Metrological Use of Loran-C Navigation Receivers

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Abstract—The paper describes the performance of accurate time and frequency measurements based on the Loran-C system using commercial navigation receivers.

Techniques, criteria of choice, and suitability of commercial equipment, sources of errors, and experimental environment are discussed and some results are compared with similar ones taken at IEN (Istituto Elettrotecnico Nazionale), the national metrological laboratory. One of the two proposed methods does not require any alteration to the equipment, whereas with both of them continuous monitoring of all the transmitters of a chain is possible using a single receiver.

I. Introduction

In spite of increasing use of the GPS system for time and frequency dissemination, Loran-C still plays a role for the continuous monitoring of local frequency standards. In this application it is convenient to monitor more than one station for redundancy.

Moreover, reception of pure *time of arrival*—instead of the *time difference*—finds another possible application in one form of the so-called differential mode Loran-C navigation and/or positioning, where the readings taken in a surveyed position are used to correct the received positioning data. In both applications, the reception of more stations is needed and consequently a number of appropriate receivers must be available.

The aim of this paper is to present two possible solutions by which a general-purpose navigation receiver, in conjunction with a personal computer and some simple additional equipment, can solve the problem. The reader is assumed to have a basic knowledge of the Loran-C system; many good descriptions can be found in [1] and [2]. The navigation receivers are relatively inexpensive.

In the following sections methods, accuracy, and the experimental setup are discussed, and some results presented.

II. Methods and Techniques

A Loran-C receiver designed for navigation purposes is different in principle from metrological equipment: the former can measure the time differences between the secondary stations and the master, while with the latter it is possible to compare the absolute time of arrival of the pulses coming from a single station with the local time scale.

The metrological use of a navigation receiver implies overriding this limitation, taking advantage of the capability of simultaneously receiving more than one station.

A. First Method: Using Pulses Available Inside the Receivers

A navigation Loran-C receiver in many cases can be easily modified for metrological applications by extracting from it a trigger pulse, synchronous with the incoming signals. This approach is followed in the first method, in which measurements are performed by direct comparison, using a digital counter, of this trigger pulse with a group repetition rate generator, driven by a local frequency standard.

A basic knowledge of the block diagram and of the theory of operation of this class of receivers is needed. Many types of commercial equipment are based on the *hard-limiting* technique, where only the sign bit of the incoming signal is processed. The block diagram of Fig. 1 is a very typical subset of a receiver. With the diagram we can consider the following.

- The system clock has the typical value of 10 MHz, which provides the usual resolution of 100 ns.
- The programmable delay generator is a counter that provides both the tracking of signals and the group repetition rate.
- In a Loran-C pulse the phase is observed only in a window consisting of some contiguous bits taken by the shift register. The window is centered on the estimated position of zero crossing and is dynamically adjusted to track the signal. The window can be shifted in order to measure the envelope shape.
- Receiving a noiseless signal, the output of the comparator is a string of 0 or 1 depending on the sign. In the presence of noise, the statistical prevalences of 0 and 1 are symmetrical around the zero crossings, the time measurements being performed from the statistical distribution of the sign bit.

In [3] the reader can find a detailed description of the theoretical basis of this detection technique. Many receivers take phase measurements from a window of eight contiguous bits, but one bit for each pulse seems to offer similar performances because the signal is filtered (usually with a bandwidth of 20 kHz centered at the frequency of 100 kHz), and consequently the noise is highly correlated in the observation time, which typically amounts to less than 1 μs.

If the receiver is based on the above-described criteria, a suitable trigger pulse can be carried out from the equip-

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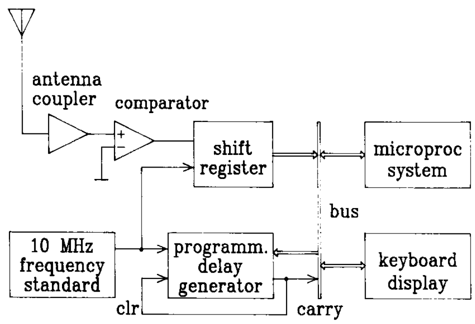

Fig. 1. Block diagram of a typical subset of a navigation receiver.

ment. The best candidate signals are the *clocks* of shift/D-type registers "near" the comparator, as well as the *clear* and *carry* signals of counters. An alternative can be the *interrupt request* signal, which can be sent to the processor with a constant delay (or advance) from the time of arrival of the Loran-C pulse, guaranteed by the hardware or by the time of execution of some firmware routines. An accurate inspection with an ocilloscope triggered by a group repetition rate generator, driven from the laboratory frequency standard, is adequate to identify the convenient point; if some doubt still remains, a frequency offset imposed on the oscillator inside the receiver can help to decide whether the pulses are locked to Loran-C or not.

Five commercial receivers, listed in Table I, were "disassembled" successfully in this way. Nothing should be inferred about criteria of choice among manufacturers or models: these pieces of equipment were available and were bought for quite different purposes. The reader should be encouraged by the consideration that the electrical diagram of the specific receiver is not necessary. So far, an unsuitable receiver has not been found.

Finally, the time resolution of the trigger pulses is the same as the receiver; consequently a high-performance counter will not significantly improve the overall results. The resolution should be the same as the receiver, so low-cost equipment is sufficient.

B. Second Method: Using a Loran-C Simulator

The second method is based on the injection of a local Loran-C like signal at the input of the receiver. The approach is similar to the well-known *self-calibration* technique, where the instrumental delay of the equipment is continuously monitored, but in our case the simulated signal is the main time reference supplied to the receiver. Moreover, Loran-C is a time division system designed for the simultaneous reception of at least three stations; the local reference can be added to the incoming signal in a free time slot, without any interference with normal operation.

This method does not require any intervention inside the receiver or knowledge of its electronic circuitry.

The receiver will be suitable if it has a digital output

TABLE I
COMMERCIAL NAVIGATION LORAN-C RECEIVERS CONSIDERED FOR TIME AND FREQUENCY APPLICATIONS

number	model	manufacturer	country
1	1024	Racal Decca	England
2	1028	Racal Decca	USA
3	9900	Texas Instruments	USA
4	200	Trimble Navigation	USA
5	LC 1500	King Marine	Japan

from which the time differences can be read by a computer; this happens in almost all practical cases.

A Loran-C signal simulator is needed, but its requirements are easy to meet: one station, the same GRR (group repetition rate) as the chain to be received, and external synchronization input. A simple and small piece of equipment has been developed for this particular application; technical details are available upon request. The specifications of the Loran-C transmitted signal, from which the specifications of a simulator can be extracted, are reported in [4].

During normal operation, the device receives master and n secondary signals of a chain ($n \geq 2$), measuring simultaneously the differences

$$TD_i = S_i - M, \qquad i = 1 \cdots n \qquad (1)$$

where S_i and M are the time of arrival of secondary and master pulses.

In the method proposed (Fig. 2) an auxiliary signal, corresponding to a simulated station and generated by the simulator, that is driven by the local time scale, is radiated near the receiving antenna or injected with a small coupling capacitance. The receiver will measure our signal without "knowing" that it is simulated. Consequently an additional time difference TD_{n+1} is available, from which the differences between the Loran-C signals and the local time scale can be calculated. The time differences are collected by the computer and averaged in order to statistically increase the resolution.

The timing equations, given in the next section, can be solved for all the stations, providing full monitoring of the chain received.

Most receivers compute geographical coordinates from the time difference and a problem arises because the "fake" signal does not fit in the table of the existing Loran-C transmitters. The receiver probably will provide all the time differences, with some warnings because the coordinates are thought to be wrong or cannot be computed at all.

In the worst case, the equipment rejects our misplaced signal. If this happens, the receiver can be used to track all the stations of a chain, except one. The simulated signal will be placed just *before* the weakest one; the *real* station will be treated as the *skywave* of the simulated one and rejected, in agreement with the theory of operation of the Loran-C system. The time gap should be chosen in order to avoid coherent interference between true and

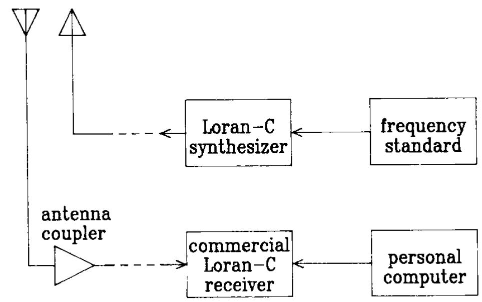

Fig. 2. Experimental setup used with the self-calibration approach.

simulated signals. Letting $t_1 = 150$ μs for safety purposes, $t_2 = 300$ μs (the length of a Loran-C pulse), $d = 1$ ms (the interval between pulses), and g the time gap (that is, the advance of the simulated signal with respect to the received signal) should satisfy

$$nd + t_2 < g < (n+1)d - (t_1 + t_2) \qquad (2)$$

where n is a non-negative integer; the value $n = 0$ is preferable. Moreover, with this strategy the simulated signal can replace the master station.

III. Accuracy Considerations

Neglecting noise and quantization, the timing equation of the first method can be stated as

$$v = r_c - d_a - d_l - d_r \qquad (3)$$

where v is the phase time difference between Loran-C electromagnetic field at the antenna location and the local time scale, r_c is the ideal reading of the counter, d_a is the delay of the active antenna, d_l is the delay of the coaxial cable link between the antenna and the receiver, and d_r is the delay of the receiver. The long-term stability seems to be limited by changes in the instrumental delay, mainly of the antenna coupler, which is exposed to weather variations. The experimental data of Table II, taken on a commercial coupler and measured at 30 μs from the starting point of the envelope, show a delay difference of 380 ns between -10 and $+50$°C.

For the same test conditions, simulating master and slaves, the delay of the receiver was 18.4 μs at 20°C, with thermal sensitivity between 6 and 7.5 ns/°C in the $+10$ to $+30$°C temperature range.

The value of d_r can be affected by systematic bias of the order of 100 ns due to nonlinearities in electronic circuitry, depending on the signal amplitudes. In [5] these problems are discussed.

As regards the second method, in the first approximation, the performance is independent of the instrumental delay of the receiving equipment because the receive signals and the local reference are processed by the same circuitry, including the antenna. Only the instrumental delay of the simulator is relevant from this point of view.

In the design of the simulator it is important to avoid filtering of the output signal and the presence of spurious signals around 100 kHz. The first condition keeps the instrumental delay as short as possible, and also minimizes its possible drift. If the second condition is satisfied, the filter inside the receiver will be sufficient to reject the spurious signals coming from the simulator.

TABLE II
Thermal Sensitivity of a Commercial Antenna Coupler (Device No. 2 of Table I)

temperature	group delay
−10°C	10.280 μs
+10°C	10.340 μs
+30°C	10.440 μs
+50°C	10.660 μs

Remembering that a navigation receiver can measure only time differences between Loran-C signals, we make a number of assumptions in deriving the timing equations:

- v is the estimated difference between local time scale and the Loran-C electromagnetic signal at the antenna position;
- r is the ideal reading of the receiver, i.e., noise-free read-out;
- (S) means simulated slave;
- (E) means simulated master;
- (X) means slave of the chain;
- (M) means master of the chain;
- d_s is the internal delay of the simulator, from GRI trigger output to the zero crossing at 30 μs from the envelope starting point;
- d_l is the delay of the coaxial cable;
- d_a is the delay of the antenna coupler, which is canceled in the equations;
- d_r is the delay of the receiver.

We can derive the timing equations as follows. For the master signal, when a slave is simulated

$$v^{(S-M)} = r^{(S-M)} - (d_s + d_l) - (d_r^{(S)} - d_r^{(M)}). \qquad (4)$$

For a slave signal, when another slave is simulated

$$v^{(S-X)} = v^{(S-M)} - v^{(X-M)}$$

which can be rewritten as

$$v^{(S-X)} = (r^{(S-M)} - r^{(X-M)}) - (d_s + d_l) - (d_r^{(S)} - d_r^{(X)}). \qquad (5)$$

For a slave signal, when the master is simulated,

$$v^{(E-X)} = (GRI - r^{(X-E)}) - (d_s + d_l) - (d_r^{(E)} - d_r^{(X)}). \qquad (6)$$

The delay of the antenna coupler is supposed to be independent of any parameter of the signals, and is canceled; in any event, the path is the same for received and locally generated signals. The coaxial cables between the laboratory and the building top are supposed to be equal in length.

The internal delays of the receiver are kept separated because of the dependency on the station as a consequence of the possible amplitude effect that has been mentioned. The systematic bias, represented by the terms inside the rightmost brackets in (4)–(6), can be eliminated for one station, master or secondary, setting an equal amplitude of the local signal.

If the internal frequency reference of the receiver has an offset or a drift, with $f = f_0(1 + \epsilon)$, the measured value r will be biased by a factor $(1 - \epsilon)$; the practical consequence is an error of 10–70 ns for each 10^{-6} unit of the relative frequency deviation ϵ. If possible, a high-quality external reference should be supplied.

Coherent interference, due to highly stable radio carriers, is possible, especially in Europe, where many time and frequency standard transmitters are active in the 50-150-kHz band; the situation should be evaluated in each case. The use of notch filters is allowed if they do not substantially alter the envelope shape; otherwise, since the receiver is fully automatic, the cycle identification may be unreliable.

The stability of the ground wave propagation is beyond the scope of this work. Many papers, such as [6], consider this aspect.

For high-accuracy timing purposes, the reader can refer to the periodical circulars [7], [8]. The former gives the TOC (time of coincidence), i.e., the time when the first Loran-C master pulse is coincident with the second of UTC; the latter reports the current differences between Loran-C chains and UTC.

IV. Experimental Setup

Both of the proposed solutions were tested with the same receiver, no. 2 of Table I. The local frequency standard was continuously monitored versus UTC(IEN), taking advantage of the short distance (6 km), with equipment that is not shown in the diagrams. This comparison was based on a VHF link, working at 160 MHz, with a resolution of 1 ns and an uncertainty of 10 ns peak to peak. The television method, with common view of the same transmitter, and a telephone cable link, working at 10 kHz, was used as a backup system. More details about the comparison system can be found in [9].

A. First Method

A block diagram of the experimental configuration is shown in Fig. 3.

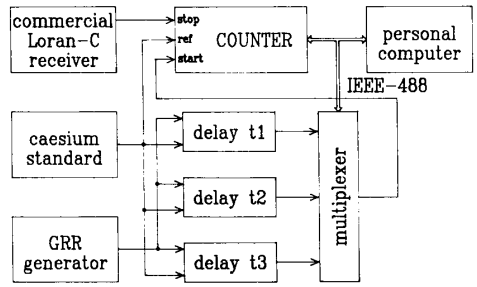

Fig. 3. Experimental setup used for testing the receiver with the direct measurement approach.

GRR and delay generators, which can be set manually, are very simple devices that can easily be built with standard parts. The delays $t1$, $t2$, $t3$ were trimmed to provide a pulse about 60 μs before the trigger pulse coming from the receiver, which, in this case, is the interrupt request.

The multiplexer is programmable, but this feature is unnecessary: a different setting of $t1$, $t2$, $t3$ allows the identification of the station from the readings of the counter, and a sequential free-running multiplexer will give the same results. For the monitoring of one station the delay generators and multiplexer are not needed.

The counter has a resolution of 100 ns, the same as the receiver. The resolution will be statistically increased by the computer.

Because of the internal time constant of the receiver, more than one reading per second will not give additional information. Consequently, any computer that can be interfaced will work with the required acquisition rate.

B. Second Method

The simulated signal was obtained by direct digital-to-analog conversion from an 8-bit memory mapped shape, which implements carrier, envelope, and phase inversions, at a sampling rate of 2.5 MHz. Between the converter and output a passive single-pole low-pass filter is used, cutting just below the Nyquist frequency.

All the digital hardware is made with synchronous counters and D-type registers, providing the minimum delay time between clock and output; the stability is guaranteed within 1 ns under laboratory environmental conditions.

The stability of the digital-to-analog converter used as the frequency synthesizer, a DAC-08, was tested under extreme conditions. Phase variations of ± 0.001 rad were measured in the temperature range between -10 and $+80°$C.

The amplitude, measured at the input of the receiver, was trimmed to be the same as the Estartit signal, the slave Z of the Mediterranean Sea chain, within 2 dB.

No problem arises from the computer because the data rate is very slow, of the order of five to ten values per minute. Despite this, it is recommended to protect the program from receiver or communication failures; the polling method usually works better than record-oriented procedures.

V. Results

The result we are interested in is the performance of the receiving system, avoiding, as far as possible, problems of long path propagation, drift of time scales, and so on. Keeping this target in mind, the differential approach was chosen, comparing the experimental values with the measurements obtained at IEN, with an accurate correction of the difference between the time scales. At IEN only time of arrival measurements are performed.

Daily measurements of the above-mentioned Estartit

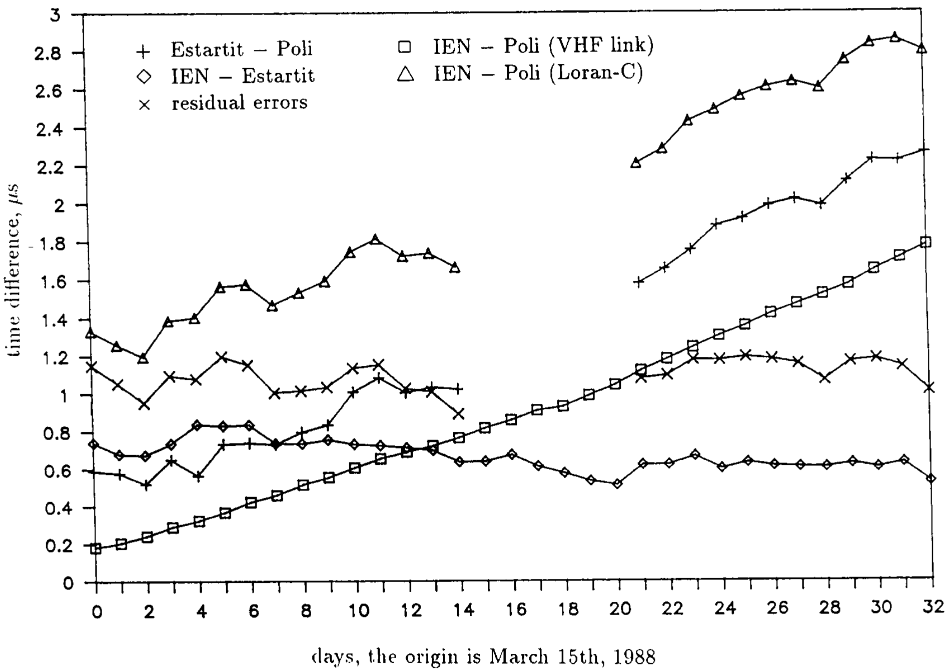

Fig. 4. Results obtained with the first method (certain values are missing because the receiver was stopped).

station were taken at the same time, 11h 00m UTC. The most significant difference between operating conditions is that IEN measurements, obtained from an Austron 2000 receiver, were averaged over 50 s, while at Politecnico it was necessary to use a far longer time constant centered around IEN measurements because of resolution problems.

Two assumptions were made, supported by calculations and experience: first, the difference in propagation anomalies from Estartit to IEN or Politecnico cannot be observed because the relative distance is around 1.2 percent of the entire propagation path. Second, the phase fluctuations of the received signals are "slower" than half the time constant, and their effects are negligible after the data fitting; this is due to the stability of the ground wave propagation and the frequency standards of the transmitters.

The results obtained from the counter are shown in Fig. 4, where each Loran-C value measured at Politecnico represents the average performed in one hour, and an arbitrary constant is added to each plot in order to use the same y scale. The graph is complex and we can extract much information.

First, a comparison of the day-to-day variations of the measurements taken at the two laboratories, observing the differences between contiguous values of the plots + and ◇, reveals that daily fluctuations of the values taken at the IEN are smaller by a factor of about 3. This is due to the difference between the receivers; at Politecnico two quantizations of 100 ns are cascaded.

Second, taking the difference between the curves + and ◇, plotted as △, we get a comparison between IEN and Politecnico time scales, performed with the common view of the same Loran-C transmitter. The slope of the plot △ shows a relative frequency difference of $5.8 \cdot 10^{-13}$ between the standards. The same comparison, performed with the high-quality VHF link (curve □), shows a relative difference of $6.1 \cdot 10^{-13}$, in close agreement with the previous value.

Finally, we consider the difference between Loran-C and VHF results (△ and □). It should be a constant value in a noiseless error-free experiment because the same time scales are simultaneously compared with two methods. In the real experiment, a residual variation (300 ns peak to peak or 50-ns rms) still remains, as shown by the plot ×. This fluctuation represents the stability of the entire system, including all the sources of errors: instruments involved at Politecnico and IEN, Loran-C differential propagation, and the additional uncertainty due to the difference between the averaging time constants.

A similar measurement was made using the data taken with the second method and adopting a time constant of half an hour. The results (Fig. 5) are presented in a slightly different way because the measurements performed at Politecnico were referred to UTC(IEN), which was "transported" by the VHF link. Plots + and □ represent daily measures taken in the two laboratories versus the same time scale, plus an arbitrary constant.

The difference between the values taken at Politecnico and IEN (plot ×) should be a constant value in an ideal

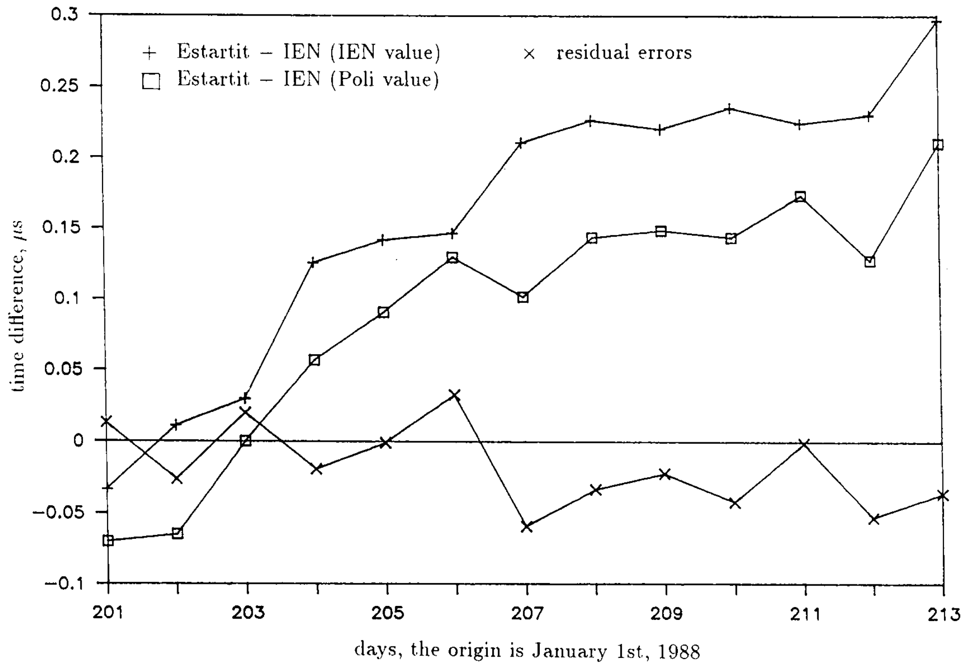

Fig. 5. Results obtained with the second method.

experiment. The residual fluctuation (90 ns peak to peak) represents the stability of the whole system, including all the sources of errors.

The plots × of the Figs. 4 and 5 have the same meaning and allow a direct comparison of the performances to be expected from the two methods.

VI. Conclusions

The monitoring of all the stations of a Loran-C chain is possible with a single navigation receiver with both of the methods.

A full test was performed on one of the receivers considered. All of the receivers are similar with regard to technology and internal parts. Consequently similar results can be expected.

The receivers were selected for quite different purposes before reflecting on this application. Five devices can be considered a significant subset of the 30–40 receivers commercially available, presuming similar design.

If long-term high stability in time monitoring is needed and the first method is preferred, the thermal effects on the antenna coupler should be carefully evaluated and possibly compensated; as an alternative, the antenna coupler can be replaced with a highly stable one.

The second method leads to a better measuring system because almost all dependence on the internal delay of the receiver and the antenna is removed. Losing the capability of tracking the weakest station, if it happens, is probably just an apparent handicap.

Comparing the reported results, the reader should be aware that the seasonal weather effects on the antenna, for the first method, will lead to bigger measurement errors during an entire year; this will *not* happen with the second method. No problems are foreseen for frequency monitoring.

Finally, both of the methods described are suitable for a disciplined frequency standard system, with single or multiple references.

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