TIME AND FREQUENCY ADJUSTMENT ON THE LORAN-C SYSTEM

by

LCDR Cyrus E. Potts

LCDR Potts is with the Systems Development Branch, Electronics Engineering Division, U.S. Coast Guard Headquarters, Washington, D. C.

This paper describes the time and frequency adjustments which are presently being made on the Loran-C system and those which will be made when some newer, more sophisticated equipment has been installed. Last year, the Loran-C system used as a medium for the dissemination of precise time and time interval was discussed in some detail, and is available in the proceedings [1]. This paper concerns itself with time and frequency performance and adjustments on the Loran-C system.

As a brief review, a Loran-C chain consists of a master and two or more secondary stations, as shown in Figure 1. In the hyperbolic navigation mode, constant time differences (between receipt of master and secondary station signals) form lines of position which are hyperbolas. A user measures the time difference between receipt of the master and secondary signals and determines a line of position. This measurement is repeated for another master-secondary pair. These measurements then establish a position in the Loran grid.

The basic characteristics of the Loran-C system are:

- Center frequency of 100 kilohertz with a bandwidth of 20 kilohertz.

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1 C. E. Potts, "Precise Time and Time Interval (PTTI) Dissemination via the Loran-C System," Proc. Precise Time and Time Interval (PTTI) Strategic Planning Meeting, Volume 1, December 1970, pp. 32-54.

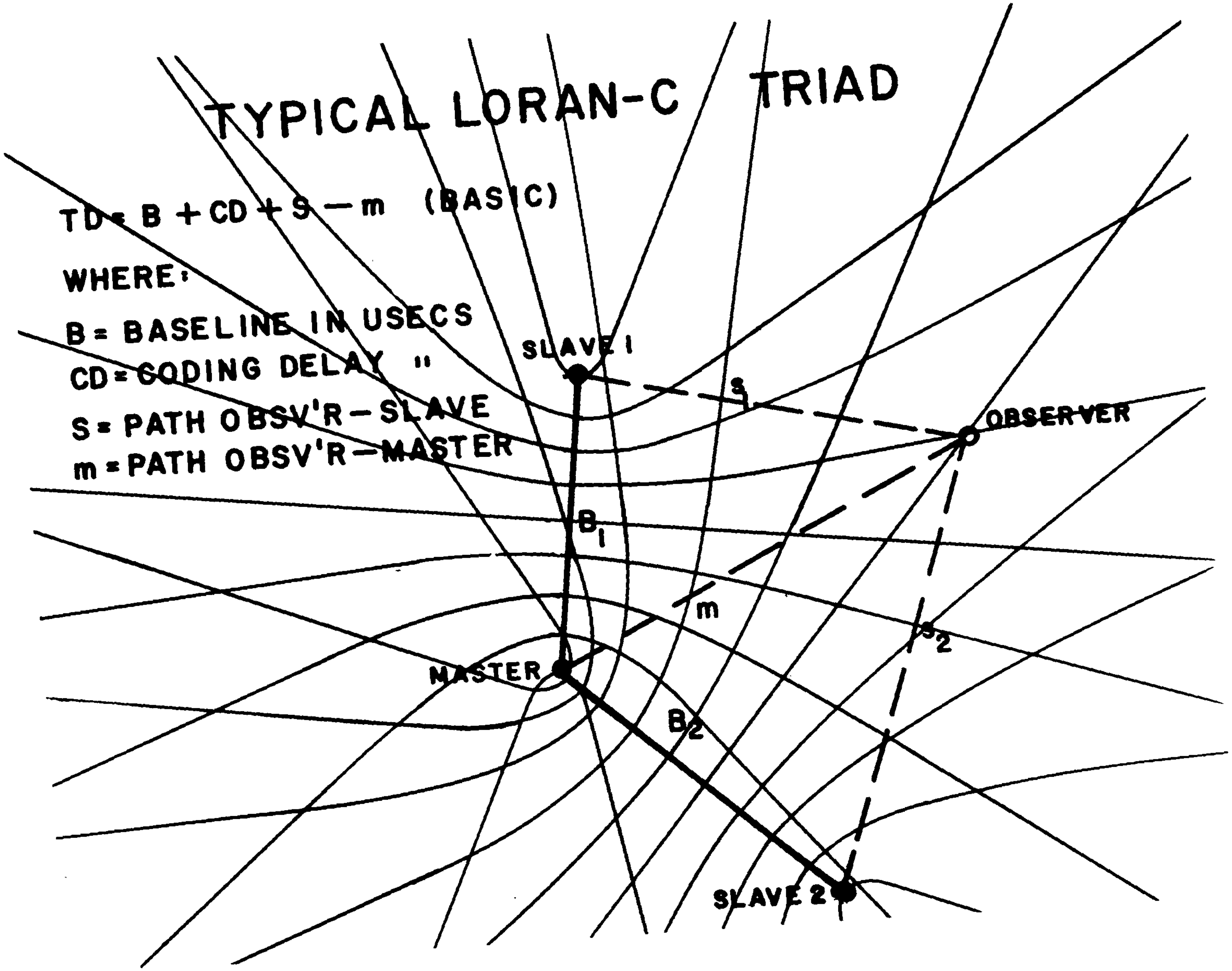


Figure 1. TYPICAL LORAN-C TRIAD

- Pulse leading edge which approximates the expression: $e(t) = t^2 \epsilon^{-\alpha t}$.

- Eight pulses per group (separated by 1000 microseconds) except for the master station which transmits a ninth pulse 2000 microseconds after the eighth pulse as an identifier.

- Group Repetition Interval (GRI) which varies from approximately 50,000 microseconds to 100,000 microseconds, chosen to maximize the signal-to-noise ratio for a given coverage area.

- Secondary stations synchronized to the master station in carrier phase, usually to a tolerance of 200 nanoseconds (3σ).

Loran-C coverage is a little difficult to describe since one needs to specify whether the interest is in hyperbolic navigation coverage, range-range (rho-rho) navigation coverage, or time and frequency dissemination coverage. An example of the types of coverage is presented in Figure 2 for a Loran-C triad (3-station chain). The hyperbolic navigation coverage is indicated by the fully cross-hatched area. The user must receive the signals from all three stations and the crossing angles of the hyperbolas must be large enough to permit accurate fixes. For rho-rho navigation the user need only receive the signals from any two stations, thus the coverage area is greater as indicated by the shaded area. A user interested in time or frequency need only receive one station so the coverage for this usage is that bounded by the outermost circles.

There are two types of time dissemination services provided by Loran-C. The first is a single pulse per second (1 pps) transmitted by Universal Time Coordinated (UTC) synchronized Loran-C master stations. The second type service is provided by the Loran-C pulse groups, the first pulse of which is synchronized periodically with the Universal Time Second (UTS, a second on the UTC scale). A null ephemeris table published by the U. S. Naval Observatory (USNO) tabulates the times that

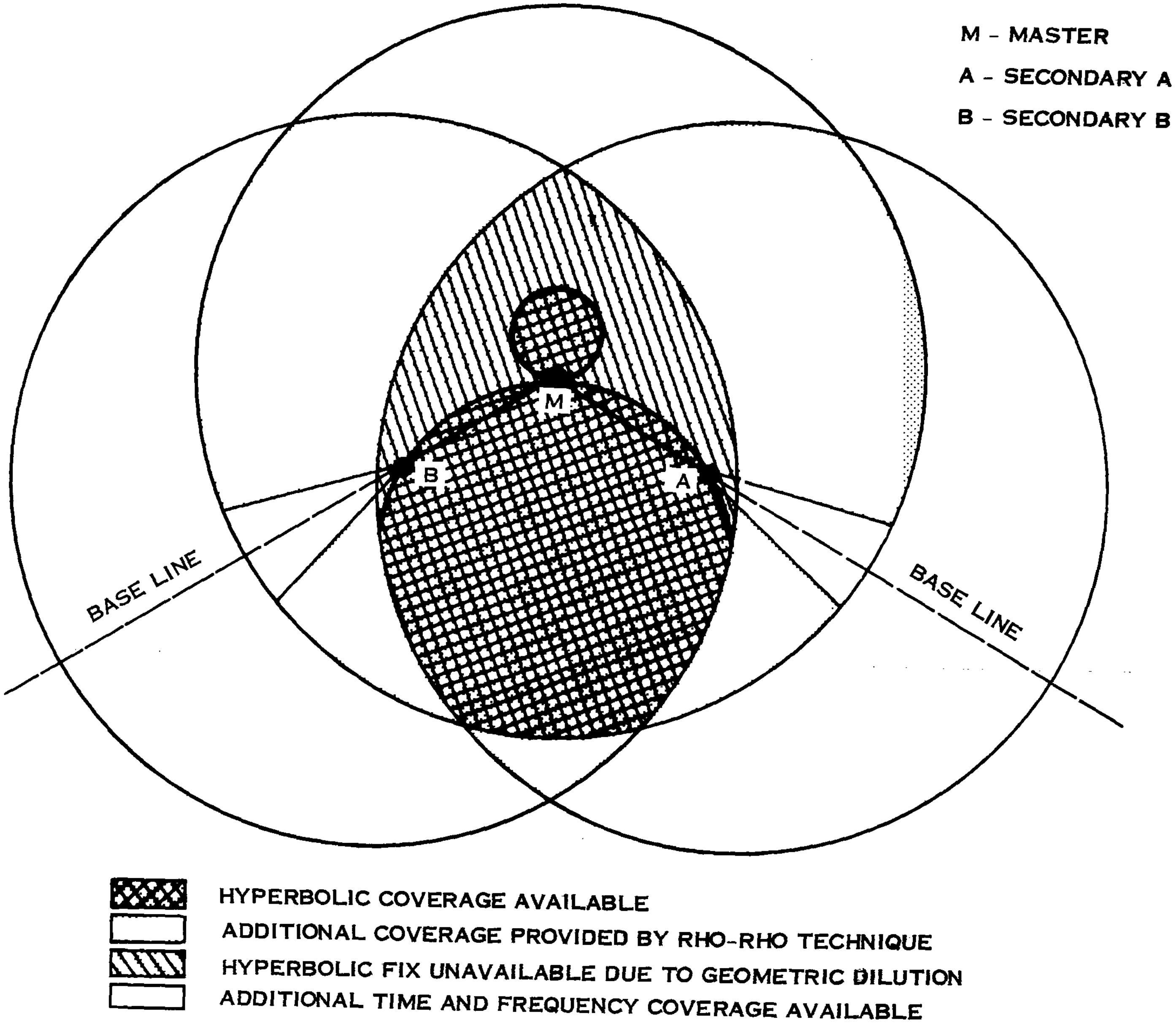


Figure 2. LORAN-C COVERAGES

the Loran-C pulse groups are coincident with the UTS. Null ephemeris tables for any Loran-C rate are available from the USNO upon request. Figure 3 illustrates the timing of the Loran-C pulse groups.

The instrumentation system shown in Figure 4 would be used to recover time information from the Loran-C 1-pps transmissions. This type of instrumentation is used when the user is within range of the master station and in an area where the signal-to-noise conditions are favorable. If the user is fairly close to the master station the band pass filter may not be necessary. The RF information is presented to the oscilloscope vertical amplifier and the oscilloscope is triggered by the user's clock at a 1-hertz rate (1-pps). The oscilloscope trace starts coincident with the user's clock pulse and the Loran-C 1-pps transmission appears later on during the sweep. The elapsed time between the start of the trace and the occurrence of the Loran-C 1-pps will be the sum of: the propagation delay from the Loran-C transmitting antenna to the user's site, any receiving equipment delay, the Loran-C phase value for that day, and the user's clock error. Since the first three factors may be ascertained readily, the remaining factor provides the user with his clock error.

To utilize all eight pulses within the Loran-C pulse groups, a little more equipment is required as shown in Figure 5. In this case, a counter is triggered by pulse occurring at the Loran rate and synchronized to the USNO null ephemeris tables. The stop triggers to the counter also occur at the Loran rate and are phase locked to the received Loran-C signals. The time interval counter displays the sum of: the propagation delay from the Loran-C transmitting antenna to the user's site, the receiving system delays, the Loran-C phase value for that day, and the user's clock error. If the signals from a secondary station are being received and tracked, the reading also includes the emission delay of the secondary station (published constant delay). Thus, the user's clock error is readily determined.

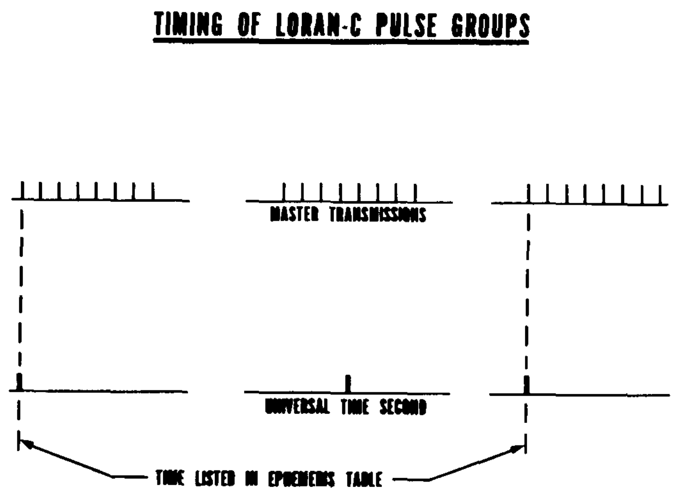


Figure 3. TIMING OF LORAN-C PULSE GROUPS

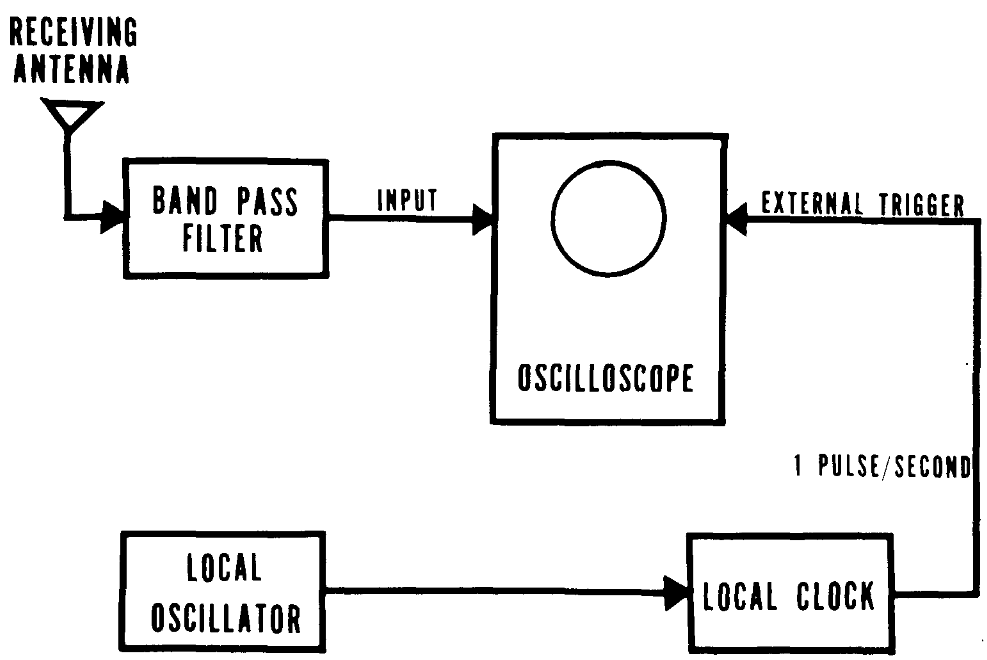


Figure 4. INSTRUMENTATION FOR ONE PULSE/SECOND SYSTEM

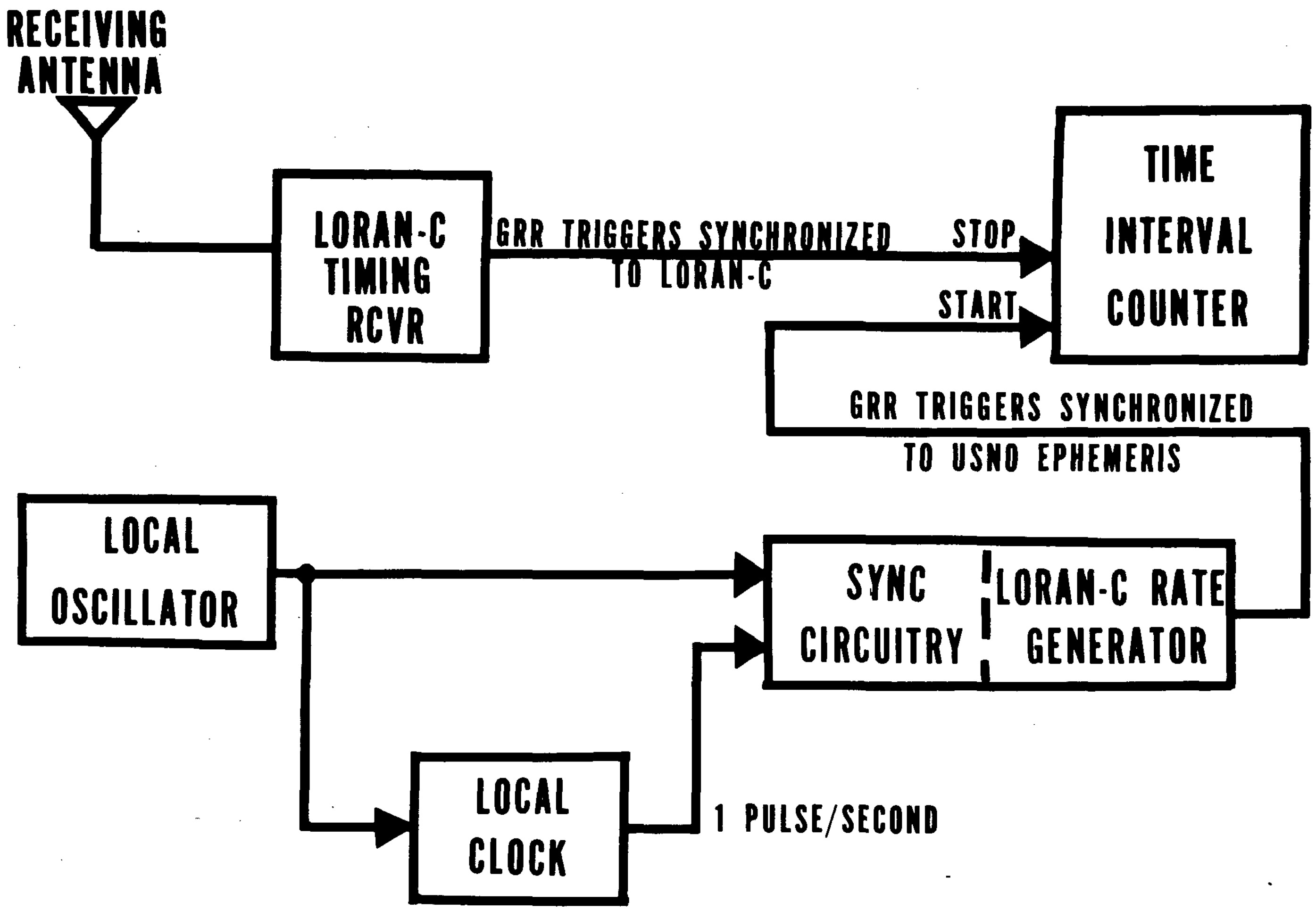


Figure 5. INSTRUMENTATION FOR UTILIZATION OF LORAN-C PULSE GROUPS

The daily Loran-C phase values are published by the USNO and indicate the time relationship between the individual Loran-C chain transmissions and the USNO master clock (UTC(USNO)). A plot of these published (USNO Daily Relative Phase Values, Series 4) values provides a user with valuable historical information on the frequency offset of the Loran-C chain with respect to UTC(USNO), and the time relationship 'UTC(USNO) - Loran-C Chain' (daily phase value) which he needs for calculating his own clock error. Table I shows the results of an analysis of the published daily phase values for six of the Loran-C chains. Periods were chosen which were free of adjustments or malfunctions and linear regressions were performed on the data. The mean value and the slope were removed, then the standard deviation and the frequency offset of the chain with respect to UTC(USNO) were calculated. The results of the standard deviation calculation are illustrated in Figure 6 where the standard deviation is plotted versus the number of days contained in each sample period. The results indicate that the expected value is 0.28 microseconds. The significance to the user is that he knows (if he has a little data history on the Loran-C chain he is using) that the expected value for a particular day's measurement is within 280 nanoseconds of the previous day's value, or of any previous value projected into the future using the calculated Loran-C chain frequency offset.

The results of the data analysis with respect to the Loran-C frequency offset are illustrated in Figure 7. The mean value for all the sample periods was 6.1×10^{-14} and the standard deviation was 5.9×10^{-13}. Note that in only three cases did the frequency offset exceed 1×10^{-12}. The significance to the user is that he can compare his frequency standard to the received Loran-C carrier phase and be assured that the Loran-C 100-kilohertz frequency is within 1×10^{-12} of UTC(USNO). If the user compiles a little data history he can compute the frequency offset of his standard

Table I. RESULTS OF ANALYSIS OF PUBLISHED LORAN-C DAILY RELATIVE PHASE VALUES

CHAIN	PERIOD	NO. OF DAYS	$\sigma(\mu s)$	$\Delta f/f (x10^{-13})$ USNO - LORAN-C	R*
U. S. EAST COAST	FEB 1 - JUN 30, 1968	151	0.28	-0.02	●
	JUL 1, 1968 - JAN 15, 1969	199	0.45	3.6	.97
	JAN 16 - MAR 30, 1969	74	0.18	-0.6	●
	MAR 31 - AUG 25, 1969	148	0.38	-3.6	.96
	AUG 26 - NOV 1, 1969	68	0.19	5.7	.98
	NOV 2 - DEC 12, 1969	41	0.11	-7.4	.99
	DEC 13, 1969 - FEB 12, 1970	62	0.28	1.3	●
	FEB 13 - JUL 7, 1970	145	0.40	5.2	.98
	AUG 8 - SEP 17, 1970	41	0.08	-11.6	1.00
	SEP 18 - DEC 31, 1970	105	0.12	1.0	●
	JAN 1 - FEB 28, 1971	59	0.21	5.3	.97
	MAR 1 - JUN 7, 1971	99	0.13	-3.8	.99
	JUN 11 - AUG 20, 1971	71	0.15	-6.7	.99
NORTH ATLANTIC	JAN 1 - JUN 30, 1970	181	0.40	3.4	.96
	JUL 1 - NOV 18, 1970	140	0.30	0.05	●
	NOV 19, 1970 - SEP 1, 1971	287	0.25	4.5	.99
NORWEGIAN SEA	OCT 15, 1968 - MAR 30, 1969	167	0.49	-3.1	.94
	MAR 31 - NOV 14, 1969	229	0.43	-3.4	.98
	NOV 15, 1969 - JAN 20, 1970	67	0.29	7.0	.97
	JAN 21 - APR 12, 1970	82	0.27	8.9	.99
	APR 13 - JUL 30, 1970	109	0.35	-4.4	.96
	JUL 31 - DEC 31, 1970	154	0.30	-7.6	.99
	JAN 1 - FEB 28, 1971	59	0.25	-1.8	●
	MAR 1 - MAY 31, 1971	92	0.21	-4.4	.98
	JUN 1 - JUL 5, 1971	35	0.21	-7.5	.95
	JUL 6 - SEP 1, 1971	58	0.27	-0.07	●
MEDITERRANEAN SEA	NOV 1, 1969 - FEB 12, 1970	104	0.40	0.3	●
	FEB 12 - JUN 16, 1970	125	0.33	2.8	.92
	JUN 24 - OCT 3, 1970	102	0.39	5.1	.96
	OCT 4 - DEC 25, 1970	74	0.27	-5.2	.96
	DEC 28, 1970 - FEB 28, 1971	63	0.23	-1.5	●
	MAR 1 - MAY 11, 1971	72	0.22	-6.6	.98
	MAY 12 - AUG 30, 1971	111	0.33	-0.6	●
CENTRAL PACIFIC	FEB 11 - MAR 31, 1970	49	0.17	1.8	●
	APR 13 - MAY 26, 1970	44	0.30	7.3	.94
	MAY 27 - JUL 19, 1970	54	0.15	-1.9	●
	JUL 20 - OCT 30, 1970	103	0.25	6.1	.99
	OCT 31 - NOV 30, 1970	31	0.15	14.8	.99
	DEC 8, 1970 - MAR 19, 1971	102	0.21	5.9	.99
	MAR 23 - JUN 22, 1971	92	0.45	8.9	.98
	JUN 23 - AUG 12, 1971	51	0.14	4.1	.97
NORTHWEST PACIFIC	MAY 1 - JUN 15, 1971	46	0.11	-7.1	.99
	JUN 16 - SEP 2, 1971	79	0.17	12.2	.99

*R IS THE LINEAR REGRESSION CORRELATION COEFFICIENT. COMPUTER PROGRAM FAILURE TO YIELD THE CORRECT VALUE DUE TO THE VERY SMALL SLOPE INVOLVED IS SIGNIFIED BY ●. R=1 INDICATES A PERFECT FIT OF DATA POINTS TO THE LINEAR EXPRESSION.

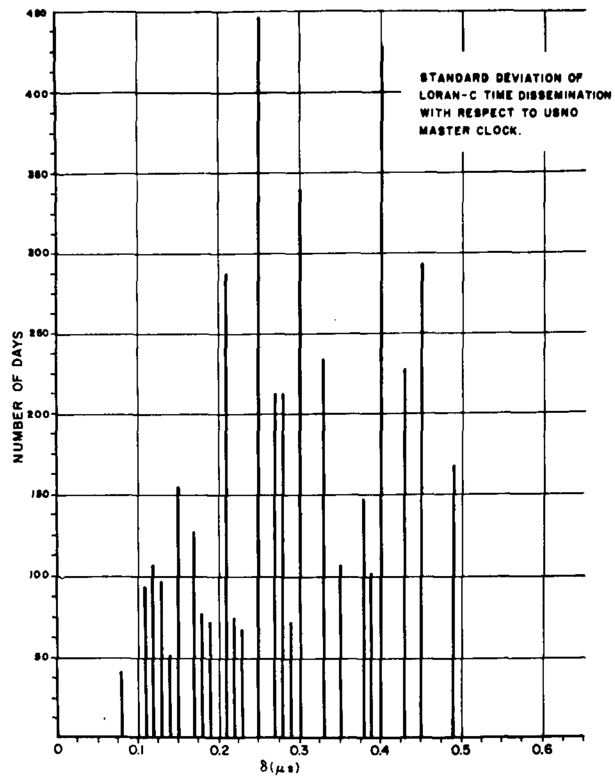


Figure 6. STANDARD DEVIATION OF LORAN-C TIME DISSEMINATION WITH RESPECT TO USNO MASTER CLOCK

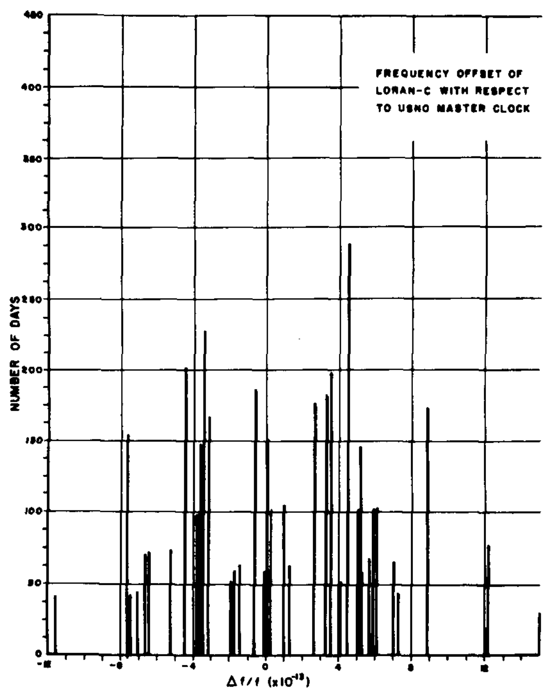


Figure 7. FREQUENCY OFFSET OF LORAN-C WITH RESPECT TO USNO MASTER CLOCK

with respect to UTC(USNO) to within a few parts in 10^{13} using the Loran-C system as a transfer medium. At the present time, all of the Loran-C stations are equipped with two or more cesium standards.

Two types of adjustments are made to the Loran-C transimssions to maintain certain tolerances with respect to the USNO master clock. By agreement between the Department of Defense and the Department of Transportation, the U. S. Coast Guard is acting as an agent of the U. S. Naval Observatory for the dissemination of precise time and time interval via the Loran-C system. Currently, the tolerance on time dissemination is $\pm$ 15 microseconds, and there is no tolerance on time interval (frequency) dissemination. Although the time tolerance is $\pm$ 15 microseconds, an attempt is made to keep the Loran-C chains within $\pm$5 microseconds of UTC(USNO), other operational commitments not withstanding. Figure 8 illustrates one type of adjustment made to the transmissions. In this case the plot of daily phase values shows the particular Loran-C chain transmitting early with respect to the USNO master clock. The frequency of the Loran-C chain is higher than the USNO master clock as evidenced by the fact that the chain is transmitting earlier each succeeding day. Near the middle of the plot the chain is seen approaching the -5 microsecond tolerance and a step retardation of the phase is introduced (noted as N microseconds) to place the transmissions near the other extreme of the tolerance. N, of course, may be any value, but is typically an integer, 10 or less. This step in phase is always announced in advance by the Naval Observatory in the Series 4 Bulletins. Note that after a time step the chain frequency remains as it was before the step.

Figure 9 illustrates the second type of adjustment made to the transmissions. In this case the frequency is adjusted to maintain the time tolerance. The adjustment is accomplished by adjusting the C field of the on-air cesium standard at the Loran-C master station. The smallest adjustment that can be made at present is approximately 5×10^{-13}, and

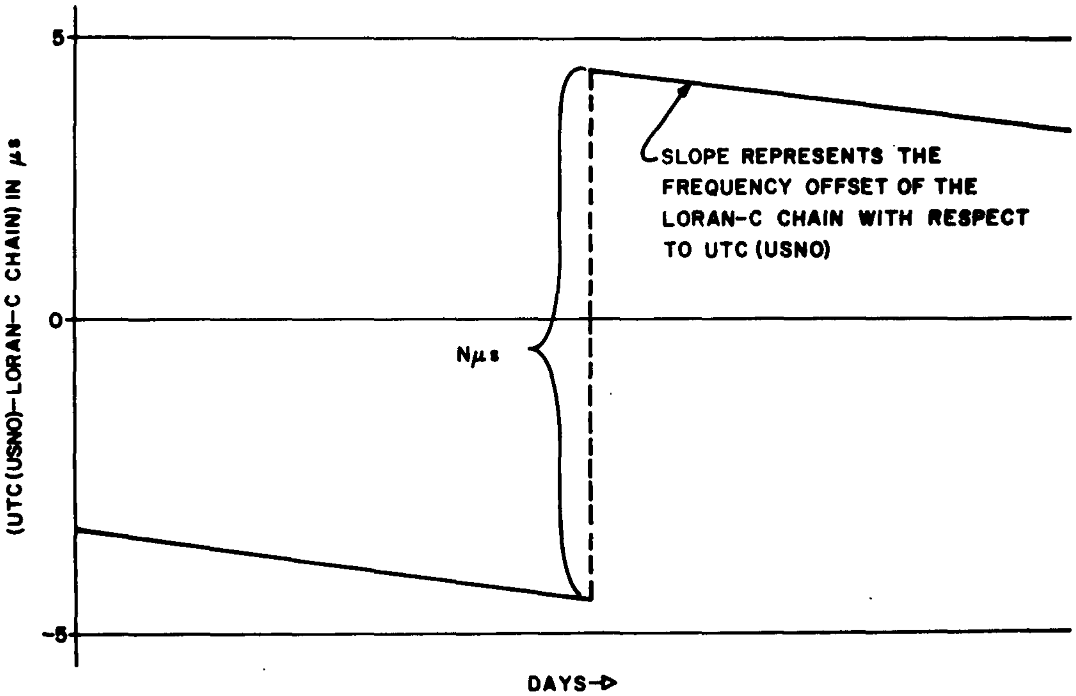


Figure 8. LORAN-C SYSTEM TIME ADJUSTMENT (Present)

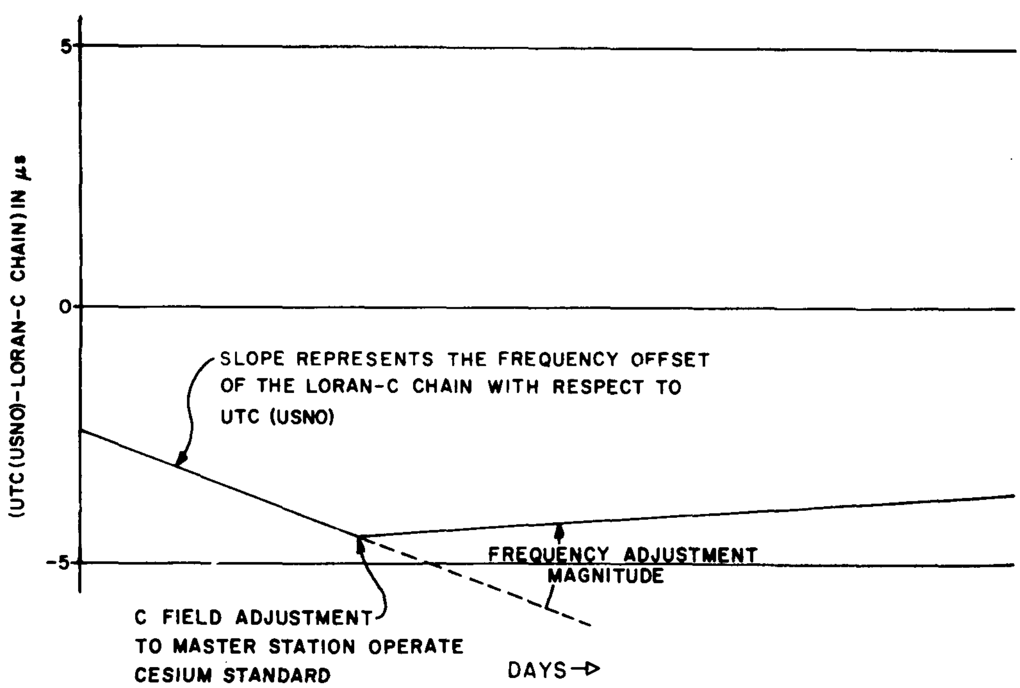
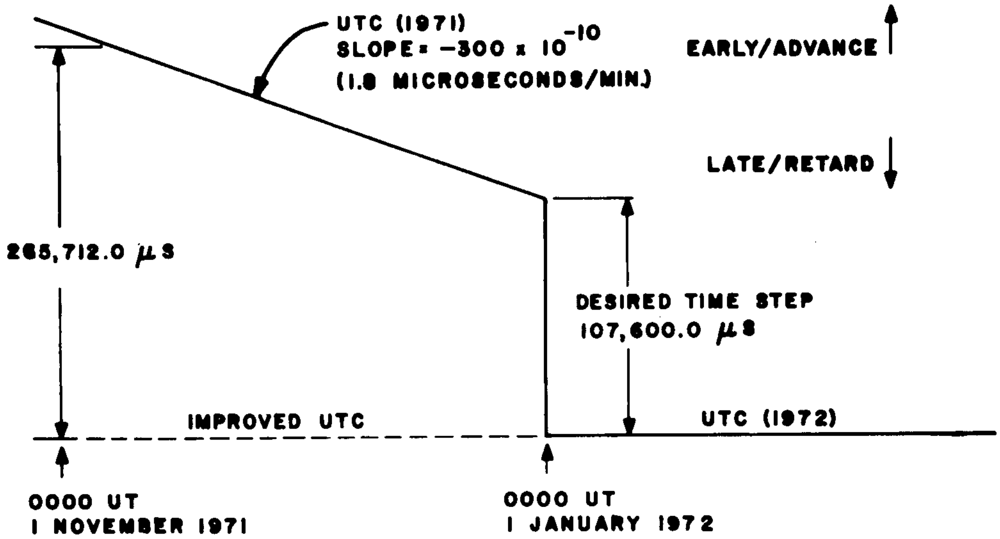
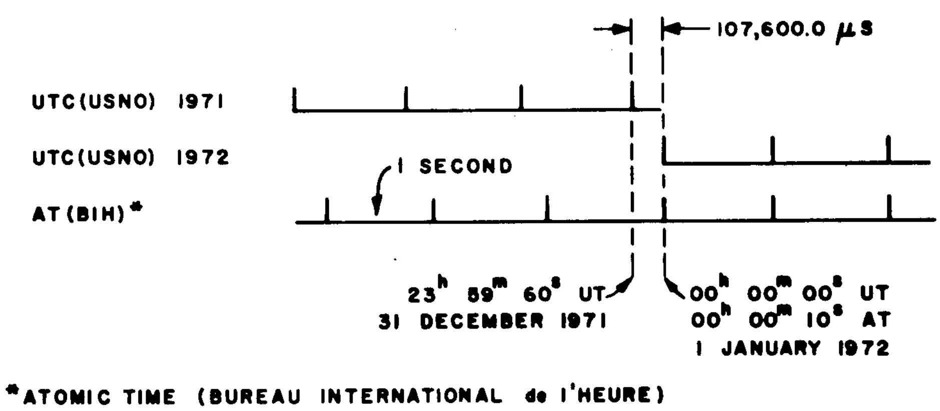


Figure 9. LORAN-C SYSTEM FREQUENCY ADJUSTMENT (Present)



UTC vs IMPROVED UTC TIME SCALE RELATIONSHIP



RELATIONSHIP BETWEEN UTC, IMPROVED UTC AND AT.

Figure 10. RELATIONSHIP BETWEEN UTC, IMPROVED UTC AND AT

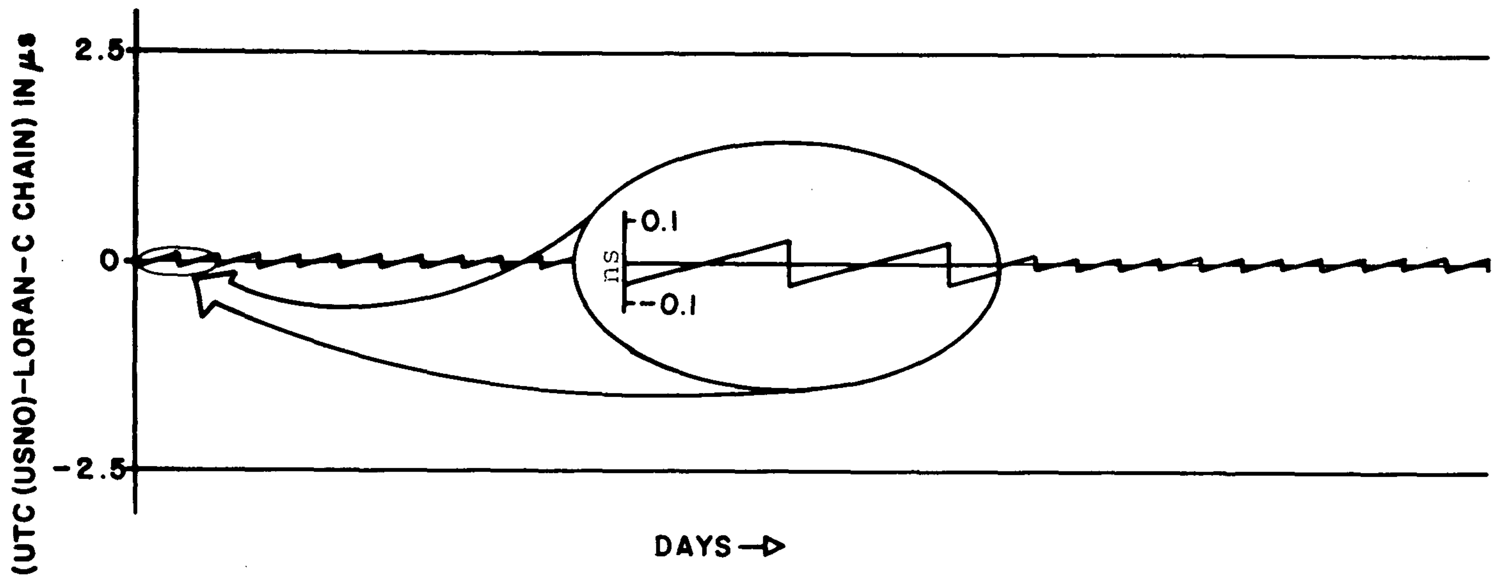


Figure 11. LORAN-C SYSTEM TIME AND FREQUENCY ADJUSTMENT (FUTURE)

multiples thereof. Loran-C chain frequency corrections are typically 5×10^{-13} or 1×10^{-12}, seldom greater.

Since 1966 the UTC scale has been offset -300×10^{-10} in frequency with respect to atomic or ephemeris time. On 1 January 1972 that offset will be removed and a retardation of 107,600 microseconds will be made to the time scale. In essence the old UTC scale is ended on 31 December 1971 at 23 hours, 59 minutes and 60.1076 seconds and a new scale is started. This is depicted in Figure 10. The new scale is started such that the start coincides with the AT(BIH) scale at the moment when the AT(BIH) scale is 00 hours, 00 minutes, and 10 seconds. At this particular instant the Loran-C chains will all change frequency by removing the 300×10^{-10} offset from the cesium standards and at the same time they will introduce a time retardation of 107,600 microseconds. To a user the step will appear to be different for each Loran-C chain. This is because the Loran GRI is less than the time step. For example, consider the case of the East Coast chain which has a GRI of 99,300 microseconds. When the time step is effected, the pulse groups will appear to have moved the difference between 107,600 and 99,300 microseconds (8,300 microseconds) and to have undergone a phase code reversal. (Alternate pulse groups are phase coded differently to reduce the effects of skywave contamination.)

In the future, time and frequency adjustments will be effected in a different manner. Both will be effected by introducing very small phase steps (on the order of 0.5 nanoseconds) periodically to compensate for the slight frequency offset of the on-air cesium standard with respect to the USNO master clock. This also ensures that the time tolerance will not be exceeded, as illustrated in Figure 11.

Synchronization of all the Loran-C chains to UTC has been approved by DOD for fiscal 1973. When the synchronization has been accomplished the new time tolerance will be $\pm$ 2.5 microseconds with respect to UTC(USNO). This will enable most users to employ the system without the need for knowing the daily phase value.

DISCUSSION

LCDR SEELY: What does the 2-1/2 microsecond figure represent? How was that established? You said it was DOD-established.

LCDR POTTS: I suspect that was a very conservative figure arrived at and agreed upon by both Coast Guard and DOD representatives. Dr. Winkler may have some specific comment.

DR. WINKLER: The reason for five microseconds tolerance is actually an Air Force requirement to provide time to within five microseconds. That figure has been in existence for several years and was provided by issuing corrections to the Loran-C actual reception. It is the intent of these new procedures to assure that you pick up time in real time without having to resort to correction tables. This represents a control problem. I believe part of your question was answered in one of the slides of Dr. Kershner, where you saw two cesium standards beating against each other. The principle was exactly the same as that which will be applied in Loran-C, and the tolerance within which you can keep is determined by the statistics or the average behavior of the frequency standards in use. If you deal with cesiums and you can measure or issue a control command once a day, the frequency variations are going to be in the order of 2 parts or 3 parts in 10^{13}; that is, about 40-50 nanoseconds which is a 1-rms figure. With improved cesium standards you could keep it smaller but is that really necessary? As LCDR Potts said, what the Coast Guard and Observatory are trying to do is to keep all of these chains on time as well as we can and as economically as we can. But since each correction requires at least one message to go to several addressees, we do not want to do that more frequently or more accurately than our users require. At the present time, as LCDR Potts has said, we will try to keep within 2.5 microseconds of the Observatory master clock in all of the synchronized chains; that is, the North Atlantic chain, the Norwegian Sea chain, the Northwest Pacific chain, the Central Pacific chain, and the East Coast chain. If increased precision becomes necessary it could be provided; it simply would mean that we would have to send more messages more frequently. In order to justify that, we must know what the requirements are. Please tell us.

LCDR POTTS: Maintaining the chain very close to UTC and frequency has a benefit for range-range navigation mode users as well. They do not particularly desire to have frequency changes in the new system; they would not really see a frequency change. They would just see a system which maintained itself coherent with the universal coordinated time scale.