Improved SNRs and Adaptive Filtering In New DSP-based Loran-C Receivers

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Abstract

Linear, all-in-view, digital Loran receivers now show SNR improvements of 20 dB or more over hard-limited devices. This capability enhances the characterization of nearby Loran signals and the ability to extract distant signals. As a result, there is a significant increase in Loran's overall range, stability, and repeatability. However, these enhanced signal-processing capabilities also uncover background interference formerly too small or transient to be recognized, let alone removed, by other receivers. For example, recent North American tests on a new generation digital Loran receiver demonstrate the presence of over 20 interferers in the frequency band located in the 80-120 kHz range in an environment where only 8 interferers were previously identified. The European environment is typically more severe.

The most prevalent type of interference impinging upon a receiver will depend on its application and environment. For example, a vehicle location or timing receiver used in an urban environment might predominantly see power line carrier interference while disturbances to an aviation or marine receiver might likely come from strong transients due to lightning. Regardless of the particular situation, some interferers will degrade the quality of Loran signals more than others. Therefore, a high performance receiver should identify and intelligently process a number of different types of interferers.

A new generation receiver now incorporates real-time, adaptive, filtering techniques to process various interferers and optimizes Loran signal reception significantly as compared to linear digital receivers without this capability. In part, these adaptive filtering techniques provide for dynamic interferer tracking, the ability to set independent Q's on individual filters, and the ability to place interferer filters so that Loran reception is enhanced. Data from North American and European environments, with and without the use of adaptive filtering, will be shown, and Loran performance with this new receiver technology will be demonstrated.

I. Introduction

In a general technical sense, Loran receivers have evolved in three major steps to date. The first encompassed hard-limited devices that clipped Loran signals and interferers alike and were severely constrained by the hardware and microprocessor power/speed that was available at the time. The second step was to linear devices which used 8-bit analog-to-digital converters (ADCs) and more advanced microprocessors. While a major improvement over hard-limited devices (e.g. signal-to-noise was typically at least 20 dB better), these linear receivers were also processor and technology bound and commonly discarded up to 90% of the available data. This paper primarily reports on the third step, the development of a completely linear digital receiver based on commercially available digital signal processing (DSP) chipsets. This step will provide the best definition to-date of how well the Loran system can actually work because it enables the acquisition and processing of nearly all Loran signals and interferers by very fast devices capable of providing excellent dynamic performance. The dynamic performance should be good enough to enable reliable receiver operation at velocities approaching the sound barrier. Although many additional steps will certainly take place in the evolution of Loran receivers, this third step will finally give us a reasonable representation as to what is truly possible for Loran range, accuracy, reliability, and other performance characteristics needed to complement satellite systems.

For the benefit of those who have not seen how far Loran technology has progressed in the last 10 years, we begin with a figure that encapsulates one aspect of performance now possible with Loran receivers incorporating contemporary hardware and software. We compare it with antiquated Loran receivers commonly used today in aviation and marine applications but incorporating 10+ year old technology. **Figure 1** shows time difference data taken from an overnight data run in the US using a newer technology receiver. The actual derivation of the data is not the emphasis of the figure, but the units shown on the ordinate are.

The bounds of the left ordinate are artificially set to ± 100 ns and compressed for illustration purposes. The 100 ns bounds represent the actual resolution that was possible with non-linear, hard-limited devices that were processor-limited to tracking a single Loran chain. The actual data shown on the right are displayed using a ± 50 ns ordinate and are from an earlier paper [1] demonstrating transmitter control problems in some aging US transmitters. Although it is clear that all data are contained within ± 25 ns, note the background noise is approximately 2.5 ns RMS. This 2.5 ns background noise indicates new receivers can resolve time differences at least 40x better than possible with hard-limited devices. In fact, new technology can actually resolve times differences to 0.1 ns, so the improvement is really 3 orders of magnitude over traditional hard-limited receivers.

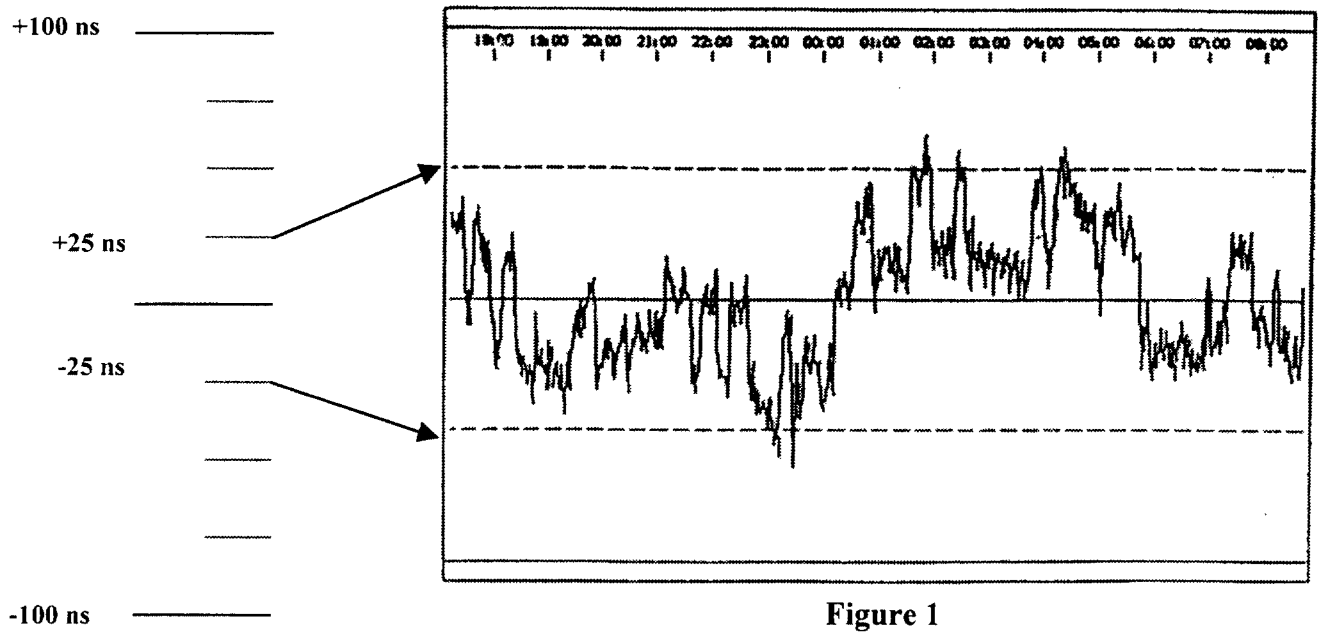

Figure 1

Figure 1. Left side shows ± 0.1 μs scale artificially compressed to illustrate resolution possible with older hard-limited Loran receivers most commonly used in marine and aviation applications. Right side shows actual data from newer linear receiver that is able to resolve time differences to 0.1 ns.

II. Completely Linear Data Acquisition and Digital Signal Processing

Although **Figure 1** gives some indication of how far Loran receiver technology has progressed, there is considerable opportunity for improvement beyond the results shown. For example, new receiver technology under development incorporates a 16-bit ADC that basically enables a receiver to operate as a linear device. The increased resolution of these devices is critical because skywaves, which are commonly 25 times as large as groundwaves, impinge upon the Loran groundwave signal and distort the ECD, reducing overall accuracy and reliability.

Figure 2 graphically illustrates the importance of this increased resolution. **Figure 2a** shows a representative skywave encroaching on a Loran signal using a linear representation of amplitude. The starting point (0 μs) and third zero crossing (30 μs) of the Loran waveform are indicated, so this skywave is approximately 15 times the size of the groundwave. **Figure 2b** shows a smoothed digital portion of the Loran pulse to indicate the actual form of the analog signal within approximately 70 μs of the starting point. **Figure 2c** shows the distorted digital waveform resulting from 8-bit digitization of that same analog waveform. Clearly, the resultant artificial contouring of the waveform prevents accurate measurement of the signal amplitude, and it also degrades envelope-to-cycle distortion (ECD) and zero crossing measurements.

Figure 2a

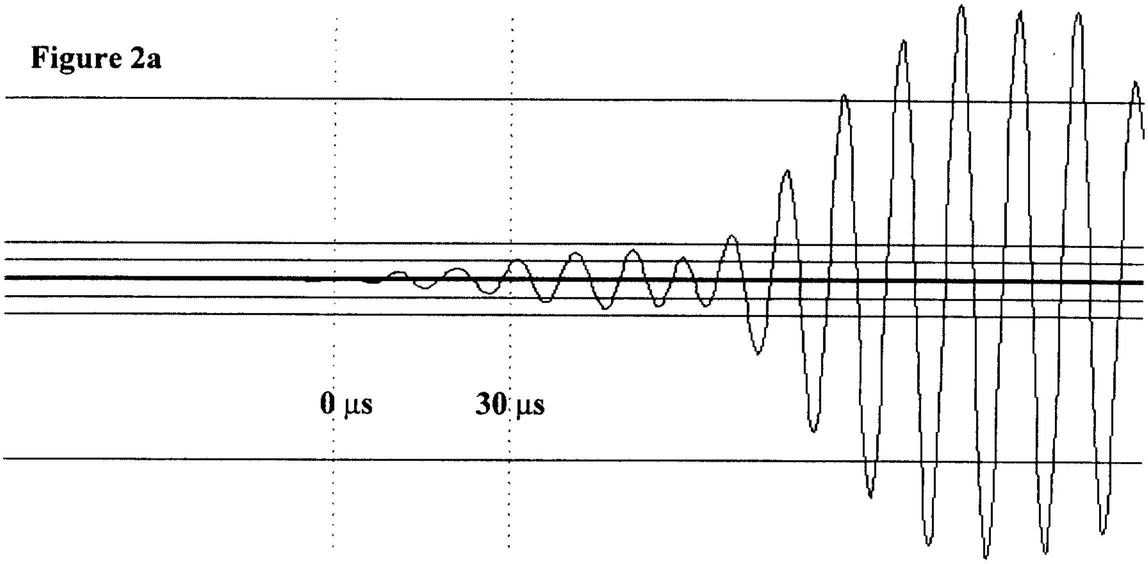

Figure 2b

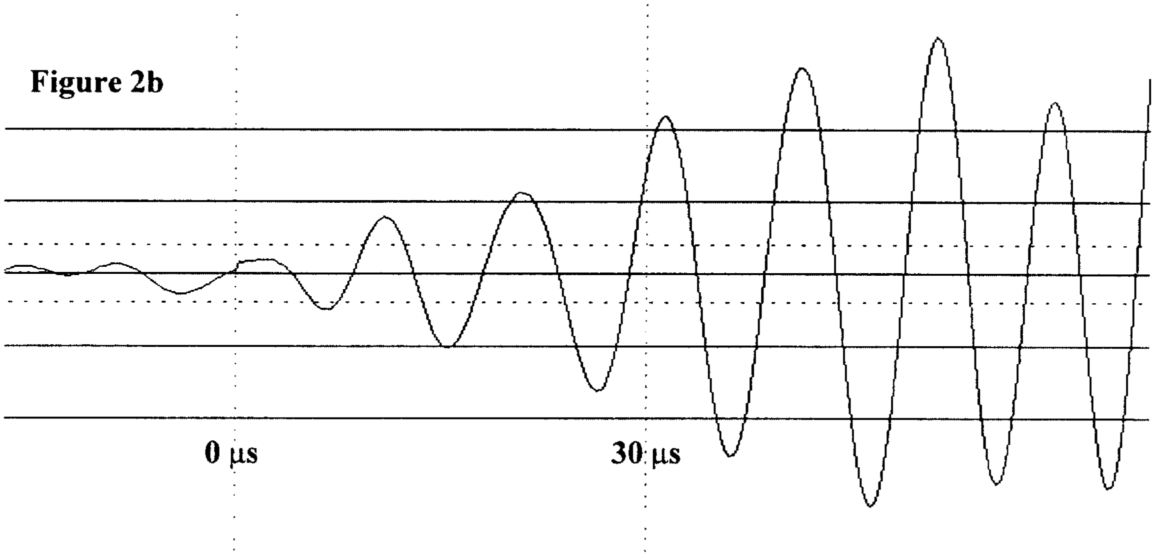

Figure 2c

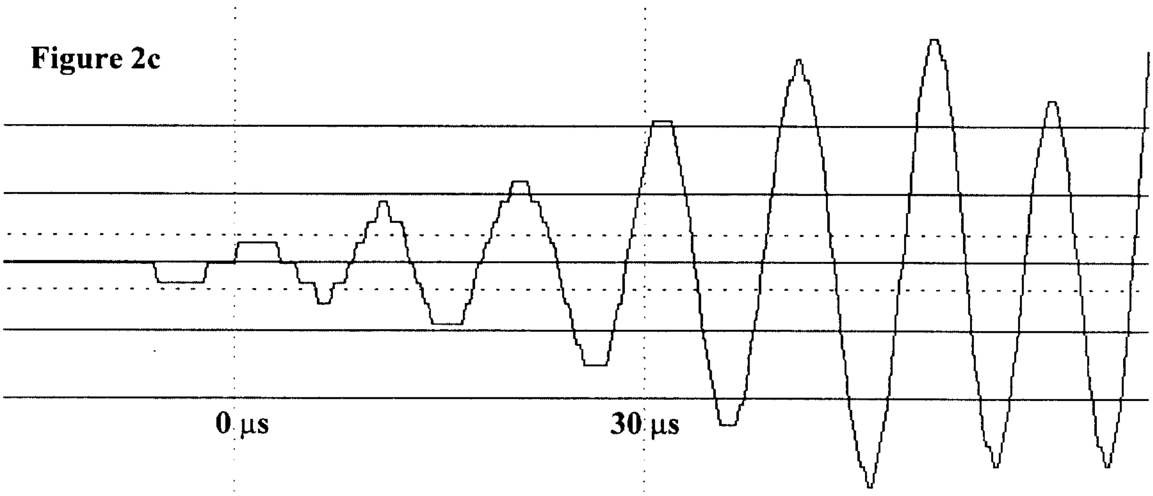

Figure 2. Representative Loran and skywave signals displayed on linear amplitude scales, **Figures 2b** and **c** on same scale.

The incorporation of 16-bit ADCs now enables a receiver to digitally reconstruct a Loran waveform without introducing any significant distortion. This new capability has several practical effects with regard to the performance as well as the size and cost of a Loran receiver. First, the need for gain ranging and control circuitry to accommodate such a wide dynamic range is eliminated. Moreover, transients introduced by such circuitry are also eliminated, so software associated with gain ranging control and reducing self-generated artifacts is no longer needed.

Second, increased ADC resolution significantly increases the signal-to-noise (SNR) of nearby stations, and time differences from these stations dominate the navigation solution. The SNR improvement can be approximately 6-15 dB better than linear receivers with 8-bit ADCs, and SNRs seen in those devices are typically 15-20 dB better than possible with the hundreds of thousands of hard-limited receivers in use today. In addition, ECD distortion is minimized to the degree that cycle slips, so common in hard-limited devices, are virtually eliminated.

In a practical sense, the SNR and ECD improvements mean a completely linear receiver will perform much better when skywaves or noisy conditions are present, such as nighttime or during a thunderstorm, and those are exactly the times when reliable performance might be most necessary. Furthermore, the operational range of Loran receivers is considerably larger than possible with hard-limited devices.

Table 1

16-bit ADC and DSP Receivers Hardware/Software Advantages
1. Increased Dynamic Range
2. Linear Signal and Noise Data Acquisition
3. Improved SNR on Nearby Stations
4. Elimination of Gain Ranging Circuitry and Software

Table 2

16-bit ADC and DSP Receivers Performance Advantages
1. Better Navigation Solutions
2. Increased Operational Range
3. Reliable Operation during Noisy Conditions
4. Smaller Size, Less Expensive

III. Spectrum Analysis and Digital Filtering

Another important benefit of incorporating DSP and 16-bit ADC technology is the improved ability to identify and eliminate interference in the Loran band. Older hard-limited receivers typically had a small number of fixed notch filters that might or might not have been under processor control. Such receivers were notoriously subject to natural and man-made interference, particularly if the interferers were intermittent. Even though more contemporary linear receivers had 8-bit ADCs and their processing power improved filtering considerably, the ADCs themselves introduced significant quantization noise and gain ranging was required. Quantization noise, gain-ranging, and microprocessor limitations made identification and processing of interferers relatively slow in these devices, although probably at least an order of magnitude faster than in earlier hard-limited devices.

Today, DSP and 16-bit ADC technology eliminates these problems and enables us to get a much more accurate picture of signals and interferers present in the Loran band. Furthermore, DSP technology enables rapid identification and removal of interferers with minimum distortion to the Loran waveform, even in highly dynamic situations. **Figure 3** shows a typical spectrum present at Locus before **(a)** and after **(b)** digital filtering on a new DSP-based receiver, and uses a relative linear amplitude scale on the ordinate. It is clear that a large number of interferers are present from approximately 75-125 kHz, and they are stronger than the Loran signals centered at 100 kHz. Under similar conditions, a hard-limited receiver with fixed analog notches would simply have been overwhelmed with the extent and level of this noise and provided unreliable results.

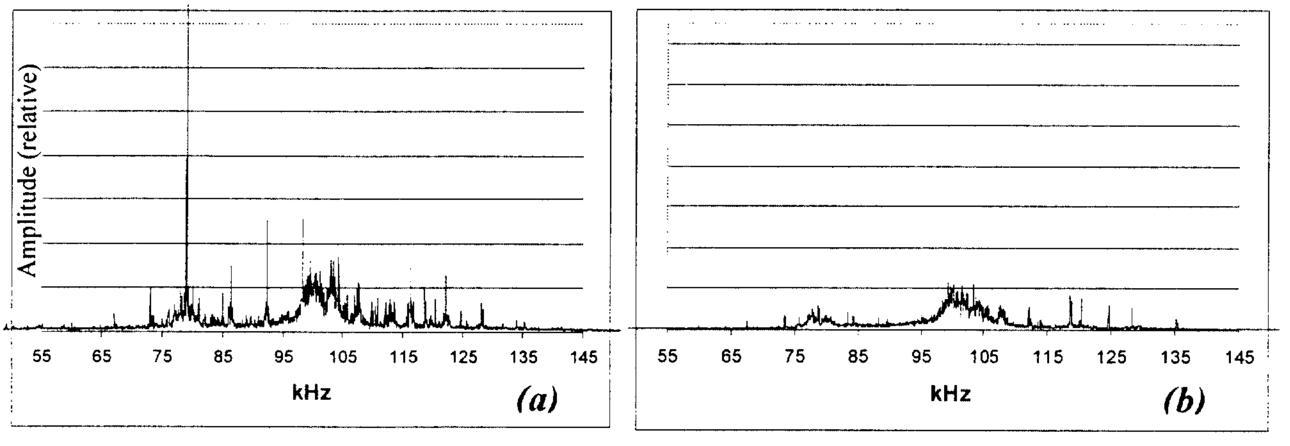

Figure 3. Spectrum from data acquisition in the 55-145 kHz band taken before **(a)** and after **(b)** digital filtering was applied. The ordinate is amplitude-designated in a relative scale for illustration purposes.

IV. Dynamics of Interferer Identification and Elimination

The speed of the DSP processors enables the new receiver to identify and eliminate interferers at least an order of magnitude faster than was possible with earlier linear receivers, which had analog filters fully under microprocessor control. It is impossible to compare the new capabilities with the notch filtering present on hard-limited receivers, which sometimes were dependent on human interaction and were notoriously slow even if under microprocessor control.

Figure 4 shows a time series of results to demonstrate the speed at which the new receiver can set up and adapt its notch filtering capabilities. Remember, hard-limited receivers would typically take many minutes to perform the same task, and then not do it nearly as well. **Figure 4a** shows the first spectrum performed to establish the baseline. Although the relative amplitude scale on the ordinate is linear, the large interferer is clipped for illustration purposes and is more than 10 times larger than the Loran signal. **Figures 4 b, c,** and **d** show the spectrum 1, 2, and 5 seconds respectively after the baseline.

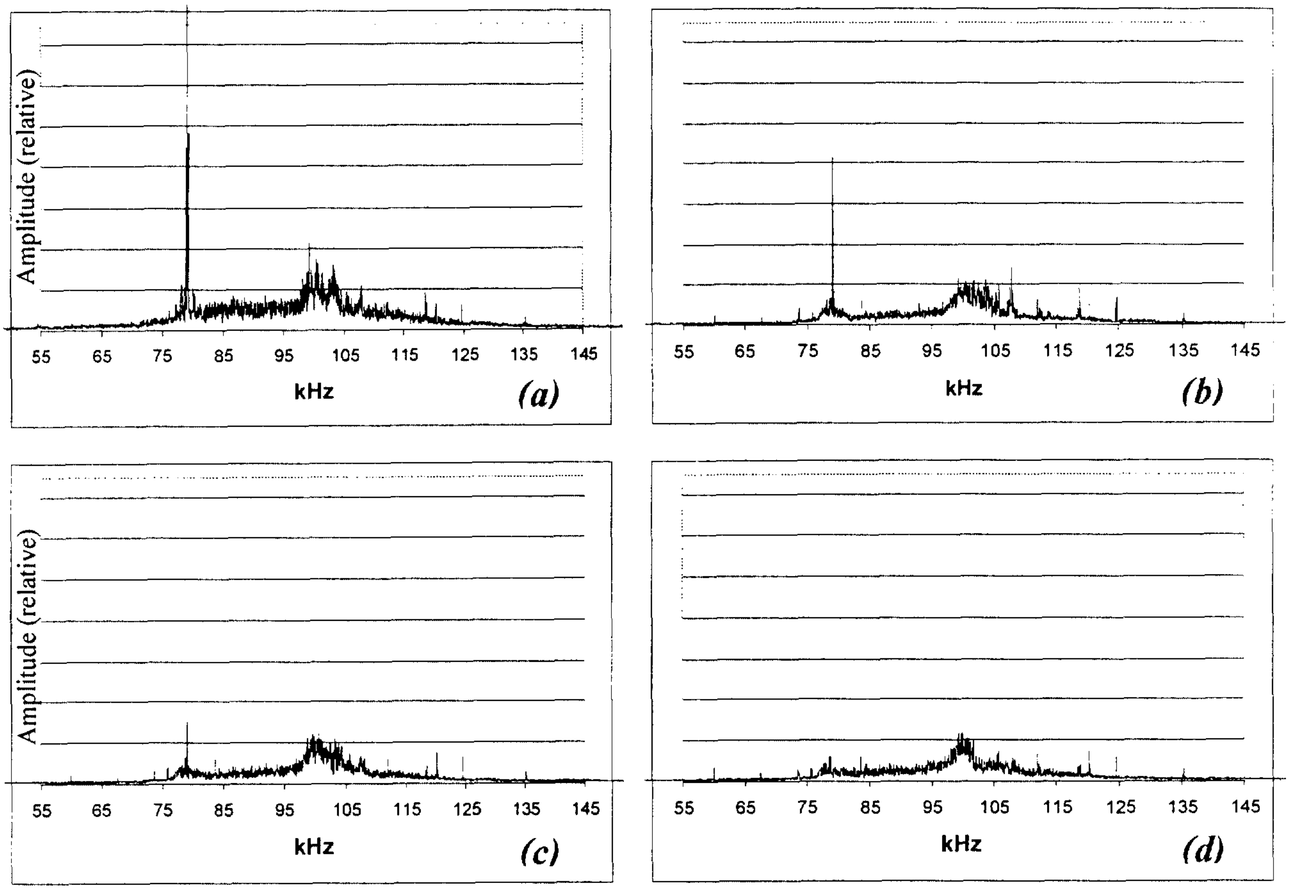

Figure 4. Time series of spectra generated by a new DSP-based receiver 1(**b**), 2 (**c**) and 5 (**d**) seconds after baseline spectrum (**a**). A linear amplitude scale is used on the ordinate although the large interferer in (**a**) is artificially compressed for illustration purposes.

V. Dynamic Position Updates

As a result of marketing competition, most Loran receiver specifications at least suggest they determine and report a new, independent position approximately once a second. Unfortunately, nothing could be further from the truth. In general, any receiver must spend some amount of time acquiring the data, processing it, determining a fix, and then passing that fix through the device. This is the same with GPS receivers, which are often over-specified as well.

For the linear receivers that our new DSP-based receivers will replace, the entire time needed to perform those tasks was approximately 10 seconds. In the case of the older hard-limited devices, which had considerably less processing power and speed, we suggest the delays were typically at least that long. In fact, our investigations of other receivers suggest some form of filtering was used to generate a smooth trace of positions, and each point was not determined independently of the others. Those receivers, and certainly some GPS receivers today, issued filtered positions at approximately 1 Hz. At least for the older Loran receivers, those positions were strongly influenced by data acquired many, many seconds earlier. In other words, those receivers issued positions/numbers based on data that were minimally 10 seconds old and, likely, very much older.

The situation was even worse for ECD determination, and that is one of the reasons Loran receivers had such a propensity to cycle slip, and their performance was often poor in areas where today, there is more than enough signal to determine the correct zero crossing. In fact, we have analyzed some Loran receivers that averaged ECD data for literally as long as the receiver was powered on, so the user could never be really sure any position generated was not cycle-slipped.

Fortunately, with use of the new DSP technology and other microelectronic components available today, these problems are eliminated, and Loran receivers can determine and generate truly independent position fixes about once per second. Furthermore, this position update rate can be generated in coverage areas larger than those shown on USCG service areas. In other words, new Loran receivers will offer dynamic performance comparable to GPS. In fact, we now estimate Loran could be used to speeds approaching the sound barrier, assuming good signal levels are present. **Table 3** summarizes the dynamics of position updates using old versus new Loran receiver technology.

Table 3

	Hard-limited	Linear w/o DSP	Linear w/ DSP
Data acquisition/processing	10 sec and up	5 sec	1 sec
Receiver pipeline delay	5 sec and up	5 sec	0.5 sec
Total receiver update rate with independent nav solution	15 sec and up	10 sec	1.5 sec

VI. Conclusion and Summary

Because hard-limited receivers clipped a large percentage of the data and accurate quantification of various aspects of Loran signals (e.g. signal level, zero crossing and ECD) was severely limited, those receivers were unable to generate reliable results with a high degree of statistical confidence. When linear receivers were introduced, they offered 8-bit ADC resolution and automatic gain ranging, so signal quantification and overall receiver reliability improved considerably. However, even those linear devices were severely processor-bound and consequently they discarded much available data. For example, processor limitations forced those receivers to discard up to 50% of available data from strong stations and up to 90% of available data from weaker stations. Since multichain crossrate lockout has been shown to be essential in reducing background noise and improves SNR ratios by 20 dB over hard-limited receivers[2], increasing processor power is another means to improve Loran performance significantly.

Locus' new DSP-based receiver is able to process approximately 90% of the available data from strong stations, and 50% from the weak stations. In other words, it can achieve the same level of confidence 2-5 times faster than an advanced, but now outdated, linear receiver. As indicated above, comparisons with the performance of hard-limited receivers are difficult because they did not quantify signals well and took inordinately long times to determine a viable confidence level. Suffice it to say that the new DSP-based receivers are at least an order of magnitude faster and, likely, much more.

In conclusion, Loran receiver technology has advanced considerably over the last 10 years, but it has by no means reached its technological and performance potential. New linear receivers based on DSP chipsets now provide processing power to acquire and process most of the available data from multiple chains and stations approximately once per second and generate highly reliable and accurate results. As microelectronics continues to evolve, Loran receivers will incorporate new capabilities that will enable them to acquire and process all available Loran data extremely rapidly. Although all aspects of Loran performance, including operation in dynamic applications, have advanced remarkably in the last several years, the next step in receiver evolution will improve performance further. That step will finally enable a receiver to process all available Loran data very quickly, and it is only then that we can realistically determine how well the entire Loran system can perform for navigation and timing applications, and as a complement to satellite systems.

Bibliography

Paul W. Schick, Senior Project Engineer
Mr. Schick is an honors physics graduate of The Cooper Union, New York, and holds a Master of Science in physics (electrical engineering minor) from the University of Wisconsin-Madison. His training has included electromagnetic fields, nonlinear waves, digital circuits, microprogramming, complex analysis, and symbolic manipulation of differential equations. He is the lead software engineer on the development of Locus' new DSP-based receiver. Mr. Schick holds several patents.

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