Loran-C Chain and UTC Synchronisation

William F. Roland

(*PVT Associates*)

There has been much discussion recently implying that Loran-C chain synchronisation using 'System Area Monitor' (SAM) control and using 'Time of Transmission (or Emission)' (TOT or TOE) are incompatible mechanisations of Loran-C chain time management because of their differing impact on users. Further, the mechanisation of UTC synchronisation is described as either satellite (GPS/GLONASS) based or Loran Chain measurement based, thereby excluding integrated use of both techniques for reliability. These differences are not mutually exclusive. Well-defined chain synchronisation can logically apply all measurement and control techniques as well as providing improved accuracy. This paper defines synchronisation and describes the history of Loran-C synchronisation control and the current methods employed. The existence of Cesium Standards at Loran stations, and the recent introduction of digital signal processing receivers, have greatly changed the potential for extremely precise timing control, detection of extraordinary timing changes, and the maintenance of very tight UTC synchronisation. This paper describes a number of techniques for defining, observing and applying the various sources of timing information, optimising performance for users and simplifying implementation for service providers.

KEY WORDS

1. Loran-C. 2. Time Synchronisation.

1. INTRODUCTION. The verb 'to synchronise' is defined by Webster: 'to adjust the periodicities of two or more electrical or mechanical devices, so that the periods are equal or integral multiples or fractions of each other'. For the purposes of defining and controlling radionavigation signals, synchronisation is deemed to include both the adjustment of periodicities, and the adjustment of the times of the signal epochs. Note that the epochs marking the length of the periods are not required to be coincident, but the time offset between the epochs of two signals is significant. Also, note that practical synchronisation specifies tolerable errors in the periods, rate of change of the periods and the time offsets between the epochs of the signals from each station. In Loran-C system control, if these parameters are not correct they are adjusted to maintain errors below some tolerance level. Alternatively, as in the GPS control, the difference and rate of change of difference of the periods and epochs may be made known to the user by communication link.

In a navigation receiver, it is essential that the synchronisation data are available. The GPS receiver obtains synchronisation data nearly continuously, from the communications channel in the signal from each satellite. The Loran-C receiver uses data

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that are published and burned into a PROM when the receiver is built. The Loran-C data consist of the locations of all transmitting antennas, the period for all stations in chain (GRI) and the 'emission delay' (ED) of each Secondary epoch with respect to the Master epoch. Loran-C synchronisation to UTC is contained in the signal definition. ED is approximately the sum of the 'coding delay' (CD) (equal to 'Secondary baseline-extension time difference' (TD (SBLE)), and the propagation time from the Master station to the Secondary station. ED is determined by the timing devices at the Secondary station, and generally is adjustable, locally or by remote control, over a small range. These adjustments are the means of controlling the epoch offset portion of synchronisation. The periodicity (frequency) is controlled by adjusting the cesium time-standard frequency.

The propagation velocity is subject to variability due to the dependence on the earth's surface conductivity and atmospheric conditions. Nominal propagation velocity (v_0) is empirically determined at the time of establishing the chain. In North America and Asia, the ED of each Secondary is set so that a specified 'controlling standard time difference' (CSTD) is observed at the 'system area monitor' (SAM) station. In Europe, the CD for each Secondary signal is set so that the ED with respect to the Master epoch is maintained. The subtle difference between these control strategies will be clear later. Figure 2 depicts the timing relationships within a Master–Secondary station pair.

Synchronisation with respect to UTC is measured and controlled such that the Master signal epoch (MREFA) coincides with the UTC epoch at certain one-second epochs of UTC, called 'times of coincidence' (TOCs). The Secondary signal epochs are offset with respect to the UTC one-second epochs in the amount of the ED. See Reference 1 for a discussion of the computation of TOC and un-TOC second offsets.

2. LORAN-C SIGNAL EPOCH.

The Loran-C signal epoch is defined as the third positive-going zero crossing of the first pulse in the 'A' group of the electrical signal being observed. For purposes of measuring and controlling signals within a Loran-C transmitting station, the transmitting antenna current is the reference. Current is defined in the classical sense in that 'positive-going' is taken to mean electron flow increasing out of the antenna. For purposes of measuring and controlling 'signals-in-space', the radiated field is the reference, and positive-going zero-crossing refers to the far electric field, and the corresponding zero-crossing of the magnetic field. Far field is only observable without significant near field contamination at three or more wavelengths away from the transmitting antenna.

It should be noted that the phenomenon of radiation causes an advance of the RF phase in the far field by 2·5 microseconds (μs). This results in an earlier far field epoch than would be calculated by using the theoretical speed of light and the epoch of the antenna current. This is a phenomenon of nature, not an error.[2] Since the far field cannot be measured in the immediate vicinity of the transmitting antenna, chain calibration, initial settings and control must be considered with care. Measurement of the 2·5 μs shift is difficult, requiring a transportable cesium clock.

3. GEOMETRIC CONSIDERATIONS.

Figure 1 represents a nominal Master Station and one Secondary Station. Geographically, the references for locating the sites are the latitude and longitude of the transmitting antenna at each site. The line connecting them is a great circle on the Earth's surface, and is called the

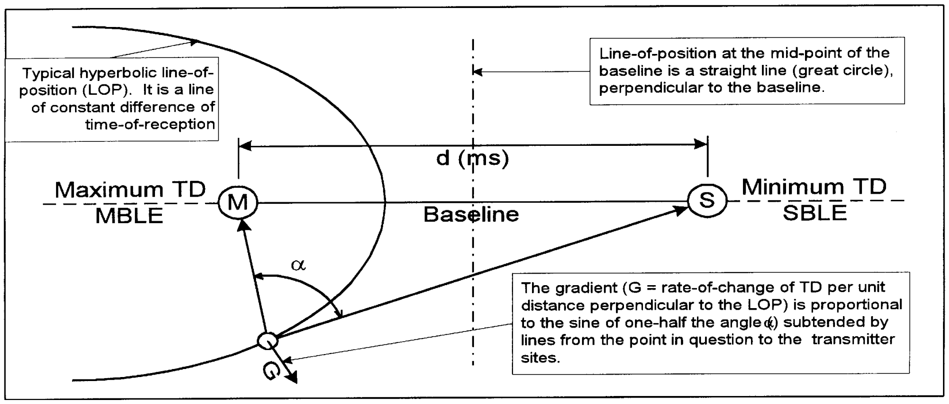

Figure 1. Naming conventions for Loran-C geometry. (Note the diagram is planar, but in reality these are lines on a spheroid.)

'baseline' (BL). All time difference lines pass through the baseline, perpendicular to it. When the baseline is extended through the station, it is called the 'baseline extension' (BLE). On the baseline extension, the time difference between the signals from the two stations is constant. When moving across the BLE, the time difference goes through either a minimum or a maximum depending on whether crossing the Secondary BLE (SBLE) or the Master BLE (MBLE) respectively.

4. LORAN-C CLOCK. The Loran-C clock is a representation of the period of the Loran-C signal[1]. The period is called the 'phase code interval' or PCI. It represents the period of time over which the complete state of the signal repeats. Dividing the output of a reference (cesium standard) oscillator to obtain the PCI generates the Loran-C clock. The clock counters are gated to generate the necessary transmitter triggers to cause appropriately timed and shaped pulses of antenna current to be generated. The antenna-current epoch (third positive going zero crossing of the first pulse of the 'A' phase code interval) is adjusted by changing the gating time of the transmitter triggers to cause the epoch to coincide with a reference trigger from the Loran-C clock. This local closed-loop control at the transmitting station is called the 'cycle compensation' loop, or 'cycle-comp'. Cycle-comp adjusts the time-of-transmission of the Loran-C signal so that it is synchronised to the transmitting station's Loran-C clock. The resolution of the cycle-comp is either 10 or 20 nanoseconds (ns) depending on the manufacture of the timer. It should be noted that all Loran-C and Chayka transmitting control systems synchronise the Loran-C clock and only indirectly the antenna current and radiated signal epochs. It is the Loran-C clock, which is either SAM or TOT controlled.

The Loran-C clock synchronisation may be adjusted by varying the frequency of the cesium standard output (AFC control) and/or the timing of the clock triggers to the transmitter (local phase adjust, LPA). The LPA control provides for adjustment of the offset of the Loran-C clock with respect to the local cesium standard. AFC control of the cesium standard frequency is provided by a 'phase micro-stepper' that is capable of adjusting frequency to a resolution of 1 part in 10^{15}, or approximately 0·31 ns per day.

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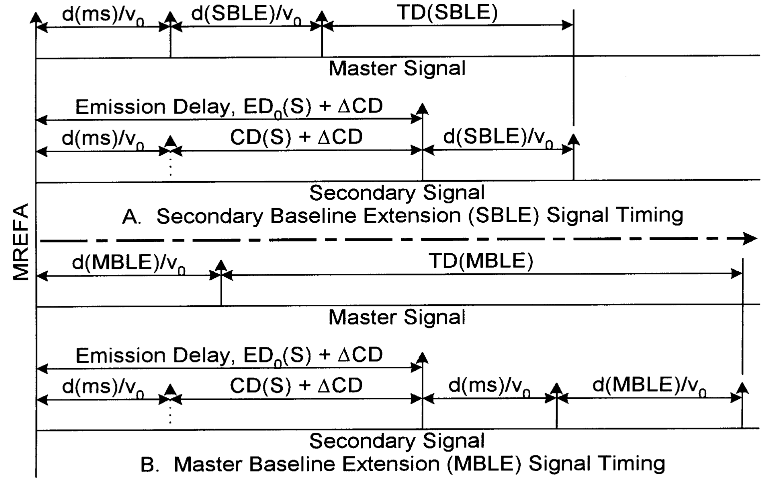

Figure 2. Signal timing diagram for baseline extension time difference observations.

5. BASELINE TIMING DIAGRAM. The timing diagram, Figure 2, illustrates the parameters involved in calculating the time differences that will be observed on the baseline extensions. Equations 1–6 show how the measurement of the BLE time-differences enables calculation of the mean velocity (v_0) of propagation, and then the actual coding delay ($CD_0 + \Delta CD$ in Figure 2). ΔCD is the clock synchronisation error at the Secondary station, and CD_0 is the nominal (advertised) coding delay at the Secondary station. MREFA is the timing reference for the Loran-C chain, and is the third positive going zero crossing of the first pulse in the A interval of the transmitting antenna current at the Master Station.

5.1. *Baseline Extension Timing Equations:*

$$\mathrm{TD(SBLE)} = [\mathrm{ED(S)} + \Delta\mathrm{CD} + \mathrm{d(SBLE)}/v_0] - [\mathrm{d(ms)}/v_0 + \mathrm{d(SBLE)}]$$

$$= \mathrm{ED(S)} + \Delta\mathrm{CD} - \mathrm{d(ms)}/v_0 \quad (1)$$

$$\mathrm{TD(MBLE)} = [\mathrm{ED(S)} + \Delta\mathrm{CD} + \mathrm{d(ms)}/v_0 + \mathrm{d(MBLE)}/v_0] - [\mathrm{d(MBLE)}/v_0]$$

$$= \mathrm{ED(S)} + \Delta\mathrm{CD} + \mathrm{d(ms)}v_0 \quad (2)$$

$$\mathrm{DIFF} = \mathrm{TD(MBLE)} - \mathrm{TD(SBLE)} = 2 \times \mathrm{d(ms)}/v_0 \quad (3)$$

$$\mathrm{SUM} = \mathrm{TD(MBLE)} + \mathrm{TD(SBLE)} = 2 \times \mathrm{ED(S)} + 2 \times \Delta\mathrm{CD} \quad (4)$$

$$v_0 = 2 \times \mathrm{d(ms)}/\mathrm{DIFF} \quad (5)$$

$$\Delta\mathrm{CD} = (\mathrm{SUM} - 2 \times \mathrm{ED(S)})/2 \quad (6)$$

These equations are derived directly from Figure 2. ΔCD is introduced to represent timing control or timing errors that change the Secondary signal's ED from the standard. The variable 'S' represents the Secondary station letter code (V, W, X, Y, or Z).

6. SHORT HISTORY OF SYNCHRONISATION. Loran synchronisation has been approached in a variety of ways. The first Loran-A stations used full time watch-keepers who observed the alignment of Master and Slave pulses (Secondaries were called Slaves until 1969, when they were freed!). The watch-keeper at the Slave station observed the Master and the local pulses on an oscilloscope,

which was triggered by the local timer. He continually adjusted the phase of a crystal oscillator to maintain the alignment of the pulse-envelope leading edge of the remote Master signal, and the locally transmitted signal.

By the late 1950s, the technology to provide automatic tracking of the signals had been developed, relieving the 'scopies' of their routine tasks. The crystal oscillator frequency was adjusted automatically, to maintain alignment at the Slave station. The Master station oscillator was not adjusted, except that the oscillator in the standby timer was adjusted to maintain synchronisation with the on-air timer, thereby minimising the impact of switching timers.

In the early 1960s, with the advent of Loran-C, and its demands for accuracy of a few tenths of a microsecond, it was necessary to develop precision, continuous, carrier-phase tracking 'timers' for the Secondary stations. These timers compared the time difference between the Master and Secondary stations' RF carrier signals, at the Secondary station. The timer continuously adjusted the frequency of the crystal oscillator signal to maintain epoch alignment. Synchronisation to UTC was not considered until after cesium standards were introduced to the stations in the late 1960s.

Each of these control schemes measures and adjusts the coding delay (CD), without regard to propagation conditions. Because propagation velocity variations became apparent during research, it was decided that 'System Area Monitor' (SAM) stations should be established near the operating centre of the Loran-C chain coverage area. The SAM's were equipped with precision Loran-C receivers. Watch-keepers at the SAM would observe the 15-minute average time differences for each Secondary. If the time difference average was different from the 'Controlling Standard Time Difference' (CSTD) by more than the control tolerance, the watch-keeper would call for a change to the coding delay at the Secondary station. This action was called a 'local phase adjust' (LPA), referring to changing the RF carrier phase. This control compensated somewhat for propagation velocity variations by setting the time differences to the correct value for accurate coordinate conversion in the area adjacent to the SAM. It was considered that this form of control would make coordinate conversion less accurate in other regions of the coverage area.

The installation of cesium standards at the transmitting stations brought some semblance of order by reducing the need for LPAs occasioned by the differences between oscillators at distant stations. The cesium standards also provided the opportunity to bring the Loran-C frequency into synchronisation with UTC. Generally, frequency was kept within 1 part in 10^{12}, or about 100 ns per day. By the mid-1970s, the US Naval Observatory was equipped to observe the timing of the transmitted Loran signals, and brought the signals to within $\pm 1 \mu s$ of UTC.

Time-of-transmission (TOT) control is a relatively recent innovation, implemented in the Northwest Europe Loran-C Service (NELS). TOT uses the 'Sum' and 'Diff' described above to control the timing of the transmitted signal, such that the ED is maintained constant. Because ED is held constant, the TD (MBLE) and TD (SBLE) will vary when the propagation velocity varies. No information on velocity variation is currently made available to the civil user.

7. CALIBRATION, COORDINATE CONVERSION AND ACCURACY. Coordinate conversion is a transformation of time difference coordinates to latitude and longitude coordinates. The relationship depends first on

precise knowledge of the latitude and longitude of the transmitting antenna. Secondly, the relationship depends on the ability to convert time measurements to distance, which in turn requires knowledge of each signal's epoch and its velocity of propagation. The antenna lat/long data are published with sufficient accuracy to satisfy all potential Loran-C accuracy requirements, and so will not be discussed further. The timing and velocity information, however, is not fully defined in current published data. These data are also variable with time, further diminishing their effectiveness.

The following discussion shows that currently published data are not sufficient to determine geographic position with the best accuracy. Additionally, it is proposed that data exist on each transmitting station, which if communicated to the users, will permit them to resolve completely both signal epoch and mean propagation velocity. This can be done without the necessity of the service provider implementing inter-station communications. As a further benefit of these data, repeatable accuracy will also be improved.

7.1. *Chain Calibration*. Chain calibration is the process by which the service provider develops the control parameters and then publishes data associated with a new Loran-C chain. First, a time transfer process is used to establish the initial setting of each transmitting station Loran-C clock. Then simultaneous measurements are made of the TD (MBLE), TD (SBLE) and TD (SAM) for each pair in the chain. The published timing data include only ED (S) and CD (S), which are derived from the measured data. The published mean baseline propagation velocity (v_0) is the velocity of propagation over seawater, which generally does not accurately represent the true v_0. The TD (MBLE) is not generally published.

To convert observed time differences accurately to latitude and longitude, or some other relationship to the Earth, the relationship between time and distance of propagation must be known. Over a smooth homogeneous Earth, the value of propagation velocity may be accurately measured and provided to the coordinate conversion process. Also the relative times of transmission can be accurately measured and controlled to assure that the time difference line-of-position remains stationary on the Earth's surface. However, nature is not so co-operative. Mountains, fjords and farmlands each affect the velocity of propagation, presenting a daunting task for the conversion routines. The manufacturer and therefore the user must use the published ED (S), CD (S) and v_0 for coordinate conversion. Some more advanced coordinate conversion routines provide a means to provide accuracy improvements through ASF (additional secondary factor) correction tables. ASF tables may be generated from a coverage area survey during calibration. These have not proved satisfactory from either the ease-of-use or the accuracy standpoint.

7.2. *Coordinate Conversion* (*Geographic*) *Accuracy*. Consider the accuracy of coordinate conversion along the baseline. Assume for now that the velocity of propagation is uniform along the baseline, but less than seawater velocity. Near the Secondary end of the baseline, where the coding delay is maintained constant, the accuracy of coordinate conversion will be quite good, while at the Master end, the coordinate conversion will be worse (see Figure 3).

If the user knows ΔCD (MBLE), or the real velocity (v), then the user can eliminate errors due to propagation. When a SAM is controlling the Secondary signal's coding delay, then the error line shifts up or down, but maintains its shape, depending on propagation velocity changes on the paths to the SAM.

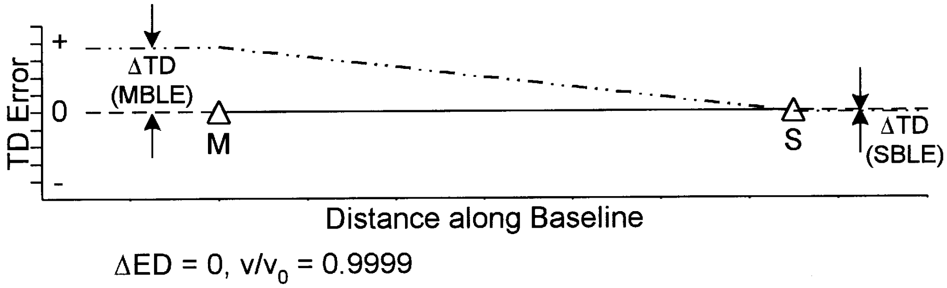

Figure 3. User observed TD error when CD is held constant and velocity less than published.

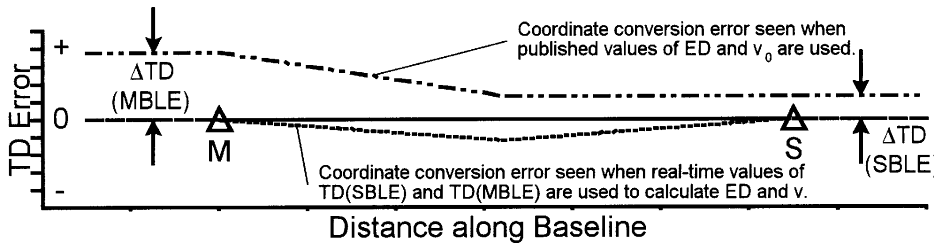

Figure 4. ΔED is positive, shifted positive by the SAM control. (v/v_0 = 0·9999 on 1/2 the BL; = 1·0000 other half.)

It is more realistic to consider a variable baseline propagation velocity. A simplified assumption is that there are two parts of the path, one over water and the other over good soil. Figure 4 shows a possible propagation velocity variation, and the resulting TD error curve.

It is interesting to note that the most severe errors will occur near the Master station, which is usually considered the most accurate region of the coverage. It is apparent that user knowledge of the TD (SBLE) and TD (MBLE) can provide considerably improved accuracy in the coverage area, particularly over land propagation paths.

7.3. *Current Operation and Accuracy*. With the current synchronisation data consisting only of coding delay (nominal TD (SBLE)) and seawater propagation velocity, there is a limited number of alternatives to improve accuracy:

(a) The receiver manufacturer may provide the ability to enter ASF corrections that impose a known offset on the observed time differences in a particular region. This technique requires tables of offsets as a function of latitude and longitude. To create the tables, either the manufacturer or the user must survey a region and determine the corrections at closely spaced points. No manufacturers have committed to such surveys.

(b) NOAA has made limited surveys along US coasts and used this data to publish charts. The magnitude of corrections compared to the scale of the charts is such that only on the very largest scale charts is it possible to notice a significant improvement in accuracy. The data were also made available in limited distribution publications. No electronic data files of these data are generally available.

8. PROPOSED ACTION TO IMPROVE GEOGRAPHIC ACCURACY. The accuracy of Loran-C is affected by the regional conditions

described above, and further by local propagation conditions associated with re-radiation from structures and distinctive geological features. It is intended to propose only that action which addresses synchronisation and regional conditions. There are improvements to Loran-C geographic accuracy that can be accomplished today without changing the current chain synchronisation methods. It is necessary to develop and implement a data broadcast that provides the synchronisation data. The Loran-Comm communication technique, called *Eurofix* [3] developed at the Technical University of Delft offers immediate access to a communications technique, without requiring additional infrastructure. A *Eurofix* message, which carries the necessary data, must be specified. The following is a recommendation for a first step.

8.1. *Data Requirements*. As shown in equations (1) through (6) above, with TD (SBLE) and TD (MBLE) the mean baseline velocity and the Secondary station clock offset (v_0 and ΔCD) can be determined. In order to transmit the latter from a station, there must be communication between stations. That is, a station can only calculate v_0 and ΔCD if it receives the TD (*BLE) from the other station. On the other hand, if the TDs are transmitted directly then both the Master and Secondary can read each other's messages and know what is the current synchronisation situation. It will then not be necessary to transmit v_0 and ΔCD, as the user can also calculate v_0 and ΔCD. The needed data may be provided either as complete data with all digits, or with published nominal values and data messages that provide real-time corrections to the nominal values. The latter is to be preferred for two reasons: first, the number of bits is reduced, allowing faster updates for a given data rate, and second, no matter how improbable, any message errors will have lesser effects.

8.2. *Proposed Implementation*. Therefore, it is proposed that the published Loran-C data, regardless of the synchronisation method, include the nominal baseline-extension time difference for every pair in every chain. It is proposed that every station transmit, using a new *Eurofix* message, the measured difference between the observed TD (*BLE) and the nominal. User equipment that uses the enhanced Loran-C data will be able to decode the *Eurofix* data message, calculate the current v_0 and ΔCD and apply these values in determining position and time.

8.3. *Future Considerations*. The magnitude of the improvement possible with this technique has yet to be determined. The potential exists to improve accuracy significantly in areas near baseline extensions, such as Southern Florida and Southern California. A measurement programme is required to evaluate the technique fully.

Cross-chain TDs have only recently become available. The technique of publishing nominal TD (*BLE) is equally valid in cross-chain measurements. In addition, it reduces the need to provide precise UTC synchronisation to gain reasonable accuracy. This application can be demonstrated with current multi-chain receivers and *Eurofix* communication. There is the potential to gain a great deal more information on propagation velocity by using this technique between Secondary stations in a chain. As more paths are analysed, the knowledge of velocity in inter-baseline regions becomes possible, further improving accuracy. It is possible to simulate the effects mathematically and determine the potential of this improvement.

Ultimately, there will be a need to survey difficult regions, and create a database of smaller scale propagation anomalies. This could result in improved accuracy in urban and mountain regions. By relating it to regional propagation, the magnitude of these local corrections can be reduced.

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