New Loran Receiver Technology Significantly Improves Overall System Performance and Substantiates Loran Viability as GPS Backup

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ABSTRACT

Although the 1991 addition of South Central and North Central Loran chains greatly improved Loran coverage in North America, Loran receiver technology had not advanced concurrently to take advantage of the increased signal availability and changes in Loran signal conditions. Over the last 5 years, however, new Loran receiver technology has been developed that generates a significant improvement in the overall performance of the Loran system. For example, SNR is typically improved 12 - 18 dB, cycle slips do not occur, and susceptibility to impulse noise and other interferers is almost nonexistent. A single receiver can simultaneously track ground and skywaves from up to 40 Loran transmitters, with some skywaves traveling 5,000 miles reaching levels of 28 dBuV/M.

In a practical sense, such performance indicates Loran signals are available for navigation and timing applications over virtually all of North America, from dense urban canyons in Manhattan to remote areas of Northern Canada. Given the recent international expansion of Loran, it also indicates Loran skywave navigation would be available for aviation and marine applications over the northern Pacific and Atlantic oceans to an accuracy of approximately 1-1/4 miles.

The Loran system has certain characteristics, e.g. low frequency, high signal level, and ground based, that enable it to function under conditions where GPS might be temporarily unavailable. Common examples would be line-of-sight blockage by buildings, man-made interference by communication broadcasts, natural interference from solar flares, and possibly terrorist jamming or spoofing. In addition, the domestic and international Loran infrastructure is already in place, very inexpensive to operate, and Loran has the world's largest existing user base. Given the significant safety and performance benefits the Loran system now provides at a remarkably low cost, Loran should be the system of choice to backup GPS.

INTRODUCTION

Largely because receiver manufacturers concentrated on the growing GPS market, Loran-C technology has not advanced significantly for about 15 years. During that time, performance evaluations of the Loran-C system and the potential for combined GPS/Loran receivers were based on the same antiquated receiver technology.

Over the last several years, LOCUS has applied contemporary analog and digital signal processing techniques and developed a new Loran receiver technology called Linear Averaging Digital Loran, or LAD-LORAN. LAD-LORAN studies illustrated below have now demonstrated: (1) some basic characteristics of the Loran-C system were previously misunderstood and can be identified and quantified (e.g. crossrate interference and skywave propagation); (2) Loran-C receiver performance can easily be enhanced by an order of magnitude or more; and (3) given its performance improvements, physical characteristics, economic advantages, reliability/integrity enhancements, and international expansion, Loran is the ideal complement to GPS.

TECHNOLOGY

LAD-LORAN technology can be briefly summarized as shown in Figure 1.

* Linear Receiver
 - 3 dB S/N advantage over hard-limited receiver
 - pulse shape, amplitude, and other parameters available for skywave identification and rejection

* Patented Ensemble Averaging Architecture
 - rapid cycle detection (~30 sec) and virtual immunity to cycle slip
 - acquisition time 10 times faster

* Proprietary Notch Filter Technology
 - eliminates filter affects on ECD, SNR, and skywaves
 - provides full automatic notch filter capability

Figure 1. LAD-LORAN Technology Overview

LAD-LORAN is currently embodied in 3 products, the LRS II, LRS III, and an OEM board provided on a private label basis. Each receiver uses an 18” antenna, which consists of a printed circuit board with integrated preamp. The LRS II receivers incorporate seven full-band, automatic notches. The OEM boards are a variation of the LRS II and are used for timing applications. The LRS III contains 12 full-band, automatic notches and is a receiver designed to monitor and control Loran transmitters. All receivers are capable of simultaneously tracking up to 40 stations and 8 Group Rate Intervals (GRIs).

Some of the features/benefits of LAD-LORAN technology are listed in Figure 2.

	OLD	NEW
Chains tracked	1 or 2	8
Stations tracked	4 - 8	40
Crossrate interference	uncompensated	locked out
Skywave interference	uncompensated	locked out
Noise interference	common	very uncommon
Cycle slips	common	eliminated
SNR		12-18 dB improvement typical
Coverage	900 miles	1200 miles

Figure 2. Features/Benefits of LAD-LORAN Technology

Note that “Old” SNRs are not reported because no uniform standard was applied by all manufacturers. However, in evaluating many Loran receivers, LAD-LORAN always performed 12 - 18 dB better than the others.

RESULTS

1. Multichain Tracking and Crossrate Compensation are Imperative.

To demonstrate the necessity of multichain tracking and crossrate compensation, LOCUS used 3 matched LAD-LORAN receivers and enabled/disabled these capabilities during overnight recordings in Madison. The LAD-LORAN receiver set to acquire “one” chain tracked the nearby GRI 8970 (the Great Lakes chain), where the third closest station was Seneca, New York, 635 miles from Madison. This represents a real-life configuration for a single chain receiver, since it would use Seneca for its navigation solutions.

Time constants were kept as close to identical as practicable. Figure 3 illustrates the signal-to-noise ratio (SNRs) and time differences (TDs) from these receivers.

Figure 3. SNRs (top row) and TDs From Three LAD-LORAN LRS Receivers Simultaneously Tracking 8 Chains, 4 Chains, and 1 Chain. Data were sampled every 60 seconds, and time constants were 60 seconds. Two brief cycle slips (a,b) occurred during the single chain operation because of the short time constant.

We readily see the 8 chain data are by far the quietest. In fact, RMS short term noise is 5.3nS, so position noise is about five feet, or 1.6 meters, at the GDOP of about 1.0. For the 4 chain run, tracking only 20 stations, noise was 13.8nS, more than double. For the single chain run, noise was 17.6nS (not counting the two spikes), more than triple the 8 chain value.

These data clearly demonstrate multichain receiver capabilities (or lack thereof) can affect ECD measurements even more severely. Figure 4 illustrates ECD measurements derived from the same recordings above.

Figure 4. ECD Measurements From Receivers Tracking 37, 20, and 5 Stations, as Shown in Figure 3.

ECD noise is 187nS, 490nS, and 937nS, respectively, for the three figures. Single chain ECD is five times noisier than ECD in normal (i.e. 8 chain) LAD-LORAN LRS operation. In order to operate at the same confidence level, the single chain receiver must average 25 times longer. Even if this is done, it still does not correct for the longer-lasting distortions. To remove them, it is necessary to average for many hours.

Also note the large, sustained deviation in the 5 station track. The deviation is important in the real world since a navigator using a single chain receiver could not identify or notice an ECD anomaly and any associated positioning error, because a sustained 2.5uS ECD error is perfectly normal. In contrast, the LAD-LORAN receiver shows only a negligible deviation, and it would be able to identify an anomaly in less than a minute at this distance and noise level.

In summary, noise received by Loran units in North America is overwhelmingly dominated by crossrate pulses. For precise timing and critical navigation (e.g. aviation) applications, it is mandatory to use a receiver capable of processing a significant level of this form of interference.

2. Skywaves are Dynamic, Prevalent, Travel Great Distances, and Require Compensation.

Skywave identification and compensation are critical to correct cycle tracking and ECD measurement. Older technology Loran receivers were subject to cycle slips, and ECD averaging times were extremely long, sometimes requiring many hours. In contrast, LAD-LORAN virtually eliminates cycle slips and ECD averaging is typically 60 seconds or less for stations conventionally used for navigation.

Figure 5 shows the skywave recorded from 8970W (Malone, Florida, about 867 miles from Madison), and the idealized Loran pulse is illustrated as the dotted line. Data were recorded at sunrise, when skywaves are most prevalent, and successive waveforms are approximately 35 seconds apart.

Figure 5.

These data illustrate the level and phase of skywave interference can vary dramatically over a very short period of time. Other work at LOCUS has also demonstrated skywave compensation cannot be a simple function of distance and power.

Figure 6 shows similar data taken from a more distant station, 7980X (Raymondville, Texas, about 1240 miles from Madison). Successive figures were taken over the 37 minute period around sunrise. The skywave begins to slip away at 5:30 (6a) and speeds up from 5:32 - 5:36 (6a -6e). Just before solar absorption sets in, the waveform is severely distorted.

Figure 6. Sequence of Waveforms at Sunrise.

In summary, skywaves are not a slowly varying phenomenon and can cause severe ECD distortion on short as well as long time scales. LAD-LORAN performs real-time skywave compensation that makes correct cycle identification and ECD computations not possible with delay and add circuitry commonplace in older Loran receivers.

Skywaves are much more prevalent at greater distances than previously recognized. In 1993, Loran-C signals were recorded on a LAD-LORAN receiver located near Fairbanks, Alaska and representative data are shown in Figure 7.

Data listed are from nearby (7960), distant (8290), and very distant (7970) chains, and include GRI/chain, station, approximate distance to transmitter, and signal level in dBu V/M. Signal levels for groundwaves (G) and skywaves (S) are maximum levels recorded over a 24-hour period. In these tests, skywaves from at least some distant stations were generally present about 80% of the time during any 24-hour recording period.

GRI/Chain	Station	Distance	Signal Level
7960/Gulf of Alaska	TOK (M)	185 mi.	78 (G)
	Narrow Cape (X)	533	54 (G)
	Shoal Cove (Y)	862	17 (G)

8290/North Central U.S.	Havre (M)	1774	44 (S)
	Baudette (W)	2225	48 (S)
	Gillette (X)	2162	31 (S)
	Williams Lake (Y)	1268	54 (S)
	Port Clarence (Z)	555	54 (G)
7970/Norwegian Sea	Ejde (M)	3441	44 (S)
	Bo (W)	3188	33 (S)
	Sylt (X)	4090	N/A
	Sandur (Y)	3055	41 (S)
	Jan Mayen (Z)	2872	30 (S)

Figure 7.

At this site, skywaves from a total of 17 GRIs could be recorded, i.e. from most of the world's Loran chains. The most distant emanated from Guam, approximately 4700 miles away, and were 28 dB uV/M. These data demonstrate that, even in remote areas, skywaves can be extremely large and prevalent.

Figure 8 shows data from a recent recording at LOCUS in Madison, Wisconsin and illustrates skywaves are just as prevalent in less remote locations. Signal level shown is dB in uV/M for the tracking point and peak of the overall signal. On January 3, 1996 at 1:00 A.M. a LAD-LORAN receiver was monitoring signals from 37 Loran transmitters. First, we chose 8970X (Seneca NY, about 635 miles from Madison) as the reference, because it is the weakest station in the closest triad, and because that triad would be the only triad used for navigation by the typical single chain Loran receiver commonly used in aviation and marine applications. Using that reference for the 37 stations, skywaves from 24 stations had peaks 5 dB or more *above* the 8970X groundwave. Clearly, skywaves are prevalent in many areas and at levels previously unrecognized, and a receiver must compensate for their interference.

A peak of this size exceeds the target groundwave for about one millisecond per group of 8 pulses, and there are 20 groups of this size or bigger which are not on the GRI. Therefore, it is fair to say the groundwave would have been quite corrupted without crossrate lockout, since its level was exceeded in magnitude by quasi-coherent interference 20% of the time.

GRI/Chain	Station	Distance	Signal Level
5930/East Coast Canada	Caribou (M)	1076 mi.	26/65 (S)
	Nantucket (X)	1000	37/65 (S)
	Cape Race (Y)	1775	43/47 (G)
	Fox Harbour (Z)	1673	26/37 (G)
5990/West Coast Canada	Williams Lake (M)	1644	39/44 (G)
	Shoal Cove (X)	2038	19/26 (G)
	George (Y)	1502	25/60 (G)
	Fort Hardy (Z)	1851	32/44 (G)
7980/Southeast U.S.	Malone (M)	867	46/68 (S)
	Grangeville (W)	859	48/67 (S)
	Raymondville (X)	1240	33/69 (S)
	Jupiter (Y)	1224	25/61 (G)
	Caroline Beach (Z)	878	42/70 (S)
8290/North Central U.S.	Havre (M)	1064	40/65 (S)
	Baudette (W)	455	64/72 (S)
	Gillette (X)	819	49/63 (S)
	Williams Lake (Y)	1644	40/44 (G)
8970/Great Lakes	Dana (M)	245	70/77 (S)
	Malone (W)	867	46/68 (S)
	Seneca (X)	**635**	**57/69 (S)**
	Baudette (Y)	455	64/72 (S)
	Boise City (Z)	852	50/63 (S)
9610/South Central U.S.	Boise City (M)	852	50/63 (S)
	Gillette (V)	819	49/63 (S)
	Searchlight (W)	1462	19/53 (G)
	Las Cruces (X)	1223	34/63 (S)
	Raymondville (Y)	1240	34/69 (S)
	Grangeville (Z)	859	48/67 (S)
9940/West Coast U.S.	Fallon (M)	1546	21/54 (G)
	George (W)	1502	22/60 (G)
	Middletown (X)	1749	45/49 (G)
	Searchlight (Y)	1462	19/53 (G)
9960/Northeast U.S.	Seneca (M)	635	57/69 (S)
	Caribou (W)	1076	30/65 (S)
	Nantucket (X)	1000	36/65 (S)
	Carolina Beach (Y)	878	42/70 (S)
	Dana (Z)	245	70/76 (S)

Figure 8.

3. Practical Implications of LAD-LORAN - Extended Coverage.

Figure 9.

Data above illustrate Loran signals are available over much greater distances and areas than previously recognized. Typically, we have found that groundwaves are available about 1800 kilometers from transmitters 24 hours/day. Figure 9 illustrates the 1800 kilometer coverage in circles about the U.S. master Loran stations. Figures 10a and 10b illustrate the same 1800 kilometer circle about the world's master stations and all Loran stations respectively. Although these figures do not constitute coverage diagrams in the traditional sense, they clearly indicate Loran groundwave coverage is substantially increased if a contemporary receiver is used.

Figure 10a.

Figure 10b.

Data above also illustrate Loran skywaves are typically available 24 hours/day about 2500 kilometers from transmitters, and often much further. Figures 11a and 11b illustrate 2500 kilometer circles about the world's master stations and about all Loran stations respectively. Clearly, skywave coverage over a significant portion of the Northern Hemisphere is now possible with a multichain receiver capable of crossrate and skywave identification and processing.

Furthermore, this observation leads to the intriguing possibilities opened if universal chain synchronization were accomplished, for example, using GPS. If this synchronization were achieved, a rough approximation is that coverage area would double and accuracy would improve 5 times over the current solutions obtained using unsynchronized chains.

Figure 11a.

Figure 11b.

4. Use of Loran as a Time/Frequency Reference.

Because Loran transmitters are Cesium based, Loran receivers have long been used as time and frequency references in telecommunications, metrology, and other related applications. Performance of older technology Loran receivers was primarily due to use of exceedingly long averaging times and depended on relatively close proximity to a transmitter. Loran time/frequency receivers were also single chain devices, and were incapable of rapidly processing background noise due to crossrate and skywave interference, and diurnal variations.

Use of LAD-LORAN technology can now enable Loran timing receivers to provide both very stable short term phase drift and long term frequency drift, even if the receiver is located at a significant distance from a transmitter. The following data taken with a Cesium reference illustrate this performance.

Figure 12.

Figure 12 shows the phase of the LAD-LORAN clock relative to a Cesium standard when the receiver is locked to 8970M (Dana, Indiana, approximately 245 miles from Madison) for about 4 days last November. Receiver time constant was set to 60 seconds, and data were sampled every 60 seconds.

LOCUS was aging a new SC cut crystal during this run, and the spikes are crystal artifacts. Note that for the first day and one-half, the phase noise was quite stable but had approximately a 200 nanosecond offset. At the end of that time, the Coast Guard made an adjustment to their clock, and subsequently, it started drifting further from the baseline. Near the end of the run, another adjustment was made.

Figure 13 illustrates a similar 3 day run late in December. Here the pattern of transmitter clock drift and adjustment are evident. Note as the crystal aged, the spikes disappeared.

Figure 13.

Figures 12 and 13 illustrate two key points. First, LAD-LORAN's short term phase drift is low, approximately 10-20 nS peak to peak, and is limited by the transmitter at times. It should also be noted some of that noise is due to the phase meter used in these measurements, and a significant amount could be due to the transmitter (see below). Secondly, the Cesium clock driving this transmitter is slowly drifting, and the Coast Guard is periodically making transmitter adjustments of about 100nS to compensate for the drift. If the transmitter clock were proportionately controlled, system stability would be greatly enhanced.

With LAD-LORAN, it is also possible to get a very high level of time and frequency performance using distant Loran stations. Figure 14 shows over two days of LAD-LORAN phase measurements relative to a Cesium standard when the receiver's clock was locked to 7980M (Malone, Florida, approximately 867 miles from Madison). Noise levels due to skywave interference are considerably higher during sunset to sunrise hours. However, it is clear during daytime hours the short term phase noise and long term frequency drift are extremely stable. These daytime data are highly reproducible and demonstrate daytime data could be used to maintain a Cesium-like standard even in areas distant from a transmitter.

Figure 14.

5. Performance of Loran Now Limited by Transmitter, Not Receiver Technology.

Using new Linear Averaging Digital (LAD)-LORAN receivers, we have learned that Loran transmitters can contribute a substantial amount of TD noise to signals available to receivers based on this technology. First, we consider data from transmitters in Baudette, MN, which is dual-rated as 8970Y and 8290W. Figure 15 shows a January 5, 1994 overnight TD recording made in Madison, WI from 1700 to 0900 hours, with TD divisions of ± 25nS on the ordinate. The figure illustrates 8970Y time of arrival (TOA) minus 8290W TOA, with the receiver's averaging time set at 60 seconds. Since those two rates are on the same tower (Baudette, MN), ASF and other effects cancel out, leaving only noise components and four local phase adjustments (LPAs) (a,b,c,d). From these data, we cannot determine which LPA is associated with which TD. In the worst possible case, all four LPAs could be associated with one TD.

Figure 15. 16 Hour, Overnight TDs Determined From 8970Y TOA Minus 8290W TOA.
Note 4 LPAs (a,b,c,d) of approximately 20nS (a,b and c) and 40nS (d).
LAD-LORAN receiver averaging time set at 60 seconds and data sampled every 60 seconds.

Figure 16 shows data derived from the same recording, and illustrates the 8970Y TD, which is 8970Y TOA minus 8970M TOA. 8970M is Dana, IN. Using the same ± 25nS divisions on the ordinate, it is evident the basic background noise seen by the receiver is about 2.5nS RMS. However, this background is clearly dominated by TD shifts and oscillations of approximately 20nS. Based on these (and additional) data, we speculate these jumps/oscillations are in the 8970M transmitter timing controller. The controller attempts to adjust the transmitter based on some interpretation of the antenna current pulse, and it is presumably “hunting” about the correct value.

GDOP=0.55

± 1 meter

Figure 16. 8970Y TD Data Derived From 8970Y TOA Minus 8970M TOA and Taken From Same Recording as Figure 15. Note numerous TD shifts/oscillations of approximately 20nS, and background noise of approximately 2.5nS RMS.

These data indicate it would be highly desirable to replace Loran timing controllers with modern devices having high or infinite resolution. This change would enable station timing to be held steady, except at the relatively infrequent occasions when an LPA or UTC adjustment is actually commanded. With these oscillations removed, very high precision Loran timing receivers would receive a steady signal; those using a secondary could easily identify the LPAs and remove them from the data. In addition, differential repeatability would be about 1 meter under appropriate conditions.

6. Additional Performance Enhancements are Still Possible.

The LAD-LORAN receivers used to generate these data incorporate analog and digital hardware. Due to processing constraints, as much as 75% of the data available to these receivers can be discarded. If the existing LAD-LORAN technology were transferred to a completely digital system using components currently available on the market, receiver performance would take another significant leap forward.

Conversion to completely digital technology would shorten time constants 4 - 8 times, depending on the instrument settings used for crossrate lockout. This would extend practical operational ranges several hundred kilometers.

Receiver dynamics would also significantly improve, e.g. batch processing of West Coast stations recorded from Madison now takes approximately 80 seconds and would drop below 15 seconds. Receiver position and velocity calculations could also be calculated about once/second. In addition, there would be a tremendous improvement in overall system redundancy. Overall, we expect conversion to completely digital technology will enhance system performance another 10 - 15 dB.

CONCLUSIONS:

Data presented indicate the performance of the Loran system can be significantly enhanced if contemporary technology is applied to receivers. Geographic coverage and signal availability are much greater, and it is reasonable to assume use of multichain Loran receivers would improve Loran reliability and integrity figures by two orders of magnitude beyond those achieved by single chain devices.

Use of Loran receivers based on LAD-LORAN or similar contemporary technologies impacts nearly every application where Loran and GPS receivers could be used. For example, recent automatic vehicle location studies in Manhattan (ref. 1,2,3) have demonstrated H-field Loran signals are available in urban canyons where no satellite signals are present.

LAD-LORAN coverage illustrations above indicate transoceanic navigation is possible for marine and aviation applications. In addition, LOCUS studies suggest synchronization of the world's Loran transmitters, perhaps using GPS, would increase coverage area approximately twofold. As error ellipses would become significantly smaller, we would also expect absolute and repeatable accuracy to improve about five times. Of course, these assumptions are based on multichain acquisition and the appropriate navigation software.

Time and frequency applications for Loran are well-established. Here we have demonstrated a single receiver can offer both short term phase stability and long term frequency stability and do so at locations very distant from a Loran transmitter. It is also interesting to note that GPS is now being used extensively for these same applications, and is commonly backed up by Rubidium oscillators. Clearly Loran can perform better than a Rubidium oscillator in short term as well as long term outages and does not require regular calibration. In addition, Loran can provide UTC. In telecommunications and other applications where high reliability is of critical importance, only Loran can offer a true back-up of or to GPS.

These data were derived from LAD-LORAN receivers wherein a significant portion of the processing is accomplished through hardware. If the technology were converted to a true DSP based system, we would expect the performance to improve another 10 - 15 dB. Overall, Loran receivers would offer 22 - 30 dB better performance than what is typical of older aviation, marine, or timing Loran receivers. These numbers and the above data strongly suggest evaluations of how Loran fits into the nation's radionavigation future should be made on how well the system can actually perform, not outdated perceptions.

The physical characteristics of the Loran system are entirely different than GPS. Loran is ground based, low frequency, and has high signal strengths. GPS is satellite based, high frequency, and has low signal strengths. Consequently, natural or man-made interferers will almost never simultaneously affect both systems. Together, they are remarkably robust. Studies at the Volpe Center using single chain receiver data demonstrate Loran augmentation of GPS aviation approach availability improves GPS availability about one hundred fold. Incorporating LAD-LORAN or similar technologies could decrease system unavailability, or catastrophic system failure, by at least an order of magnitude.

Loran is also very inexpensive to operate. Its entire U.S. operations and maintenance budget is now $17 million annually, and this figure could easily be dropped well below $10 million if the transmitters were upgraded and a new control system were installed. The upgrade is conservatively estimated at $100 million.

For comparison purposes, operation and maintenance of the VOR/DME system is now over $250 million, and obviously, this system only serves the aviation community. If the VOR/DME system were terminated one year earlier, the savings would pay for the upgrade and maintenance of the Loran system for over 15 years. Since Loran would serve aviation, marine, terrestrial, and time/frequency markets, the economics of the situation are obvious.

Finally Loran is expanding internationally, mainly because of its comparatively low costs and political concerns regarding control of GPS. Loran-C ideally addresses other countries' needs, because they can establish an extremely reliable, very inexpensive, autonomous radionavigation system that is uniquely complementary to GPS. Indeed, it would seem our nation's best interests would be served by supporting domestic Loran-C and encouraging international expansion. Such a policy would place liability responsibilities with individual countries, would facilitate DoD's maintenance of GPS' strategic advantages, and would promote "seamless" international use of two complementary radionavigation systems.

In addition, U.S. support of a combined GPS/LORAN system would finally establish a federal radionavigation system that truly represents a cogent domestic policy encompassing virtually all domestic users and applications, and is international in scope. Such a policy would be a significant improvement over current programs that are fragmented into individual aviation, marine, and terrestrial systems, with little regard to our international obligations or previous domestic policies and promises.

In conclusion, combined, complementary radionavigation systems are prudent and necessary, and from safety, economic, and political perspectives, Loran is the ideal complement to GPS.

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BIOGRAPHY

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Thomas Blandino has been an electrical engineer at LOCUS for 15 years. He is primarily responsible for LOCUS' LAD-LORAN hardware and holds 6 patents. Paul Schick is a physicist by training, has been a software engineer at LOCUS for 9 years, and is primarily responsible for LAD-LORAN software. He holds 3 patents.