# Wagging the Tail & Flying with Loran-C Data Communications

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**BIOGRAPHIES**

Dr. Ben Peterson is President of Peterson Integrated Geopositioning, LLC. He is a 1969 USCG Academy graduate, a retried Coast Guard Captain, and earned a Ph.D. in Electrical Engineering from Yale University in 1984. He was the 1997-98 president of the U.S. Institute of Navigation. Mr. Ken Dykstra is a software engineer with Peterson Integrated Geopositioning, LLC. He is a 1974 Coast Guard Academy graduate and earned Masters Degrees in Electrical and Computer Engineering from RPI in 1978. Dr. Peter Swaszek is a Professor of Electrical and Computer Engineering at the University of Rhode Island. He received his Ph.D. in Electrical Engineering from Princeton University. His research interests focus on digital communication systems. James (Jay) M. Boyer is a Lieutenant Commander in the United States Coast Guard and presently assigned as the Chief, Engineering Division at the Coast Guard LORAN Support Unit in Wildwood, New Jersey. LCDR Boyer received his MSEE degree from the University of Rhode Island. Kevin M. Carroll is a Lieutenant in the United States Coast Guard and presently assigned as a Project Manager at the Coast Guard LORAN Support Unit. LT Carroll received his MSEE degree from the University of Rhode Island. Mitchell Narins is the System Engineering Lead within the Navigation and Landing Product Team, AND-702, and is responsible for configuration management, risk management, human factors, security, navigation system architecture, and type acceptance policy. Additionally, he is leading the FAA/USCG/Academic/ Industry Team evaluating whether the Loran-C system can provide benefits to aviation. Mr. Narins holds a Bachelor of Engineering (EE) degree from the City College of New York and a Master of Engineering Administration/Management degree from the George Washington University
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**ABSTRACT**

This paper reports the results of flight tests in an ongoing project to develop methods for transmitting GPS Wide Area Augmentation System (WAAS) data over LORAN. The Federal Aviation Administration is funding the project to determine what potential benefits LORAN-C might provide to the National Airspace System (NAS). The full 250-bit WAAS message is transmitted in one second. This information bandwidth is achieved via 16-ary Intrapulse Frequency Modulation (IFM) and Reed-Solomon forward error correction.

The tests were conducted using the Tok, Alaska LORAN transmitter at a Group Repetition Interval (GRI) of 48,300 usec. The FAA Technical Center's Convair 580 and a King Air C-90SE aircraft of Ohio University flying at speeds of up to 300 knots were used in the testing. In the two days of testing, the aircraft cover much of Alaska from Prudoe Bay on the North Slope to Juneau and southwest past Homer.

The results indicate the WAAS message was received out to approximately 420 NM including the North Slope. Antenna steering and erasure decoding improved performance to varying degrees.

Lastly, the FY02 goals are outlined based on the positive results of this test.

**INTRODUCTION**

The U. S. Coast Guard LORAN Support Unit (LSU) and the FAA, in cooperation with Stanford University, are developing an enhanced LORAN-C Communications capability for Global Positioning System (GPS) integrity, and potentially for GPS correction data. The LORAN

Recapitalization Project LRP is a multi-year FAA/USCG initiative to “modernize the U.S. LORAN-C system to meet present and future radionavigation requirements while leveraging technology and funds to optimize operations, support and training, and reduce total cost of ownership” [1]. This paper continues the discussion of the joint effort and status of the evaluation that may lead to the development of an alternate data link using the LORAN-C signal.

This is a report of the critical Alaska flight test of LDC conducted 16 – 24 August 2001. It is essentially the same paper as was previously presented at ION-GPS in Salt Lake City in September 2001 [15], except that since that presentation, we farther along in the analysis of the flight test data and that is reflected in this paper. Previous papers [2-5] discuss the various modulations schemes, message formats, and forward error correction codes considered before the test. In November of 2000, at the International LORAN Association Conference [3], we presented a fairly lengthy discussion of the pros and cons of the various approaches, and the potential impact of each approach on legacy receivers. In June 2001 [5], we presented an update that included a detailed section on the communication system performance of the different forward error correction codes. The papers also detail the reasons for narrowing down the August 2001 test to Intrapulse Frequency Modulation (IFM), full 250 bit WAAS message and Reed-Solomon forward error correction code. These papers are available via the Internet at: www.uscg.mil/hq/lsu/webpage/lsu.htm.

**BACKGROUND**

The LORAN-C navigation system, developed by the U.S. Department of Defense (DoD), has been operated by the U.S. Coast Guard since the 1950’s. Initial installations were primarily outside the continental U.S., but by the early 1970’s, the Coast Guard had determined the LORAN-C system should be used as a federally provided maritime navigation system throughout the coastal areas of the United States. The system was expanded to provide coverage in the coastal waters of the continental U.S. and Alaska.

Interest by the Federal Aviation Administration (FAA) led to additional installations that provided coverage throughout the continental U.S. Through the mid- to late-1980's the FAA also undertook the development of requirements, procedures, and ground system support to allow certification of LORAN-C system for use in the non-precision approach phase of navigation. Initial attempts by user equipment vendors to achieve aviation certification disclosed the need for significant hardware and software improvements that primarily involved the need for improved aircraft antenna systems and advanced receiver processing to take advantage of all available LORAN-C signals. These and other related problems produced shortcomings in the "availability" and "continuity of service" parameters of the certification requirements.

Despite the lack of certification, there was widespread use of "VFR LORAN-C" in the general aviation community through the mid-1990's. However, as the Global Positioning System (GPS) began to mature, users found a comparable niche for this new system and a migration from LORAN-C began. The migration was accelerated when the U.S. Government announced in its 1994 Federal Radionavigation Plan (FRP) plans to terminate LORAN-C in the year 2000.

Following the 1994 FRP announcement, support to continue LORAN grew from some groups within the aviation community that resulted in directions from the U.S. Congress, via the budgetary process. This resulted in the 1999 FRP announcement that LORAN services would continue “in the short term” while the merits of its long-term operation are evaluated. Over the past several years, the Congress has continued to provide substantial LORAN-C funding to the Federal Aviation Administration (FAA) ($25M in FY 01) and has requested it to continue the development of LORAN.

In compliance with these Congressional mandates, the FAA initiated a LORAN-C evaluation program to determine whether LORAN could benefit aviation, and if so, by what means. While LORAN-C currently can be used as a secondary navigation system in both terminal and enroute environments, it does not support the approach phase of flight. The FAA established an Interagency Agreement with the U.S. Coast Guard (USCG), the operators of the LORAN system, and formed an evaluation team to help determine whether LORAN would be capable of providing lateral navigation (LNAV – RNP.3) services to the National Airspace System (NAS) and/or other ancillary capabilities. Thus, efforts to determine whether LORAN can meet the accuracy, availability, integrity, and continuity requirements to support LNAV approaches are well underway and significant progress has been made to date.

However, the FAA/USCG Evaluation Team, including numerous academic and industry members, recognized early in the program that LORAN had the potential for being more than just a means of lateral navigation services. In 1999, the Northern European LORAN System (NELS) started using their LORAN stations to broadcast differential global positioning system (DGPS) corrections at rates of 25 to 35 bits/second under a system developed at Delft University and dubbed “Eurofix.” Although the USCG tested this capability and was able to duplicate the results here in the U.S [11], it was recognized that this rate of differential corrections would not be sufficient to support aviation uses.

The FAA's Wide Area Augmentation System (WAAS), [9] is the means by which differential GPS corrections will be provided to aircraft operating in the NAS to support both lateral (LNAV) and vertical (VNAV) navigation. The current WAAS architecture envisions a number of geostationary satellites to transmit differential correction messages to aircraft at L-band frequencies at a rate of 250 bits/second. WAAS messages are currently transmitted on the GPS L1 frequency for non-safety related services via two leased geostationary (geo) satellites.

While system operational capability will improve significantly with the addition of more geos and additional L-band frequencies, there may be some northern areas of the NAS where the combination of look-angle and topography could limit or preclude aircraft from being able to receive the geo's WAAS signal ($W_G$). A loss of the WAAS signal can also occur as a result of aircraft attitude causing the airframe to obstruct the line of sight view to the geo. Additionally, the *very* recently published GPS Vulnerability study, conducted by the U.S. Department of Transportation's Volpe Center [6], has highlighted a number of concerns regarding the use of GPS and WAAS and has made specific recommendations that include continuing evaluation of LORAN-C as both a navigation system and source of differential corrections

LORAN's significant coverage of the NAS, its robust signal (400 – 1600 kW), and its diverse spectrum (between 90 kHz and 110 kHz) made it attractive for further exploration. The problem was simple – how could LORAN transmit the entire WAAS message at the 250 bit/second rate without significant modification of the signal specification and, thereby, denial of service to existing legacy users?

**HISTORY OF IFM**

Intrapulse Frequency Modulation is the concept involving the gradual change in the frequency of the LORAN-C signal within the pulse itself. The extent and rate of change of frequency is constrained by the requirement that 99% of the power is contained within the allocated frequency band of 90-110 kHz. This avoids interference with other users of the frequency spectrum and ensures adequate (relatively long) range [7-8]. IFM induces a different phase pattern to the pulse. The choice of starting time and the duration for the frequency shift, and the phase difference for each level are chosen to balance among spectrum considerations, impact on legacy navigation and timing users, and communications system performance. IFM is especially interesting because it does not require balancing schemes; all the realizable combinations of frequency change can be used for data [3-5].

**ALAKSA FLIGHT TESTS**

The idea of LORAN transmitting WAAS data initiated in the effort to provide a land based data channel to supplement space based augmentation systems like WAAS. The primary areas for a land based system are the urban and mountainous areas and in northern latitudes where geo-stationary satellites provide limited coverage due to low horizon location (Figure 1). The Alaska flight tests were a natural progression after the April and June 2001 successful tests in transmitting the full 250-bit WAAS data over LORAN using IFM [5]. The Graphical User Interface of the receiver with the nominal parameters for the Alaska trials is shown in Figure 2. A Group Repetition Interval (GRI) of 48,300 usec was chosen to uniformly distribute data hits on the LDC signal from the GRI 9990 and 5990 signals from other stations in the area which also uniformly distributes the cross rate hits on navigation receivers due to the LDC signal, and thus to minimizes the effects of cross rate interference for both LDC and navigation receivers. A WAAS message was encoded at the transmitter into ten Phase Code Intervals (PCI's) or 966 milliseconds. Every 29$^{th}$ or 30$^{th}$ message was repeated. Ten PCI's are 60 bytes of data, 32 bytes for the 250-bit WAAS message plus the Z count modulo 64, and 28 bytes of Reed Solomon forward error correction. Operationally, it is envisioned both rates on a dual rated transmitter would be modulated, and 20 or more GRI's per second would typically be available.

The receiver simultaneously implemented both a receiver steering the antenna pattern to maximize signal relative to noise and interference [14] and a receiver adding the two RF channels in quadrature for an omni-directional response. The displayed statistics are for the steered receiver but the data from both receivers is logged for future analysis. The data files consist of three types;

1. The raw RF data, which is In Phase and Quadrature (I&Q) data at 40 kHz. This data accumulates at 1.0 Gbytes/hour.
2. An ASCII table of the data shown in the lower half of the GUI with one line every ten seconds.
3. The demodulated bytes of both the steered and omni-directional receivers. If the receiver successfully decodes the messages as in the example in Figure 2, it knows what bytes were transmitted and can determine the byte error rates itself. In addition, the transmitted bytes are stored at the transmitter to enable post-processing analysis of byte error rates including messages not successfully decoded.

If the parity check based on the 24 CRC bits within the 250 bit WAAS message fails, the receiver sorts the 60 bytes in order of its confidence in them and begins erasures decoding and rechecks the 24 bit CRC after erasing the bytes most likely to be in error. The message rejection rates both before and after this erasures decoding are logged. Finally the received WAAS message is sent out the serial port to a Stanford University computer which verified it was identical to the message from a WAAS receiver tracking the geo, implemented a WAAS based position solution, and logged data.

For additional details on receiver architecture see [5].

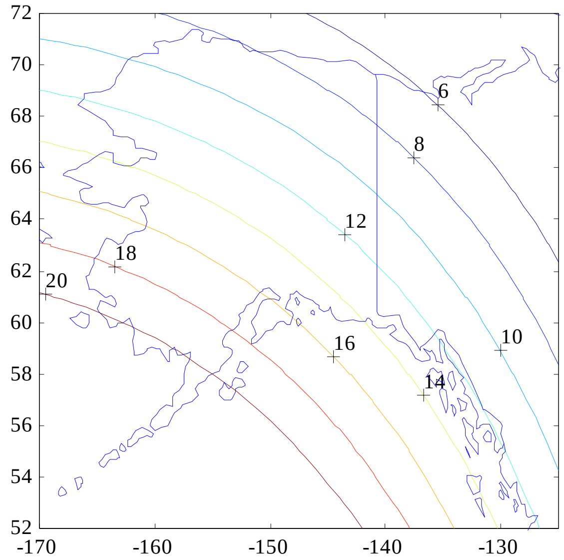


Figure 1. Elevation of INMARSAT Pacific Ocean Region (POR) geostationary satellite in Alaska

The decision to conduct a "live" LDC test at an operational LORAN Station required a great deal of coordination between many players. A "live" test meant removing an entire chain from operational status for the duration of the tests. LORAN Station Tok located in Tok, Alaska was chosen as the transmitting stations for two significant reasons. First, Station Tok is a single chain station therefore only one LORAN chain would be inoperable during the test. Secondly, Station Tok had the best potential for LDC coverage in Fairbanks, Anchorage and Juneau areas (Figure 3). The non-shaded area is where Station Tok's signal strength is greater than any other LORAN station based on Millington's Method [10].

Some actual signal strength readings [12], suggest that the western boundary should be moved east slightly. (Note: While calculations of the relative signal strengths will be possible by analysis of the raw RF data logged on the flights, at the deadline for this paper, this analysis of the raw RF data had not been started.) The more mountainous region of eastern Alaska attenuates Station Tok's signal strength compared to the area covered by the Station Port Clarence signal over the flatter tundra of western Alaska (figure 4).

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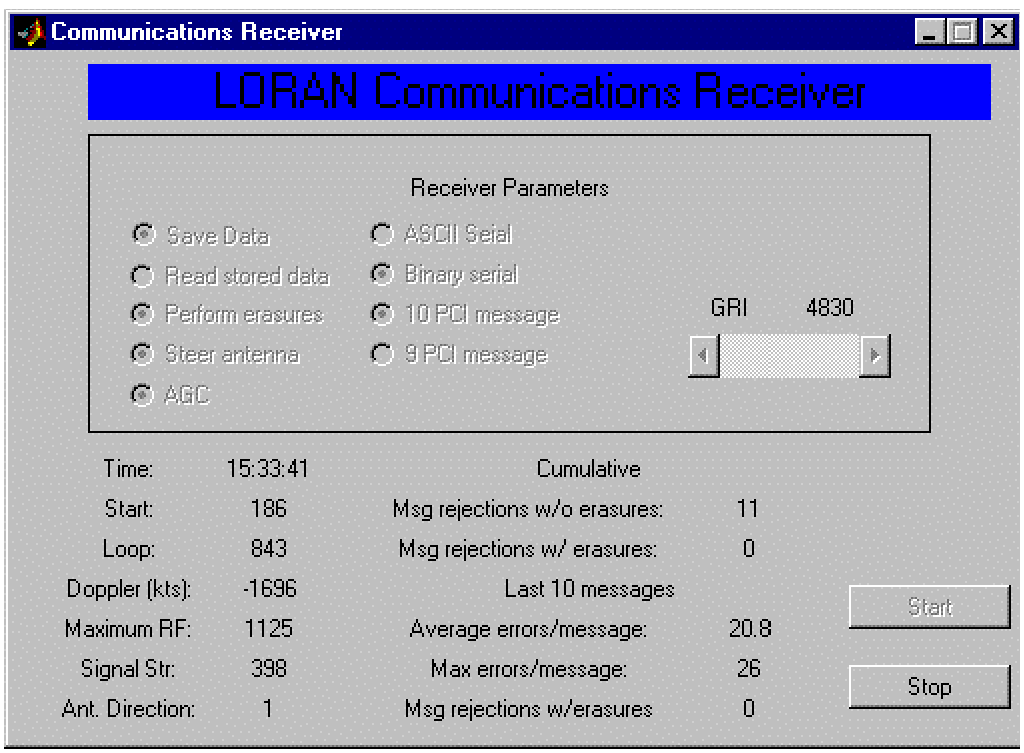


Figure 2. Graphical User Interface (GUI) of LDC receiver.

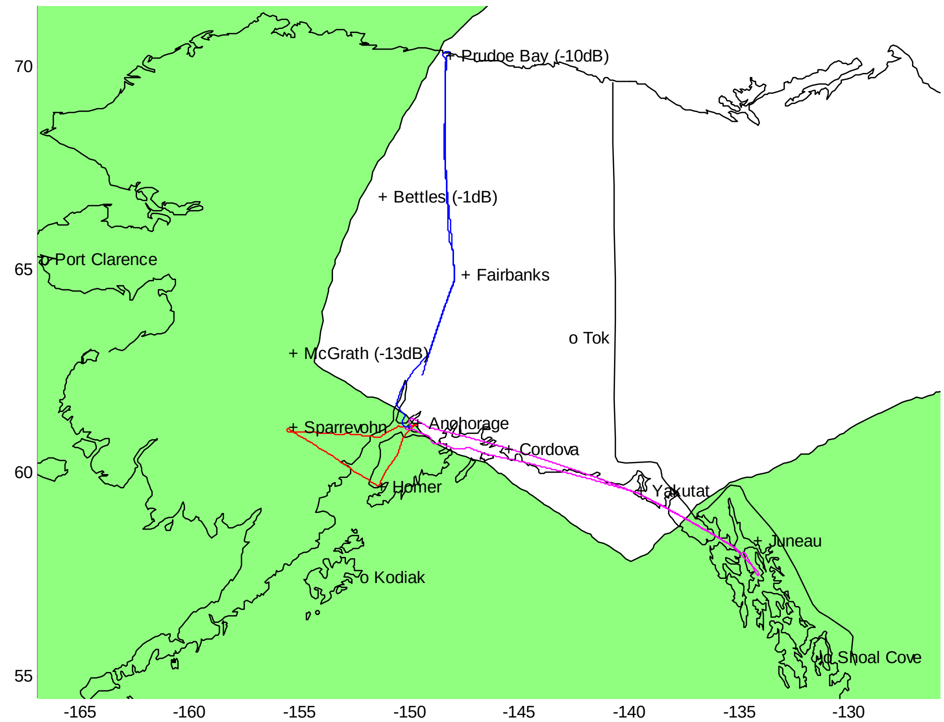


Figure 3. Fight Paths for LORAN Data Channel tests and required coverage of Tok signal. Green Shaded Area = Other signals stronger as predicted by smooth earth model. Numbers in ( ) are Tok signal strength relative to Port Clarence measured in 1988 FAA survey [12]. Paths of data collection flights are indicated by blue - Convair 580 on August 23rd, magenta - Convair 580 on August 24th, and red – Ohio University KingAir on August 24th.

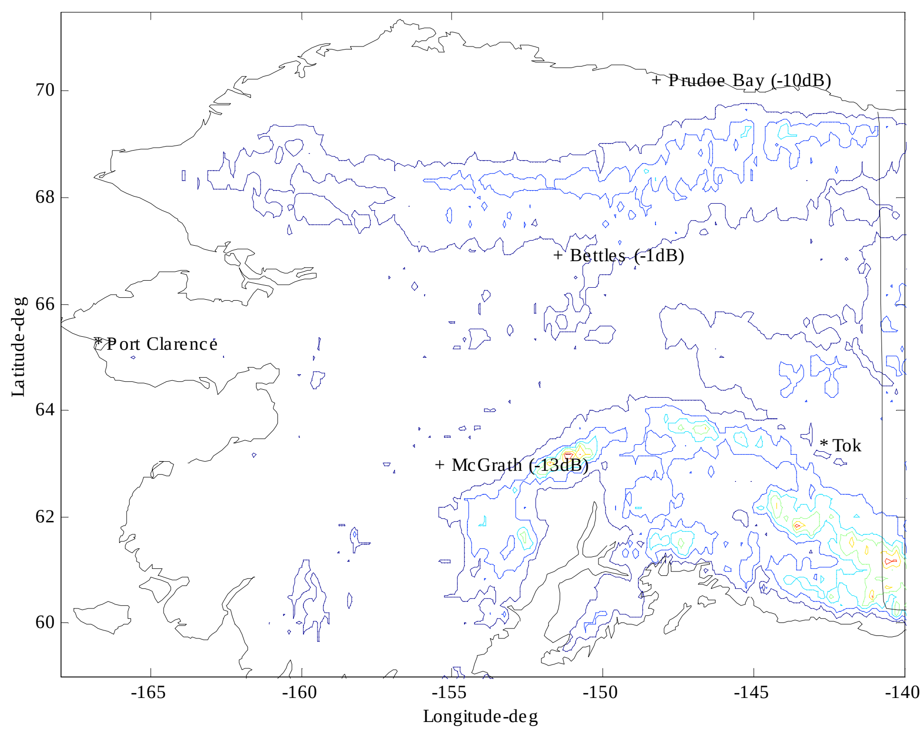


Figure 4. Elevation contours in increments of 2000 ft and signal strengths of Tok relative to Port Clarence.

The aircraft flown in the tests were the FAA's Convair 580 and Ohio University's King Air C-90SE. Each aircraft carried a LDC receiver and geo-satellite based WAAS receiver for comparison data. The aircraft routes (charted on Figure 3) were specifically assigned to fly within and outside the limits of the estimated LDC coverage area. We wanted the aircraft to fly beyond the demodulation range of the signal to see where and how the system failed for comparison purposes. In addition, a static receiver was set up at the University of Alaska flight simulator room in Anchorage, AK.

**AIRCRAFT ROLL ANGE AND GEO LOSSES**

As seen in figure 1. the geostationary WAAS satellite is over the horizon for all of Alaska, but at low elevation angles. There are two possible mechanisms for loss of the geo signal due to low elevation angles. One would be that a mountain is in the propagation path for an aircraft flying close to the terrain. Since our flight tests were done altitudes of approximately 20,000 feet and most approaches and landings were at Anchorage, this was not a factor in our tests. This issue will be further studied by the University of Alaska at Anchorage. A second mechanism is when the aircraft rolls away from the geo in a turn such that the geo signal drops below the response of the antenna. Figure 5 illustrates how this roll angle can be estimated from accurate position versus time data. After calculating roll angle then the azimuth of the geo relative to the planes heading is used to determine the change in geo elevation relative to level flight. What is seen from this and many other example from the data, is that when the plane rolls such that the geo is below the horizontal axis of the plane, the geo signal is lost for some 10's of seconds. With the LORAN data channel, the WAAS message becomes available independent of roll angle and becomes a viable backup to the WAAS geo signal.

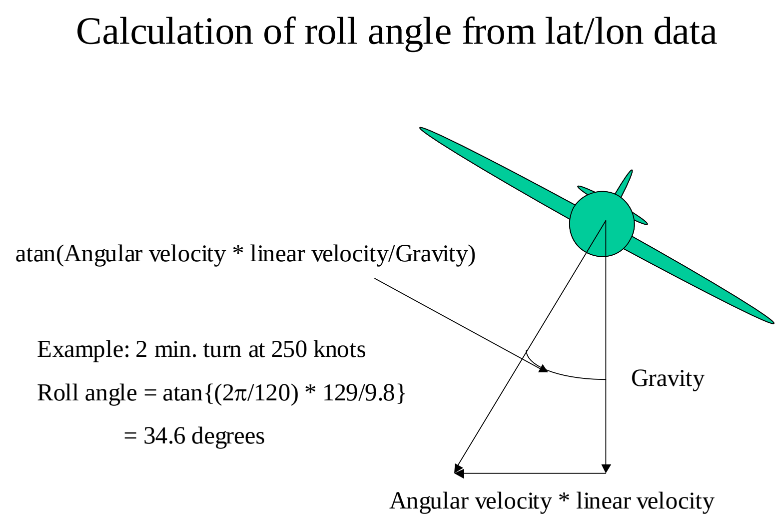


Figure 5. Estimation of roll angle from position data.

Figure 6 and 7 illustrate two examples of loss of geo coverage due to the roll angle of the aircraft. Figure 6 is an example showing WAAS message availability during the turn around at the mid point of the August 24th flight of the Convair. In this example the geo was below the antenna horizon for approximately 40 seconds. After the geo again becomes visible the receiver takes another 80 seconds before successfully demodulating the WAAS message. This was at the extreme limit of LORAN WAAS coverage and occasional LORAN messages were being rejected, but the combination the GEO and LORAN provided virtually continuous WAAS messages.

Figure 7 is an example where just before the Ohio U King Air landed at Merrill field, the WAAS geo was below the antenna horizon for only 2-3 seconds. In this case, the GPS/WAAS receiver recovers immediately and only drops a few messages.

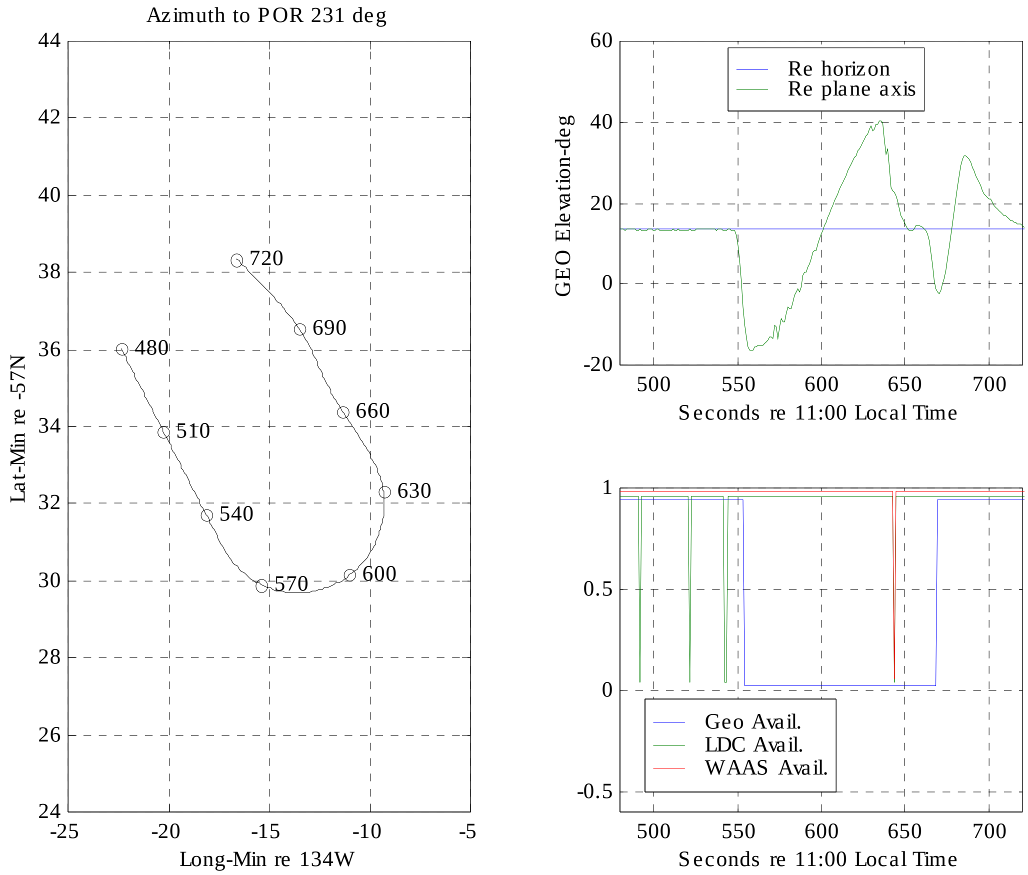


Figure 6. Example geo elevation calculation and WAAS message availability during turn south of Juneau Convair 580 on August 23rd, speed over ground 300kts, distance to Tok 423 nm.

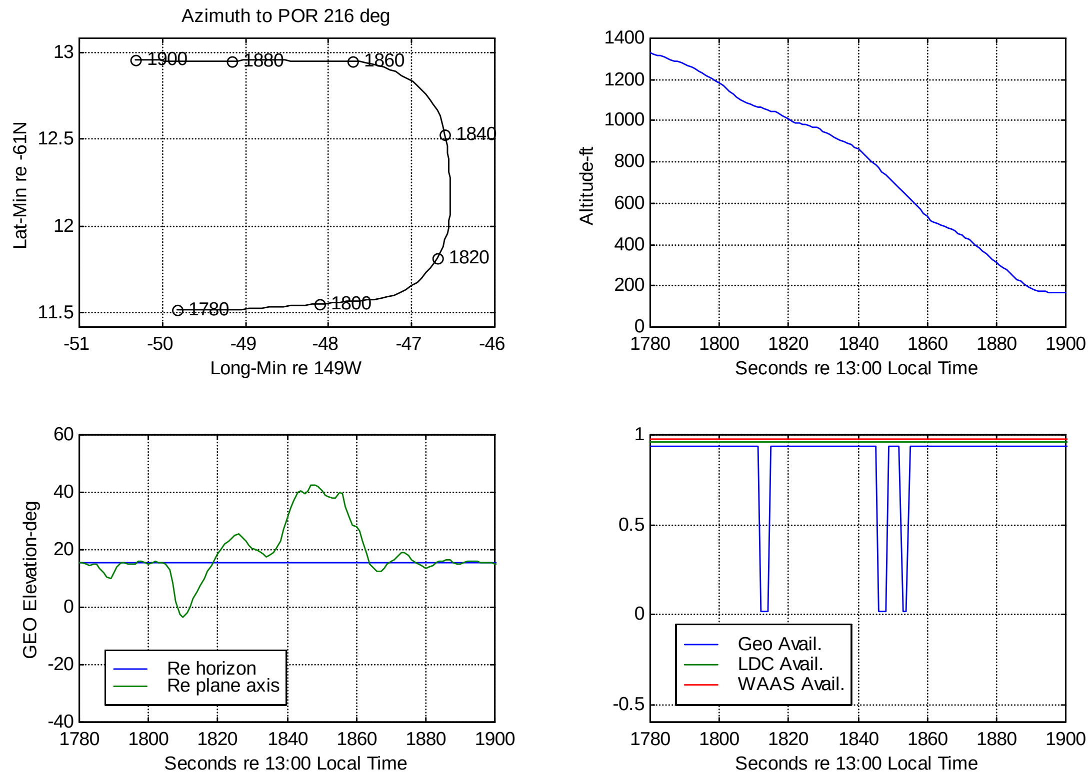


Figure 7. Geo elevation and WAAS message availability during landing at Merrill Field, Ohio U. King Air on August.24th.

## FLIGHT TEST DATA ANALYSIS

Figure 8 shows the path of the FAA Technical Center's Convair 580 on August 23rd. The times are in Alaska Daylight (local) time. The path went from Anchorage via Fairbanks to Deadhorse/Prudoe Bay and returned along the same path. It reached a maximum range to Tok of 443 nm at 11:15.

Figure 9 shows the byte error rates for both a steered (blue) and an omni-directional (green) antenna response. The transmitted power from Tok is shown in the lower half of the figure for the same time period. The normal peak power of Tok is 560 KW. Due to the elongated pulse of the LDC signal, the peak power is about –1.5dB relative to this nominal value. In addition at 10:52 the transmitter tripped off air for about 1 minute and was then operated at reduced power until 11:23. It was again off air from 11:35 to 11:48 and then operated at reduced power levels until 13:22. Figure 10 shows the message rejection rates after erasures decoding for the same period of time. The rejection rates before erasures decoding are slightly worse. What we see from these plots is that the signal can be successfully decoded over most of the path to Prudoe Bay, although most of the messages were lost in the immediate vicinity of Prudoe Bay (11:05 to 11:20). However as was noted earlier, the signal from Port Clarence is 10 dB stronger than that of Tok in this area What the performance would have been if Tok would have been at normal peak power is difficult to estimate. The lost messages at 09:52 and 11:56 are believed to be due to the aircraft coming into Distance Measuring Equipment (DME) range around Fairbanks. What happens when the planes DME equipment begins to respond, the transmissions even though far out of band, do saturate the antenna pre-amp resulting in periodic spikes in the RF. The duty cycle on these spikes is low enough so that they do not present a problem per se. The Automatic Gain Control (AGC) adjusted the gain 27dB downward more rapidly than the averaging time constant of the template averaging software resulting in inaccurate templates until they were allowed to again reach steady state. This problem will be easily corrected in future versions by rescaling the pulse templates every time the gain is adjusted. It should be noted that both before the gain had been significantly adjusted, even though the DME pulses were saturating the A/D converter and after the templates had recovered so that the DME pulses were more than 100 times the amplitude of the Tok signal, the messages were successfully demodulated.

Except for brief periods, most notably at 13:05, steering the antenna pattern resulted in significantly better performance. At 13:05, some interference source became co-linear with the Tok signal and caused the antenna beam to be steered through 180 degrees, which steered the null through the Tok signal.

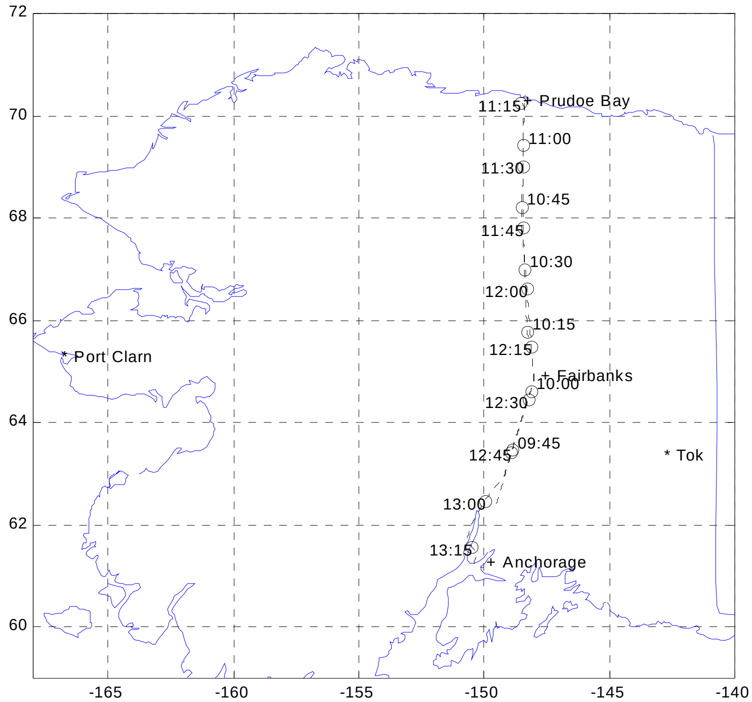


Figure 8. Path of Convair 580 on August 23rd.

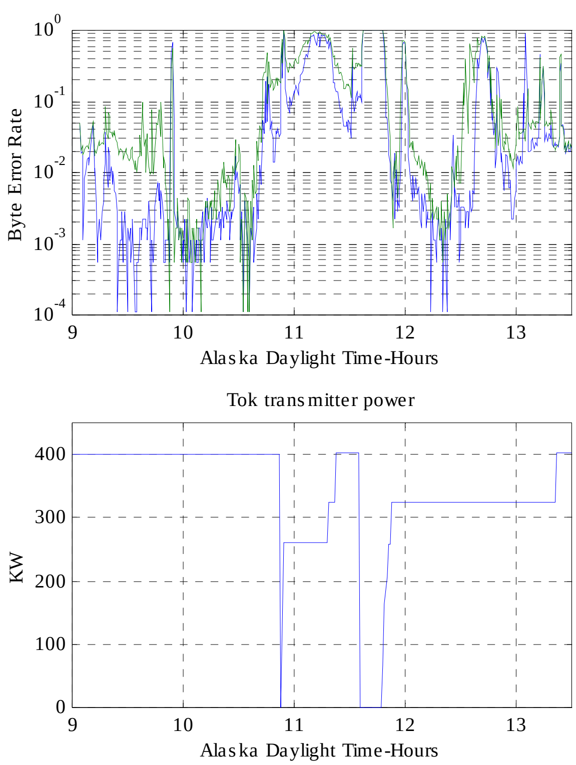


Figure 9. Byte error rates for Convair 580 and Tok transmitter peak power for August 23rd.

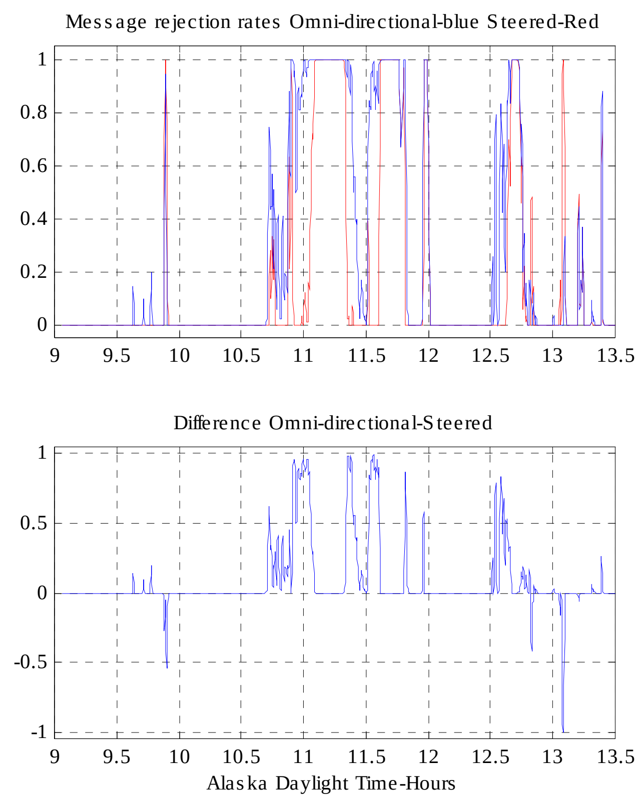


Figure 10. Message rejection rates for Convair 580 for August 23rd.

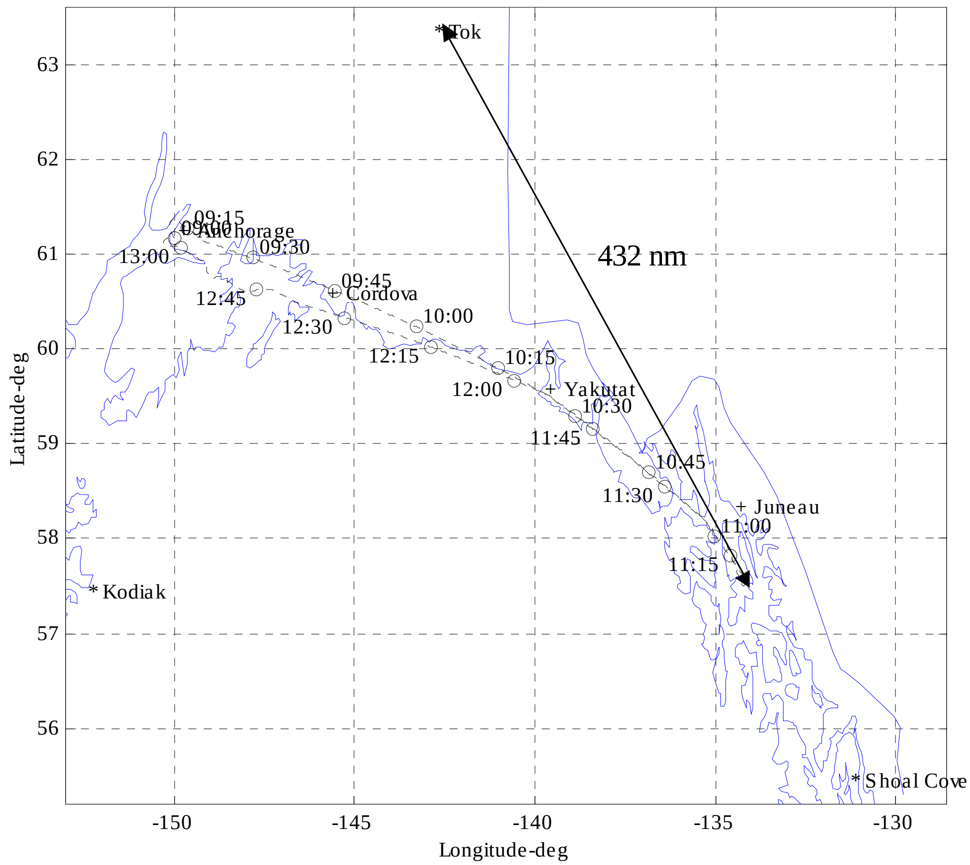


Figure 11. Path of Convair 580 on August 24th.

Figure 11 shows the path of the Convair 580 on August 24th. The aircraft flew from Anchorage to a point approximately 60 nm south of Juneau at a distance of 432 nm from Tok and then returned along the same path. The Tok transmitter was operated at 400 KW peak power for the entire flight time.

Figure 12 shows the message rejection rates for this flight. The steered antenna version of the receiver is again seen to perform significantly better than the omni-directional version, particularly between 11:45 and 12:15 between Yakutat and Cordova on the return leg. In this area, the signals from the LORAN transmitters at both Kodiak and Shoal Cove are stronger than the Tok signal and steering the antenna reduces the data hits due to cross rate interference to the point where forward error correction recovers the message. The receiver is able to get virtually all of the messages except for the period when the aircraft was in the vicinity of or south of Juneau.

Figure 13 shows the flight path for the Ohio University King Air for August 24th. It flew from Anchorage southwest to Homer, then west to Sparrevohn Air Force Station and reached a maximum distance of 384 nm from Tok. The King Air had also flown on 23 August but was unable to get any meaningful data due to severe aircraft generated interference. The exact cause of this interference is still being studied. It should be noted that the same aircraft and antenna had been very successfully used with no interference problems in the May tests reported in [5]. On the 24th a decision was made to shift to share an electric field antenna signal with a LORAN navigation receiver. Figure 14 shows these results of these tests. The receiver successfully decoded virtually all the messages on the leg from Homer to Sparrevohn Air Force Station. Comments from the people on the aircraft operating the receivers indicated that the periods of lost messages coincided with time when the aircraft was flying through clouds and the E field antenna was experiencing precipitation static problems. The legacy LORAN navigation receiver ceased tracking at the same times as the communications receiver failed.

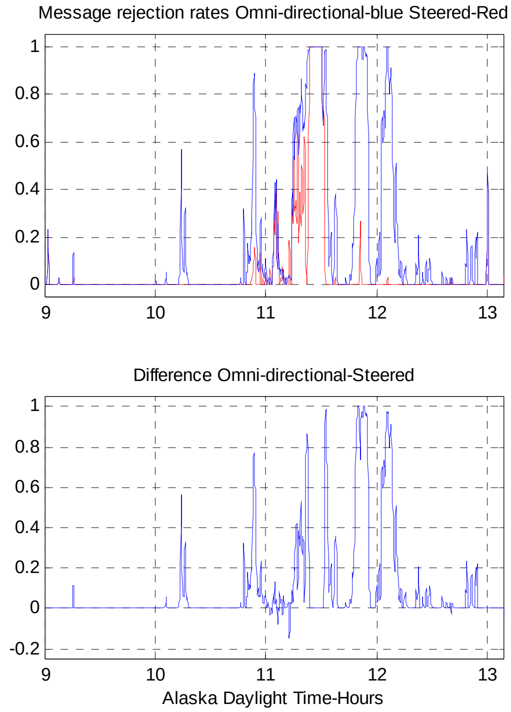


Figure 12. Message rejection rates for Convair 580 flight on August 24th.

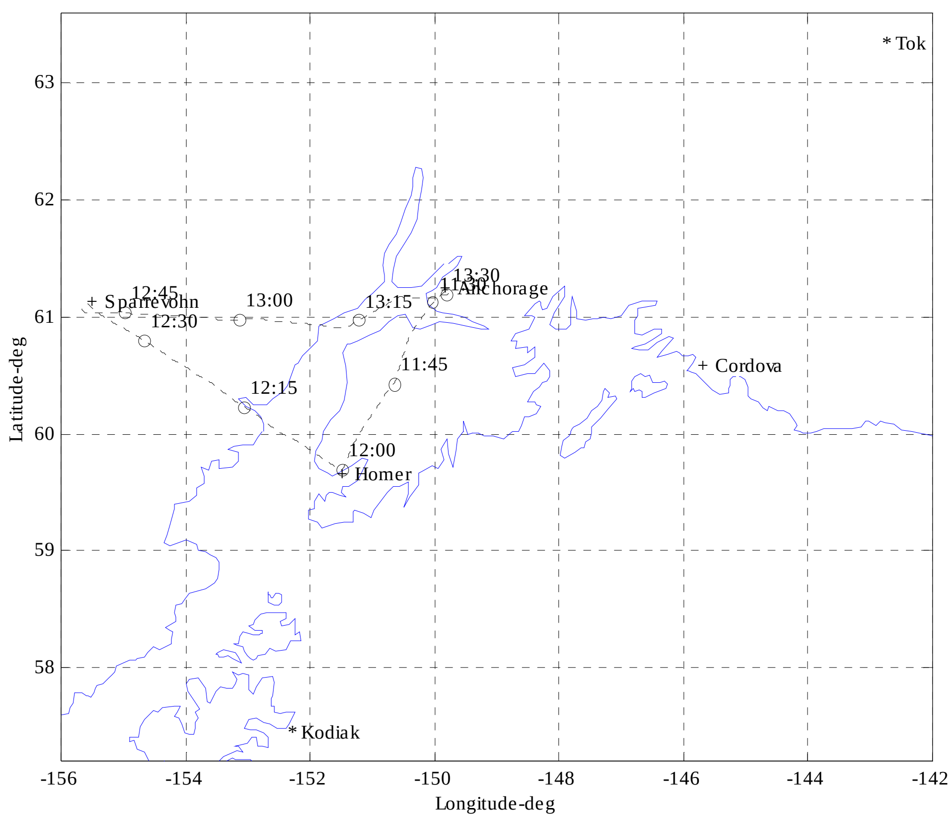


Figure 13. Flight path of Ohio University King Air on August 24th.

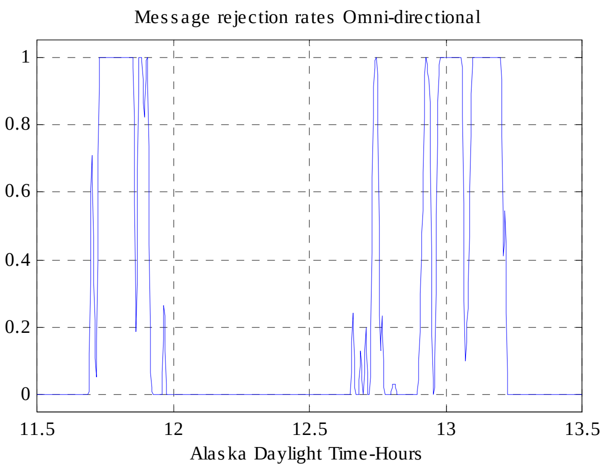


Figure 14. Message rejections rates for Ohio University August 24th flight using an electric field antenna.

**MESSAGE REJECTION RATES IN AREAS WHERE TOK IS STRONGEST LORAN SIGNAL**

Figure 15 shows the signal strength of the Tok LDC signal and the strongest signal on the other LORAN rates in the area, which continued to operate. In the upper half of figure 15 fro 23 August, the signal strength is the strongest secondary on 9990, which is Port Clarence from 10:00 to 12:40 and Kodiak prior to 10:00 and after 12:40. In the lower half of figure 15 for the flight of 24 August, 5990 is Shoal Cove and 9990 is Kodiak. For the concept to be proven valid, we need to be able to successfully demodulate Tok when Tok is the strongest signal. Figure 16 shows this data. Each set of 10 messages was assigned to a bin of size 1 dB according to the signal strength of Tok relative to the strength of the strongest other LORAN signal. The total number of messages and the number of rejected messages were counted for each bin. These counts are shown in the top half of figure 16. The total was 30570 messages for all bins. Since most of the flight paths were chosen to be on the limits of the expected coverage, most of the data was collected when Tok was –17 to 0 dB relative to the strongest cross rate. (Note: All values of less than –17dB were put in that bin and the data when Tok was off-air was disregarded. Includinmg that data would have increased both the total number and the number rejected for –17dB.) The bottom half of figure 16 shows the ratio of the two curves in the upper half or the message rejection rates. We see that the performance was acceptable until Tok reached –4dB relative to the strongest other station.

**CONCLUSIONS**

The current LDC system of IFM with Reed-Solomon codes can provide full WAAS message capabilities within the interior Alaskan region. The August Alaska tests proved successful as aircraft received and demodulated the signal from the North Slope to nearly Juneau.

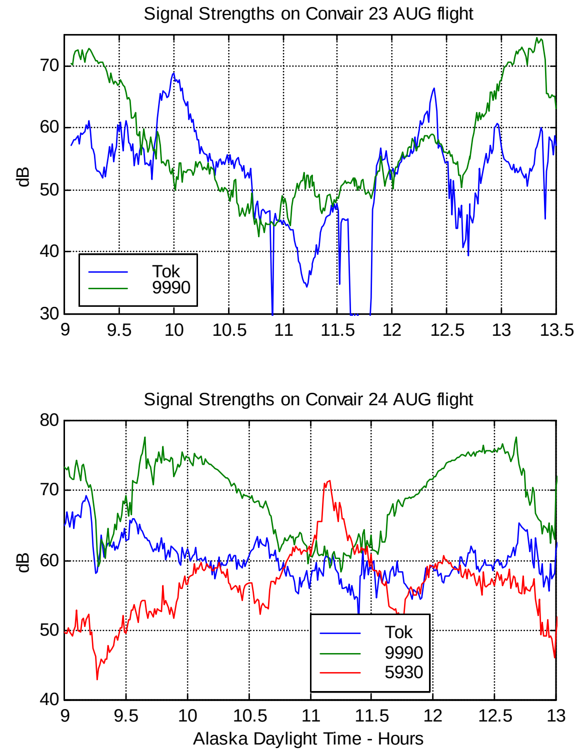


Figure 15, Signal strength of Tok and other LORAN signals for Convair flights on 23 and 24 August.

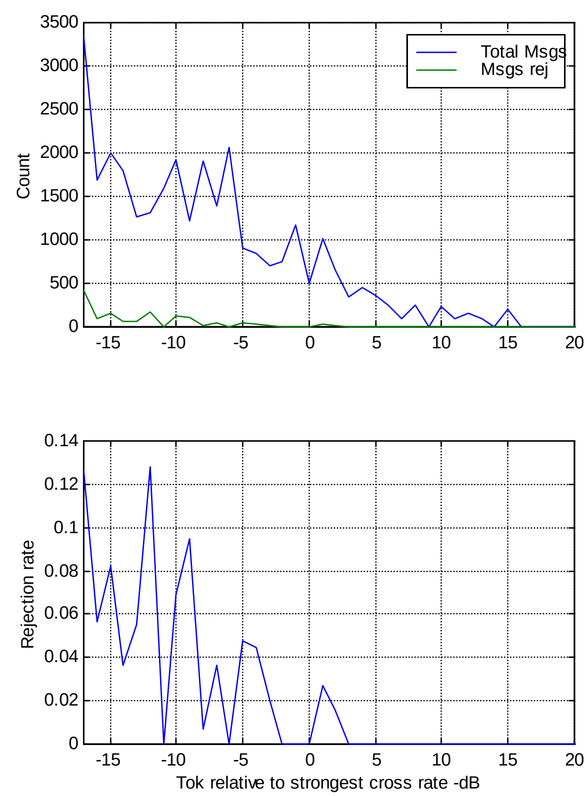


Figure 16. Message rejection rates as function of Tok relative to strongest other LORAN station.

In particular, demodulation was successful when Tok was the strongest signal. In all tests, steering the antenna to maximize SNR and erasure decoded improved performance to varying degrees. In a scenario with all stations transmitting LDC, a receiver could travel the majority of Alaska without message rejections.

Antenna steering proved to significantly decrease the message rejection rate. Geographic position was the critical factor in performance of antenna steering. As the aircraft approached the baseline between Station Tok and another station, antenna steering was less effective in reducing message rejection rates. These results were expected, as the antenna cannot null signals 180 degrees from the desired signal.

The tests demodulated the signal using both errors only and erasure decoding. Previous tests from Wildwood, NJ indicated in erasure decoding eliminating 50% of the errors only rejected messages. The Alaska tests indicated only a slight improvement (≈ 10%-12%) using erasure over error decoding. Although the improvement is slight, erasure decoding still provides enough improvement to be implemented in the receiver. The latency factor added by erasure decoding is extremely low for the system. The aircraft lost ability to demodulate LDC when greater beyond a radius range greater than 400 to 420 NM. These results closely support the conclusion that all LORAN stations in Alaska would have to transmit the LDC to ensure full LDC coverage in the Alaskan region.

One flight was done using an E field antenna and in areas of considerable precipitation static. The performance was seen to be significantly degraded by this precipitation static.

## FUTURE PLANS

We will continue to evaluate the recorded data from the tests. Where the system worked successfully and unsuccessfully must be correlated with aircraft position, transmitting power and signal interferences. Signal interferences will be examined for their source and method of mitigation in future tests. The receiver's software will be modified to ensure the averaging templates change at nearly the same rate and the AGC.

The FAA assigned the University of Alaska to determine the coverage area of geo satellite WAAS signal in the Alaska area. Their primary focus will be land and water areas, used to take-off and land aircraft.

One goal is to preserve the long-standing navigation capability of LORAN. The successful of tests in Alaska of transmitting and demodulating the LDC signal bears the question on how the navigation side was affected. The answer to this question was not a desired outcome of the Alaska test but now must be examine before any long-term testing of the LDC signal on operational LORAN rates. In conjunction to legacy receiver testing, a thorough analysis of the entire transmitted signal will need to be conducted. The effects on Envelope to Cycle Difference (ECD), cycle compensation, droop, jitter, spectrum, etc., all require examination.

A simulator is being developed to test the navigation performance of the LDC signal with various LORAN receivers. The Coast Guard has modulated data on LORAN in the past [2]. Those modulation techniques and EUROFIX all resulted in some degraded effect of navigation capabilities. Therefore, the simulator is prudent to conducted initial test without risking legacy receivers using it for navigation. Eventually, the receivers will be tested with LSU transmitting the LDC signal in the 9960T slot.

All the receiver testing leads to the end of FY02 goal of broadcasting the LDC signal on an operational rate continuously for an extended period. There are many technical questions concerning the receiver as well as transmitter to be answered first. In addition, the logistical challenges to transmit on an operational rate will all be addressed.

Stanford University is continuing their work on developing a system integrating LDC WAAS data with GPS raw data to produce a WAAS position solution and confidence bounds.

The current Solid State Transmitters within the Coast Guard cannot transmit LDC without modification of hardware and software. LSU will start examining what modifications are required and the process to complete them.

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**REFERENCES**

1. Arsenault, A.N., "LORAN Recapitalization Project (LRP)", Proceedings of the 29th Annual International LORAN Association Conference in Washington DC, 2000.

2. Peterson, B. B., Schue, III, C. A., Boyer, J. M., & Betz, J. R., "Enhanced LORAN-C Data Channel Project," **Proceedings of the International Symposium on Integration of LORAN-C/Eurofix and EGNOS/Galileo**. Bonn, March 2000.

3. Boyer, J. M., "High Speed LORAN-C Data Channel Communications," **Proceedings of the 29th Annual International LORAN Association Conference,** Washington DC, 2000.

4. Peterson, B. B., Dykstra, K., Swaszek, P., Boyer, J. M., " High Speed LORAN-C Data Communications - 2001 Update," **Proceedings of the 2nd International Symposium on Integration of LORAN-C/Eurofix and EGNOS/Galileo**. Bonn, February 2001.

5. Peterson, B. B., Dykstra, K. U., Swaszek, P. F., and Boyer, J. M., "High Speed LORAN-C Data Communications—June 2001 Update," **Proceedings Institute of Navigation Annual Meeting**, Albuquerque, NM, June 2001.

6. "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System, Volpe National Transportation Systems Center, August, 2001. PDF version available from www.navcen.uscg.gov.

7. Mathews, C. S., "LORAN-C Spectrum: Navigation and Communications," **Proceedings of the 3rd Technical Symposium of the Wild Goose LORAN-C Association**, Great Gorge, NJ, October 2-4, 1974.

8. Specification of the Transmitted LORAN-C Signal, COMDTINST M16562.4A, Commandant, USCG, May 1994.

9. RTCA, "Minimum Operational Performance Standards for GPS/Wide Area Augmentation System Airborne Equipment," RTCA/DO 229B, October 1999.

10. Millington, G., "Ground Wave Propagation over an Inhomogeneous Smooth Earth," **Proceedings of the IEE**, Series 96, No. 3, p53, 1949.

11. Peterson, B. B., A.W.S. Helwig & G.W.A. Offermans, "Improvements in Error Rate in Eurofix Communications Data Link via Cross Rate Canceling and Antenna Beam Steering," **Proceedings of the Institute of Navigation Annual Meeting**, Cambridge, MA, June 1999.

12. Erickson, Robert H., "Loran C Coverage in Alaska after Dual Rating Port Clarence," DOT/FAA/CT-TN88/22, FAA Technical Center, June 1988.

13. Enge, P. & S. Lo, "Analysis of the Enhanced LORAN Data Channel," **Proceedings of the 2nd International Symposium on Integration of LORAN-C/Eurofix and EGNOS/Galileo**. Bonn, February 2001.

14. Peterson, B.B., D. M. Dermanelian, S. R. Katz, and K. U. Dykstra, "DGPS & LORAN SNR Improvements by Null Steering and De-Coupling Magnetic Loop Antennas," **Proceedings of the Institute of Navigation Annual Meeting**, June 1997.

15. Peterson, B. B., Dykstra, K., Swaszek, P., Boyer, J. M., Carroll, K., and Narins, M., "High Speed Loran-C Data Communications - Flight Test Results," **Proceedings of the Institute of Navigation GPS 2001,** Salt Lake Citry, September, 2001.