern seen is the result of the extra message every 29-30 messages. The additional message latency causes a degradation of the VPL calculated by the user and the VPL is larger than that of the one calculated using the GEO WAAS messages.

There are a few points that are significantly larger (nearly 50 meters). From an accuracy standpoint, the system does not differ significantly from that of the GEO WAAS signal.

Similar results were obtained on August 23 and 24. Power issues at the Tok station on August 23 resulted in many intervals where the Tok transmitter was not broadcasting.

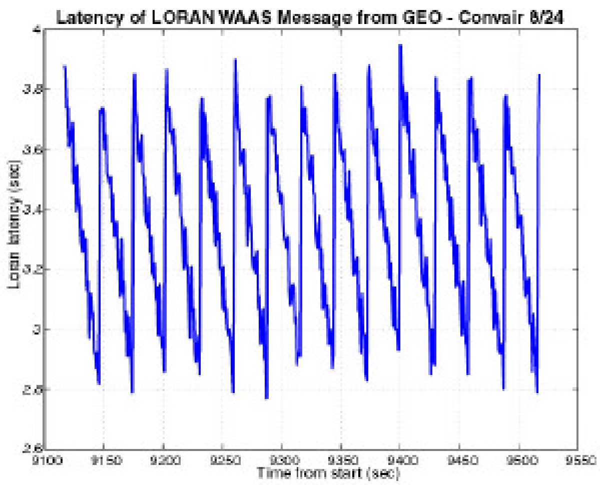

Figure 7 LDC WAAS Latency

FLIGHT TEST RESULTS

In this section, data from the two flights of August 24 will be presented. These flights are presented since the transmitter power issues of August 23 makes it difficult to discern the actual performance of the channel. Furthermore, the flights of the 24th have the Convair employing an H-field antenna and the King Air employing an E-field antenna. While the flight tracks were different, the set up allows for some qualitative comparison between the performance of the two antennas.

Since there are no truth references for the WAAS solution, the performance analysis conducted uses comparisons of the results of each system for assessment. In post processing, the latency of the LDC WAAS can be removed and a combined WAAS solution using the WAAS message from either channel can be formed. As seen later, the message loss on the two data channels are independent and the combined WAAS has much fewer message dropouts. In both flight tests, the combined solution had no dropouts excluding the initial acquisition period. This can be used as the reference performance standard and a comparison is made using VPL from the GEO, LDC and Combined WAAS signals.

High-grade inertial navigation systems (INS) were not carried aboard either aircraft and so the bank angle was not measured. Since bank angle is not known, it is estimated. Dr. Peterson analyzed the bank angle and the angle of the antenna relative to the geostationary satellite by assuming perfect banking [3]. This method is seen in Figure 8 and will also be used here. The turn rate is estimated using the change of the velocity vector.

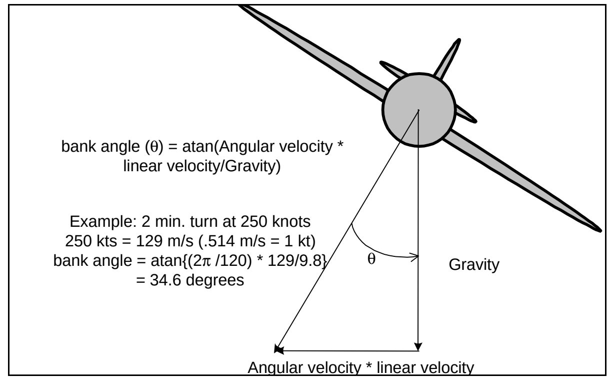

Figure 8 Estimating Bank Angle [3]

Convair 550 (08/24/2001)

The August 24th flight path of the Convair 550 traversed a course from Anchorage to Juneau and back. Much of the flight occurred at an altitude of roughly 20,000 feet. Figure 9 shows a color code flight history of the Convair along with a time history of the WAAS message losses for both GEO and LDC WAAS. The LDC channel experienced 845 lost messages while the GEO channel experienced 462 lost messages. The message availabilities of GEO and LDC WAAS were 96.95% and 94.41%, respectively. The majority of LDC lost messages occurred at the extent of the predicted Tok LDC coverage area.

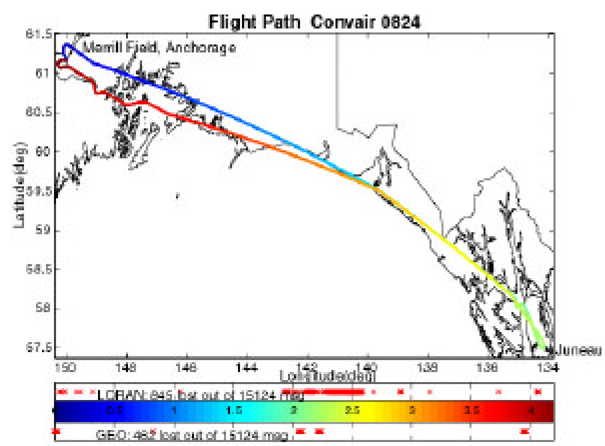

Figure 9 Flight History of the Convair with Message Loss History (August 24, 2001)

These LDC losses are related to the losses on the GEO channel. The message losses on the GEO broadcast were correlated with bank turns that obscured the line of sight of the geostationary satellite as seen in Figure 10. Extended periods where the line of sight of the satellite is blocked leads to loss of lock, which forces the Novatel to reacquire the signal. If the receiver does not lose lock, the OEM 4 has a tendency of losing a minimum of three messages. Again, this is because the OEM 4 was not specifically designed for flight.

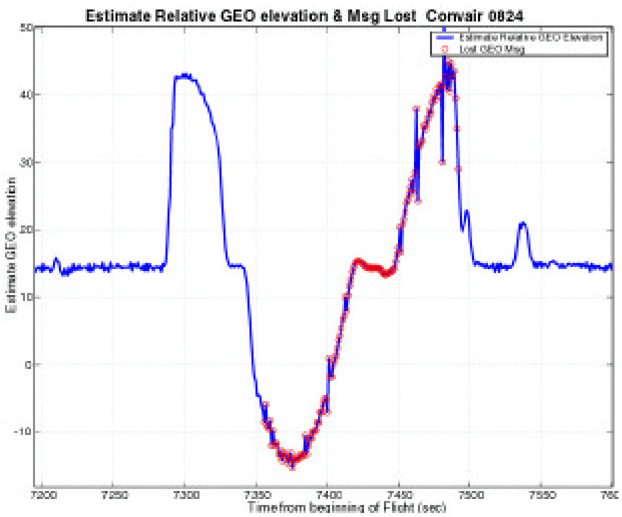

Figure 10 Estimated Bank Angle & GEO WAAS Drop Out

The combine WAAS solution was determined by post processing the collected data and removing the LDC latency. For each epoch, combined solution used either the LDC or GEO WAAS message. These messages are the same since the latency was removed. Message loss is only declared if both channels do not have a WAAS message. There were no instances of this during this flight except on initial acquisition.

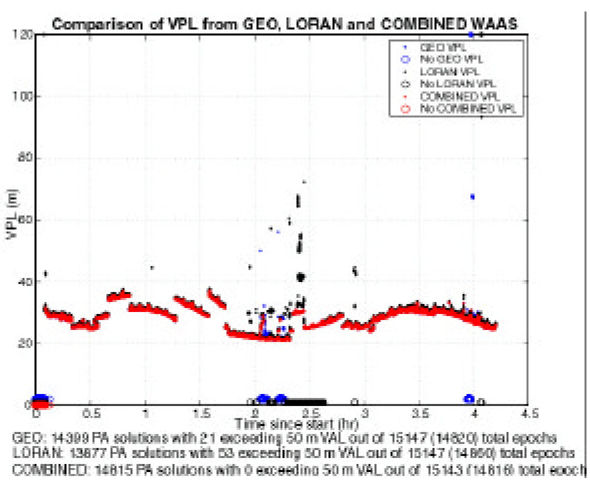

Figure 11 VPL of the GEO, LDC and COMBINED WAAS Solutions for Convair (August 24, 2001)

A comparison of the VPL of the GEO, LDC and Combined WAAS solution is shown in Figure 13. As seen from the plot, the combined solution has 14815 out of 14816 epochs having a precision approach (PA) solution with none of these PA solutions having a VPL exceeding the LNAV/VNAV VAL of 50 meter. Provided that there were no cases of HMI, i.e. where true vertical error exceeded the VPL, this means that the combined solution had greater than 99.99% availability for LNAV/VNAV. Since we utilized no position reference that is better than WAAS, a measure of the true error cannot be known. However, years of WAAS research show that it is very rare with a probability less than one in ten million. Hence, we can say with reasonable confidence that there were no HMIs. As a result of message losses, the GEO solution has PA solutions in 14399 out of 14820 epochs and the LDC solution has PA solutions in 13877 out of 14860 epochs. In these PA solution epochs, the GEO solution has 21 instances where the VPL exceeds 50 meters while the LDC solution has such 53 instances. Hence the total number of GEO and LDC epochs with VPLs less than 50 meters is 14378 and 13824, respectively. This results in a LNAV/VNAV availability of 97.02% and 93.03%, respectively.

Beechcraft King Air (08/24/2001)

The King Air flight path is shown in Figure 14. The King Air utilized an E-field antenna, which experienced a significantly higher rate of message loss when compared to the H field antenna on the Convair. Some of the loss occurred near Homer where interference from Loran station Narrow Cape is significant. The other source of message loss is probably precipitation static (P-static) caused by the aircraft traversing through the cloud layers. P-static is charge build up and discharge that occurs on aircraft, especially in adverse weather conditions.

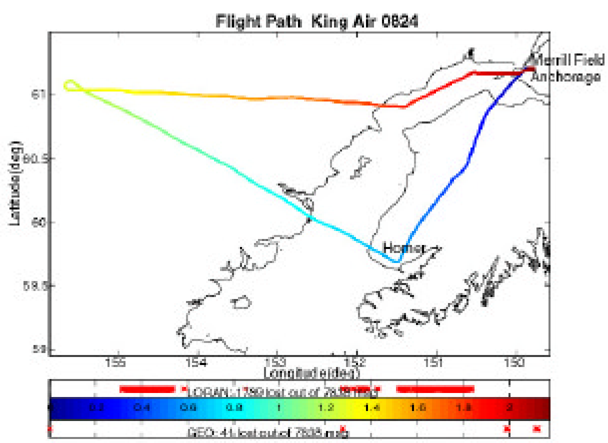

Figure 12 Flight History of the King Air with Message Loss History (August 24, 2001)

The idea is given some support by Figure 15, which shows a plot of the LDC message loss as a function of altitude and time. The first large set of losses occurs near Homer as the aircraft is ascending in altitude through several cloud layers. The second occurs on the eastward flight back to Anchorage, with most of the message drop outs occurring as the aircraft descends in altitude and through clouds. The message availability of LDC WAAS was 77.17%

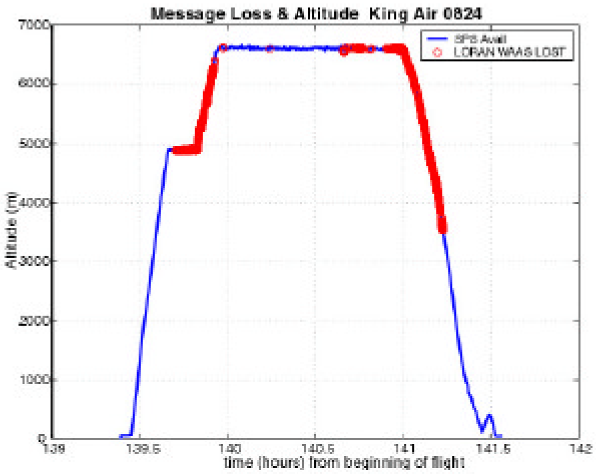

Figure 13 King Air Altitude & Message Loss

The losses on GEO WAAS are again due to blockage of the line of sight and are seen in Figure 14. With fewer steep banks and a higher elevation angle of the geostationary satellite, the GEO WAAS message losses are less than that of the Convair. The message availability of GEO WAAS was 99.48%.

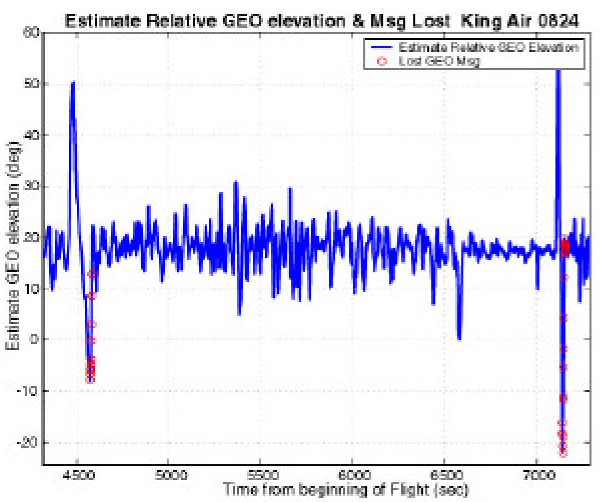

Figure 14 Estimated Bank Angle & GEO WAAS Drop Out

The VPL of the GEO, LDC and Combined WAAS solutions are calculated and compared. The comparison is shown in Figure 15. With no message losses for the combined solution, the LNAV/VNAV availability is greater than 99.9999% with no VPL exceeding 50 meters and every epoch having a PA solution. With lower GEO WAAS message losses than the Convair, the LNAV/VNAV availability is greater at 99.58%. The greater LDC WAAS loss rate results in an LNAV/VNAV availability of 66.02%.

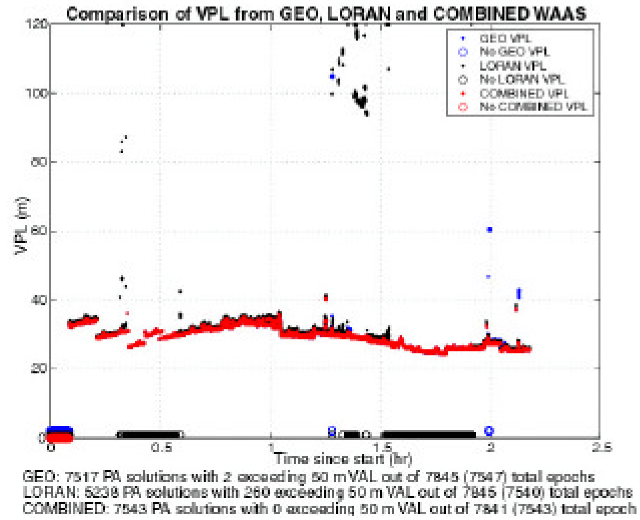

Figure 15 VPL of the GEO, LDC and COMBINED WAAS Solutions for King Air (August 24, 2001)

CONCLUSIONS

The Alaska tests demonstrated several characteristics of GEO WAAS. The low elevation of the geostationary satellite was generally not a problem with the exception of severe banks. GEO WAAS was received with few message losses even in the northernmost reaches of our flight path (Prudhoe Bay). GEO WAAS message losses only occurred in several banks where the aircraft turns away from the geostationary satellite. Such banks are not expected to occur on final approach, which is the phase of flight that requires the most accuracy. One recommendation is the use of receivers that can quickly reacquire the GEO signal. It is expected the certified aviation grade receivers will have this capability. The OEM 4 is not a certified aviation grade receiver and such receivers may perform even better. It is a slightly different story on the ground. We had difficulty tracking and receiving GEO WAAS on a test drive near Tok, AK with the receiver equipment mounted on a car. WAAS solutions were available less than 20% of the time. Foliage and other natural features that obscured the line of sight is suspected to have attenuated signal from the low elevation geostationary satellite resulting in these difficulties.

The trials also indicated the potential of Loran. While the LDC never provided LNAV/VNAV with 99.9% availability, the channel certainly showed that it could provide some back up capability to WAAS. It demonstrated some significant LNAV/VNAV availability. Improvements will make the future LDC better and more reliable. The combined solution demonstrated the utility of a Loran as a redundant data link. The independence of GEO and LDC WAAS loss makes the two systems highly complementary. Probabilistically we can quantify the probability of having a WAAS message in a combined system ($P_{msgavail}$) using the following equations.

$$P_{msgavail} = P_{GEOmsg} + \left(1 - P_{GEOmsg}\right) P_{LDCmsg}$$

$$P_{msgavail} = P_{GEOmsg} + P_{LDCmsg} - P_{GEOmsg} P_{LDCmsg}$$

or in terms of message loss rate

$$P_{msgloss} = P_{GEOloss} P_{LDCloss}$$

With GEO WAAS having an average message loss rate of 2.19% and LDC WAAS having an average rate of 11.47%, the combined solution is expected to have a message loss rate of 0.25%. The LDC average should show definite improvement if the King Air flight were able to use an H-field antenna. However, the expected message rate of the combined system is still quite reasonable. Previous research has indicated that message loss rates of one percent may be tolerable [7] while WAAS Minimum Operational Performance Standards [8] specify that a 0.1% message loss rate must be tolerated.

The test also demonstrates the advantages of H-field antennas over E-field antennas for LDC. Significant improvements can be made using the H-field antenna. However the tests also show that these antennas require more care in terms of installation. The lessons learned from this trial will be used to make such improvements.

The August trials demonstrated that the GEO WAAS is highly capable for flight in Alaska. It performed well even at high latitudes. Banking does have some impact on the availability of the GEO WAAS message though that is not expected to have an effect on approach. LDC WAAS shows some promise in providing a backup data link for WAAS and a combined system could greatly improve message and hence LNAV/VNAV availability. The LDC WAAS could also prove to be especially useful for terrestrial users.

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For further information, please contact:

Sherman Lo
Wide Area Differential GPS Laboratory
496 Lomita Drive, Room 250
Stanford, CA 94305-4035
650-723-6754, FAX 650-725-5517
sherman.lo@stanford.edu

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