TIMING CALIBRATION OF THE NORTHEAST U.S.A. LORAN-C CHAIN(9960)

R.E. Keating, C.F. Lukac, G.H. Luther, and L.G. Charron
U.S. Naval Observatory
Washington, D.C. 20392-5100

Introduction.

The U.S. Naval Observatory (USNO), from the very first day of its establishment in 1830 as a chronometer rating office, to the present, has been deeply involved in the specialized field of Precise Time and Time Interval (PTTI). During this period of one and one half centuries, the accuracy specification that defines Precise Time and Time Interval, or "PTTI", has monotonically increased from seconds to nanoseconds! The 1-second-PTTI era began in the early 1860's, when Western Union adopted USNO's 1 sec PTTI, which event led to the defacto use of Standard Time in most parts of the world. In 1904, Naval Radio Station NAA in Arlington, Virginia, began the first radio time transmissions of USNO's PTTI; and this event introduced the era of 0.001 sec PTTI. In May 1961, upon the delivery of LORAN-C timing receivers built to specification for the purpose, USNO began providing steering and control of the East Coast LORAN-C; and this event began the era of dissemination of 1 microsecond PTTI. Currently, USNO's involvement with the Global Positioning System (GPS) is introducing the era of 1 nanosecond PTTI.

Although dissemination of 1 nanosecond PTTI is clearly dependent on the implementation of GPS, USNO still continues to publish 1 microsecond PTTI values of UTC(USNO MC) - LORAN-C (Ref. 1). This year is the twentyfifth year of the USNO's involvement in the use of LORAN-C to disseminate 1 microsecond PTTI. The published values disseminated, however, are based upon a variety of instruments, receivers, PTTI substations, as well as various direct and indirect measurement techniques. Over a period of several years, it is possible that, unless field checks are made, changes in instrumentation, receiver delays, re-configurations of LORAN-C chains, etc., could result in systematic errors being introduced, from time to time, into the published values of UTC(USNO MC) - LORAN-C. And so, from time to time, USNO sponsors field calibration checks of LORAN-C Chain PTTI timing. This paper gives a report on a field timing calibration against UTC(USNO MC) carried out during May---July 1986 on the Northeast U.S.A LORAN-C chain.

Procedure.

A small van was fitted with two cesium portable clocks, two heavy duty DC batteries, a DC to AC inverter, two Austron 2000C LORAN timing receivers, a whip antenna, a GPS receiver, an HP85 computer, and a combination voltmeter/time interval counter controlled by the HP85 computer (Figs. 1, 2, and 3).

At USNO, the LORAN timing receivers were locked to the Master Transmitter (Seneca) of the Northeast U.S.A LORAN-C(9960) chain. The van, with the cesium portable clocks and the operating LORAN timing receivers continuously tracking the Seneca LORAN Master, was then driven from USNO to New York to the vicinity of the Seneca Master Transmitter.

FIG. 1 Mobile Electronic Laboratory

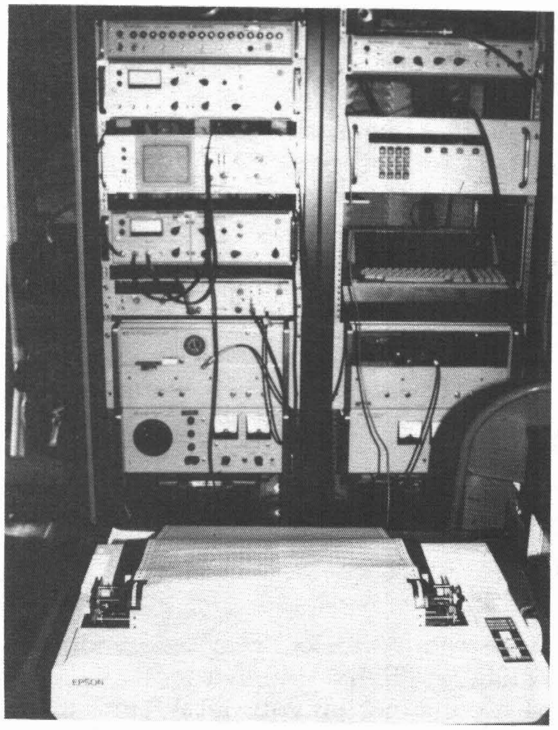

FIG. 2 Instrumentation

FIG. 3 Mounted WHIP Antenna

FIG. 4 "OVID" Benchmark

In the vicinity (i.e., within 30 Km) of the Seneca Transmitter, several suitable geodetic survey benchmarks (Fig. 4) were located. The van was then driven to the site of the benchmark and the LORAN whip and GPS antennae set over the benchmark. The LORAN receivers were used to measure cesium Portable Clock (PC1710) time of reception ("TOR") of the Seneca(9960) Master signal at the benchmark. The GPS receiver was used to determine GPS positions for the benchmark and also to determine the time difference PC1710 - GPS. Although every effort was made to identify and locate a radial sequence of geodetic benchmarks located at increments of one LORAN wavelength (2996.91 meters) from the Seneca Master, this was not always possible. Accordingly, measurement sites were identified which were located at approximate integral multiples of one LORAN wavelength from the Seneca Master; and the GPS receiver was used to determine the precise positions of these non-benchmark sites. The GPS determined positions were then used to calculate, using Sodano's Fifth Method (Ref. 2), the geodesic distance between the Seneca Master and the Precise Position/Benchmark. At USNO, measurements made of UTC(USNO MC) - GPS were also made; and these measurements were later combined with the UTC(USNO MC) - PC1710 closure measurements made at the beginning and end of the trip to derive the timing behavior of PC1710 during the operations in the field (Ref. 3). The resulting UTC(USNO) - PC1710 time differences obtained during operations in the field are accurate to about 10 nanoseconds.

Nine Precise Positions/Benchmarks were located and measured (Table 1). Four of these sites are geodetic benchmarks; the remainder are Precise Positions determined with the GPS receiver. The Precise Positions/Benchmarks are in a radial sequence in which the farthest, "WATERLOO" is 7.6 LORAN wavelengths from the Seneca Master Transmitter, the next, "HOLIDAY", is 7.1 wavelengths away, followed by "SILVER" at 6.0 wavelengths, "NICASTRO" at 5.0 wavelengths, "SWEETSHILL" at 4.2 wavelengths, "YALE" at 3.0 wavelengths, "REYNOLDS" at 2.2 wavelengths, "OVID" at 1.5 wavelengths, and "ROMULUS" is 1.2 wavelengths from the Seneca Master Transmitter. See Fig's 5 - 12. In Table 1, when a geodetic benchmark was used, the North American Datum 1927 position is given in addition to the GPS WGS-72 position.

TABLE 1

SENECA PRECISE POSITIONS/BENCHMARKS

		°	'	"	°	'	"	Distance (Km)
1. ROMULUS	NAD1927	42	44	41.318 N	076	49	01.868 W	3.50*
2. OVID	WGS72-GPS	42	40	25.265 N	076	49	11.337 W	4.514
	NAD1927	42	40	24.978 N	076	49	11.784 W	
3. REYNOLDS	WGS72-GPS	42	46	21.624 N	076	50	13.206 W	6.572
4. YALE	WGS72-GPS	42	47	35.760 N	076	50	38.268 W	8.920
5. SWEETSHILL	WGS72-GPS	42	49	37.284 N	076	50	41.226 W	12.642
	NAD1927	42	49	36.874 N	076	50	41.636 W	
6. NICASTRO	WGS72-GPS	42	51	00.306 N	076	50	58.296 W	15.232
7. SILVER	WGS72-GPS	42	52	30.546 N	076	51	13.842 W	18.039
8. HOLIDAY	WGS72-GPS	42	54	20.551 N	076	50	21.290 W	21.317
9. WATERLOO	WGS72-GPS	42	55	03.177 N	076	51	39.244 W	22.785
	NAD1927	42	55	02.916 N	076	51	39.926 W	

* The ROMULUS Azimuth Mark No. 3 was located, but the ROMULUS Benchmark itself was not found. The Azimuth Mark No. 3 was used; but, because the benchmark description is not yet available, the distance was determined by map scaling. The NAD 1927 position given is for the primary ROMULUS Benchmark.

Note: The distance from the Seneca transmitter is, except for ROMULUS, the geodesic geometric distance in kilometers as calculated using Sodano's Fifth Method, WGS 72 positions, and WGS 72 Spheroid and Datum.

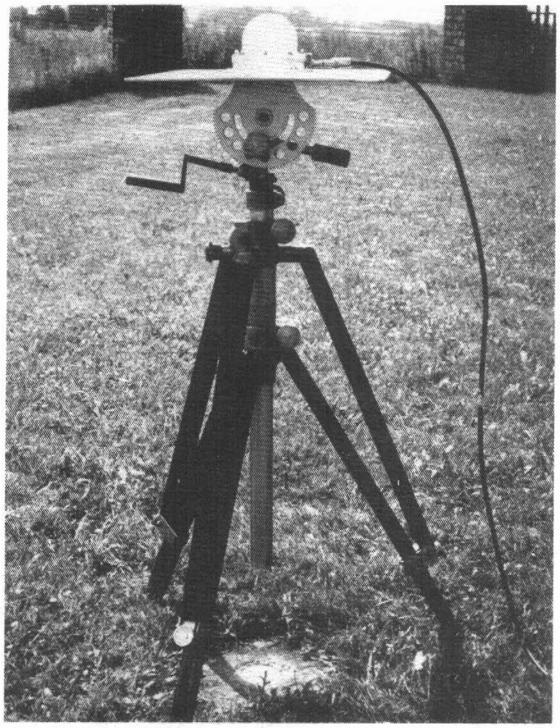

FIG. 5 "WATERLOO" Benchmark

FIG. 6 "HOLIDAY" Inn Position

FIG. 7 "SILVER" Creek Position

FIG. 8 "NICASTRO" Position

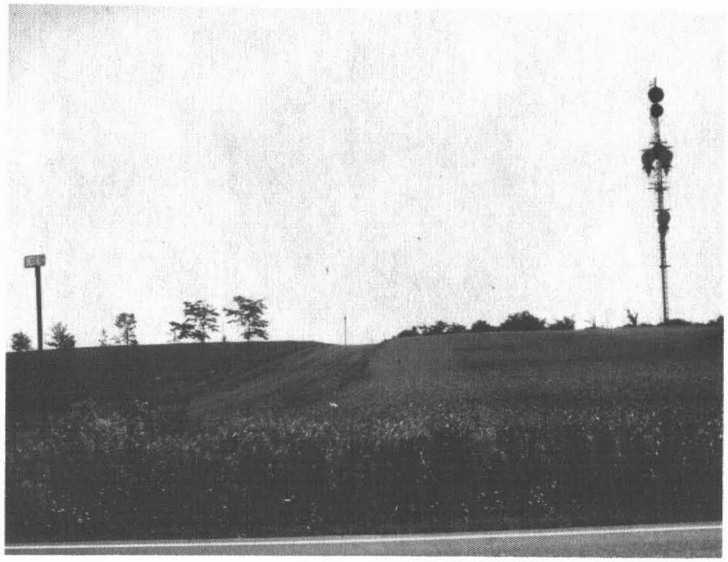

FIG. 9 "SWEETSHILL" (View from highway)

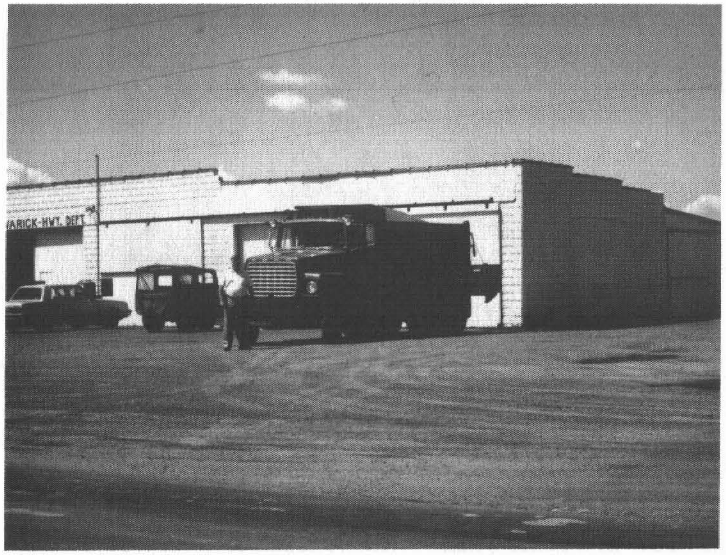

FIG. 10 "YALE" (County "Barn")

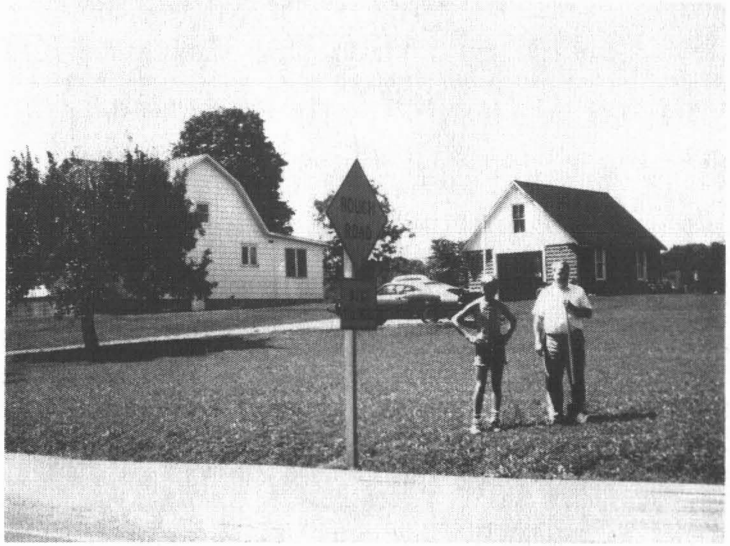

FIG. 11 "REYNOLDS" Position

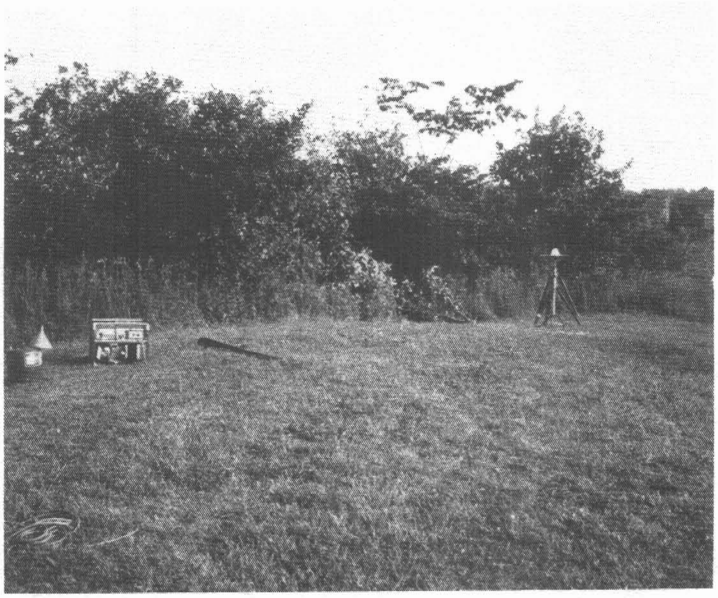

FIG. 12 "OVID" Benchmark Site

Although listed as a Precise Position, no GPS position measurements were made at "ROMULUS." The original "ROMULUS" benchmark could not be found. However two "ROMULUS" Reference Marks were located; and the LORAN TOR measurements were made at the "ROMULUS" Azimuth Mark No. 2. Until the station geodetic description (which was not, and still is not, available to us) has been received, the LORAN TOR measurements at "ROMULUS AZ No. 2" cannot be reduced with precision. It should be noted, however, that the resulting value for PC1710 - Seneca(9960) is in reasonable agreement with values obtained at the other Precise Positions/Benchmarks even though only a rough map estimated position was used for "ROMULUS AZ No. 2." When the precise NAD-1927 value for "ROMULUS AZ No. 2" is obtained, it will be converted to WGS-72, and the precise geodesic distance from the transmitter calculated. The LORAN TOR measurements at "ROMULUS AZ No. 2" will then be at the same precision as the other Precise Positions/Benchmarks.

Approach TOR Measurements

Upon completion of the LORAN TOR measurements at the Precise Positions/Benchmarks, the van, with its continuously operating LORAN receivers, was driven slowly to the site of Seneca Master Transmitter (Fig. 13). At various points on the road leading to the Seneca Transmitter, the van was stopped (Fig. 14) and the Seneca(9960) LORAN TOR was recorded in the sense PC1710 - R1(Seneca, 9960). The reading of the van milage indicator was recorded to identify each site as well as such notations as "M.G." for "Main Gate" to the Army Depot on which the Seneca Transmitter is located. Subsequently, these van milage positions were identified on a high resolution geodetic map and the map-scaled distance to the Seneca Transmitter determined. The results of these measurements are given in Table 2.

FIG. 13 Seneca Transmitter Entrance

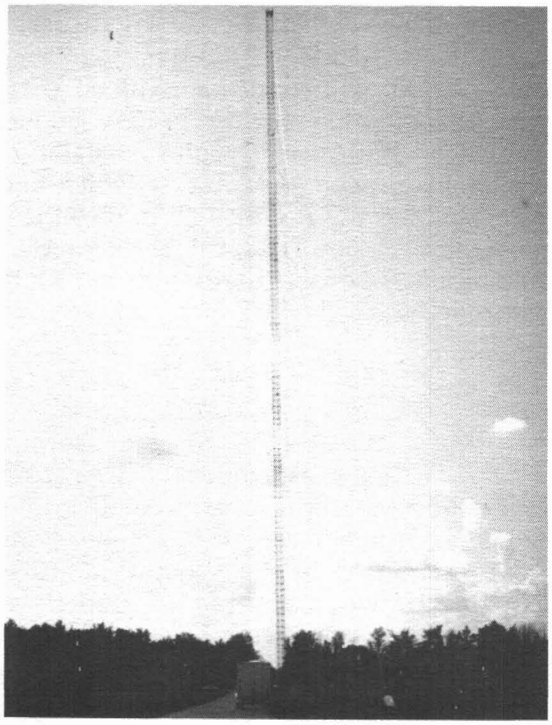

FIG. 14 Van approaching Seneca Transmitter

TABLE 2

LORAN(Seneca, 9960) MAP SCALED MONITORING SITES
12-15 July 1986

APPROACH To Seneca Transmitter

	Comment	d	PC-R_1	d/(c/n)	φ_c	φ_t	C	PC-Seneca
		Km	μs	μs	μs	μs		μs
12.	Romulus	3.50	76.00	11.68	0.40	12.08	4	4.87
11.	"96.4 M.G."	3.45	125.75	11.52	0.40	11.92	9	5.36
10.	"97.2"	2.63	123.30	8.78	0.45	9.23	9	5.60
9.	"97.55"	2.173	120.76	7.25	0.50	7.75	9	4.54
8.	"98.45"	0.975	118.02	3.25	1.00	4.25	9	5.30
7.	"98.85 Y 96"	0.525	117.97	1.75	2.27	4.02	9	5.48
6.	"99.10 Entr"	0.37	118.36	1.24	3.38	4.62	9	5.27
5.	"99.15"	0.29	118.65	0.97	3.83	4.80	9	5.38
4.	"99.20"	0.21	118.55	0.70	4.25	4.95	9	5.13
3.	"99.25"	0.13	118.60	0.43	4.58	5.01	9	5.12
2.	"99.30"	0.050	119.05	0.17	4.85	5.02	9	5.56
1.	"99.33"	0.010	120.64	0.03	4.97	5.00	9	7.17
0.	"99.33 Park"	0.008	121.29	0.02	4.98	5.00	9	7.78

The phase correction, φ_c, is based on NBS Cir. 573 with $\sigma = 0.005$ mhos/meter and $\epsilon_2 = 15$.

PC - R_1 is the recorded time difference PC1710 - R_1(Seneca,9960,NB,C), where NB = Narrowband, C= wideband cycle tracking point number.

d is the geometric radial distance in kilometers from the Seneca transmitter to the site. d was scaled from the geodetic map after using Van milage to locate and identify site.

The total phase, φ_t, is the sum of the light time d/(c/n) and the phase correction φ_c.

PC - Seneca, the last column, is obtained by evaluating the expression:

$$\text{PC1710-Seneca} = (\text{PC-}R_1) - \text{Corr(C)} - \varphi_t - \text{S1DELAY}$$

where:

Corr(C) = 89.42 μs for C=9 and NB (to correct to WB 3'rd - 30 T.P.)
= 40.00 μs for C=4 and WB
S1DELAY = 19.05 μs for R1 System (use WB delay and correct for WB-NB)

The cycle number, C, is counted as seen in receiver wideband; and this convention is used for identifying the tracking point even when receiver is in narrowband: e.g., when receiver is tracking 8th narrowband cycle it is identified as the C=9th wideband cycle.

MEASUREMENT SYSTEM CONFIGURATION

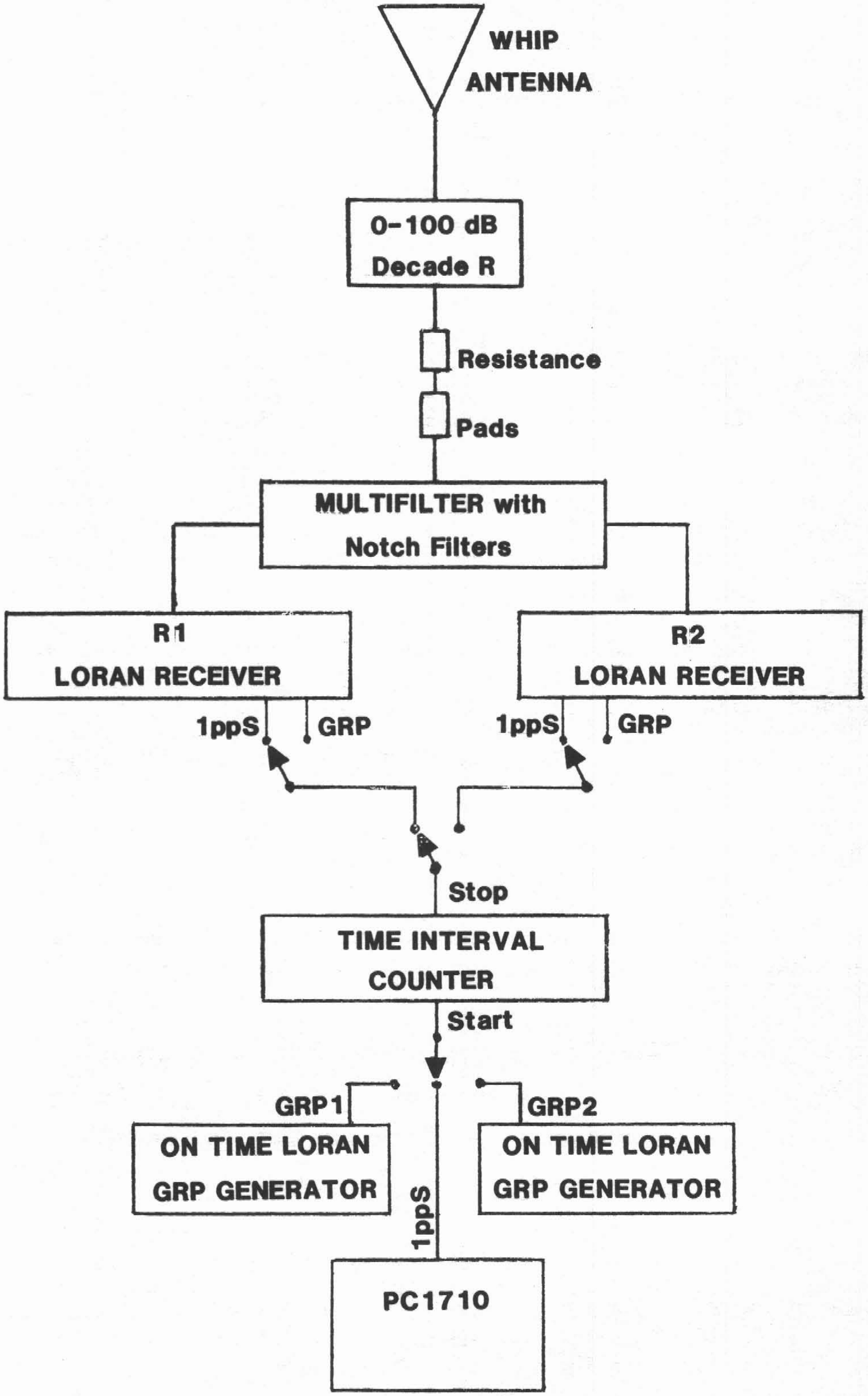

FIG. 15

INSTRUMENTATION SETUP FOR DIRECT COMPARISON OF PORTABLE CLOCK TO TRANSMITTER

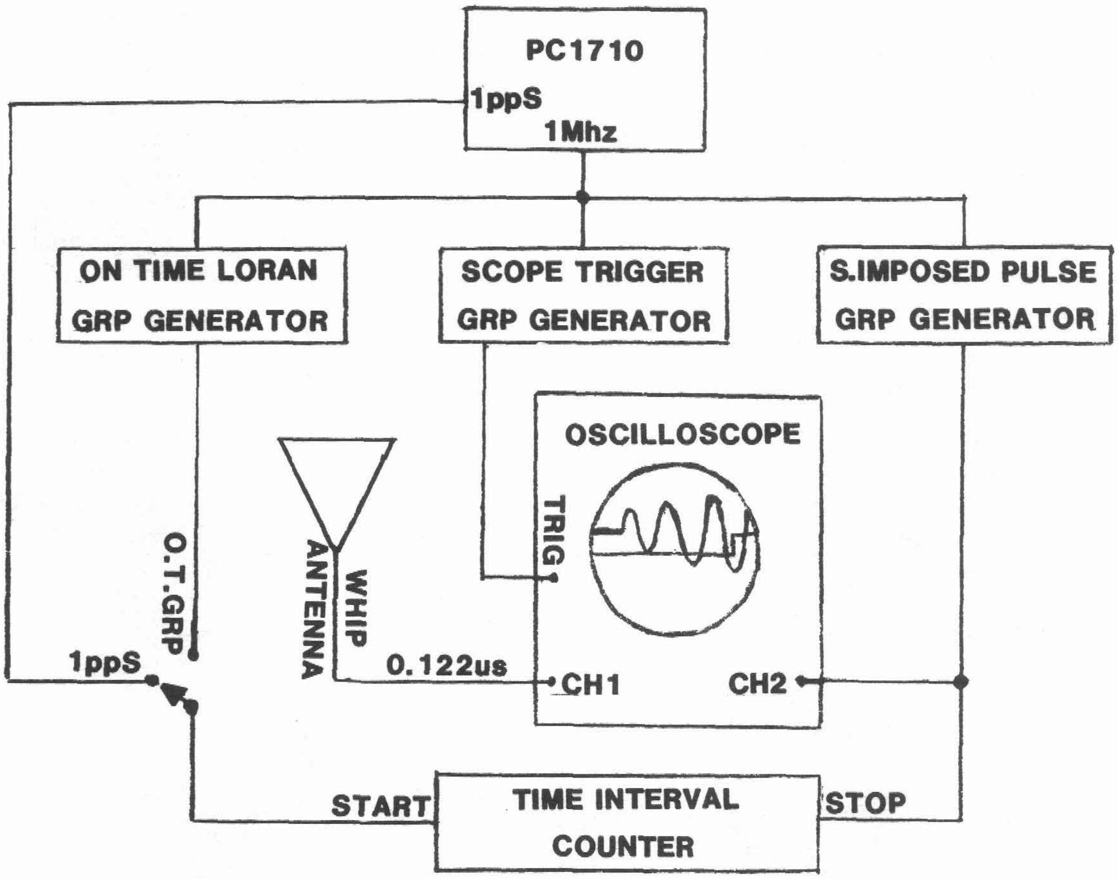

FIG. 16

In Table 2, the 1'st column is a count; the "Comment" column gives the van milage reading plus any comment used to further identify the site on the road to the Seneca transmitter. The 3'rd column gives the map-scaled distance from the site to the transmitter in kilometers. The 4'th column gives the measured TOR reading PC1710 - R1(Seneca, 9960). The 5'th column gives the geometric air propagation time and equals the map-scaled distance d divided by the air velocity v (= c/n) of the LORAN radiation, n is the index of refraction (=1.000338) and c = 299792458 m/s is the vacuum velocity of light. The 6'th column gives the phase correction calculated according to NBS Circular 573 (Ref. 4) using earth conductivity σ = 0.005 mhos/m and earth permittivity ϵ_2 = 15 for a distance d. Column 7 gives the total phase, which is equal to the sum of columns 5 and 6. Column 8 gives the number of the cycle at the end of which the receiver R1 <u>tracking point</u> (TP) was set. Column 9 gives the time difference PC1710 - LORAN(Seneca,9960), which is obtained by subtracting the sum of the Receiver 1 System Delay (S1DELAY), cycle TP correction (CORR(C)), and the total phase φ_t ,column 7.

Note that the values obtained for PC1710 - LORAN(Seneca, 9960), in spite of the crude manner in which the positions were obtained, are consistent right up to the transmitter antenna.

Transmitter Site Measurements.

At the Seneca transmitter site, the regular measurement system (Fig. 15) was modified. The modification consisted in connecting the Seneca 9960M signal from the LORAN-C whip antenna directly into the channel 1 input of an oscilloscope. See Fig. 16. Three slewable LORAN-C Group Rate Generators ("GRP's") are used in the instrumental setup shown in Fig. 16. The "On Time GRP" was TOC ("Time of Coincidence") synchronized to PC1710. The "Scope Trigger GRP" was used to trigger the oscilloscope so as to display the Seneca 9960 signal taken from the LORAN-C whip.

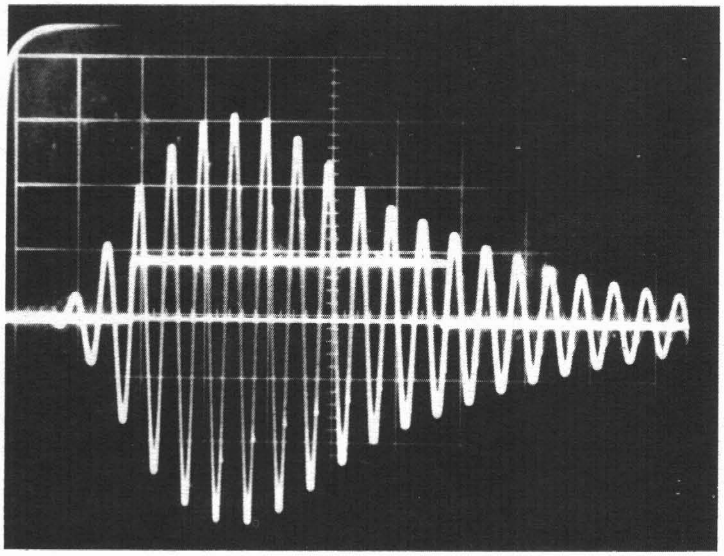

FIG. 17 Seneca Transmitter Master pulse taken directly from Van WHIP antenna with GRP pulse leading edge superimposed on end of 3'rd cycle

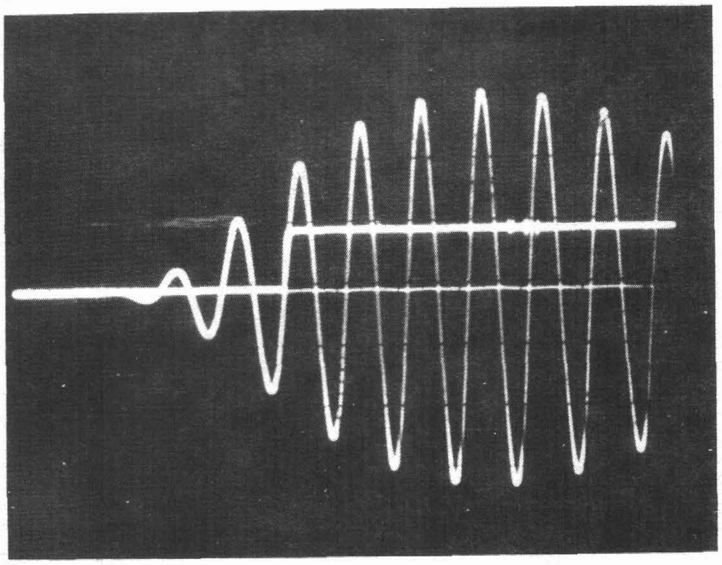

FIG. 18 Same as Fig. 17 but amplified and expanded.

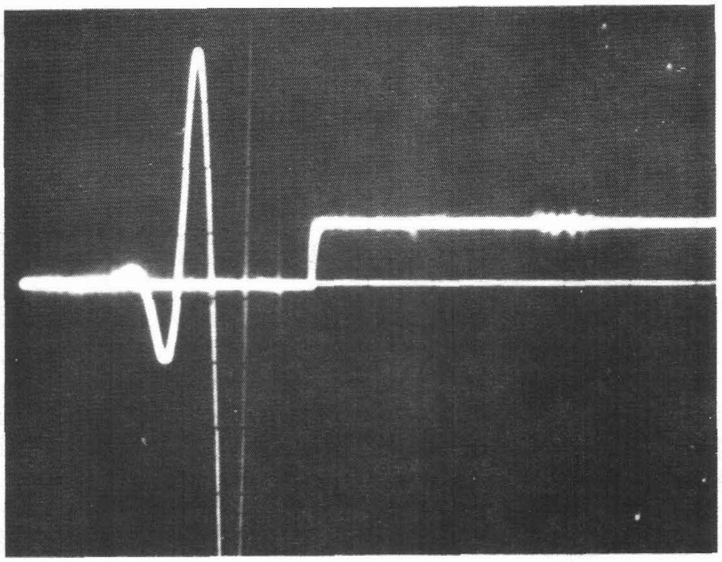

FIG. 19 Same as Fig.'s 17 & 18 but with maximum (Chan. 1) signal amplification. Note linear rise of positive first halfcycle.

The "Superimposed GRP" was slewed so as to align the "Superimposed GRP" leading pulse edge on the 30 microsecond TP; and this aligned "Superimposed GRP" pulse was then used as the stop input to the time interval counter.

Fig's 17, 18, and 19, are polaroid photographs showing, with increasing vertical amplification and horizontal sweep times, the relationship between the Seneca 9960 signal from the whip and the "Superimposed GRP" pulse. Note in particular the fact that the end of the third cycle (30 microsecond TP) is clearly and unambiguously identified.

This method bypasses completely the LORAN Receiver filters and the Antenna multicoupler. There is therefore no problem with receiver filter precursors or with propagation precursors.

PC1710 - LORAN(Seneca, 9960M, DIRECT)

Time	Date		PC1710 - WHIP
21:00 UT	15 July 1986		42.16 μs
less:	Corr(C=3)	30.00 μs	
	Near Field Phase	5.00 μs	
			35.00 μs
21:00 UT	15 July 1986		7.16 μs

FIG. 20

Fig. 20 gives the timing measurements PC1710 - LORAN-C(Seneca, 9960, Whip) made using the "Superimposed GRP" pulse. In the near field close to the transmitter tower (the whip was located about 8 to 10 meters from the base of the main Seneca transmitter tower), the whip and the transmitter tower may be considered to be mutually coupled; and the signal in the whip may be considered to be picking up the so-called "static" field component of the near field. This component, which is dominant at this distance, is advanced in time by π radians over the phase of the far radiation zone field component. To determine the effective far zone signal timing from the observed near field "static" field component, it is necessary to subtract 30 microseconds to correct to the nominal signal start and also subtract the time advance (5 microseconds) corresponding to the π radian phase advance of the static transmitter field component over the far field radiation zone component. When this is done, the result, as Fig. 20 shows, is PC1710 - LORAN-C(Seneca,9960,Whip) = 7.16 microseconds. This value is in good agreement with the final values obtained via the LORAN receiver given in column 9 of Table 2.

Shortly after arrival at the transmitter, we believe that the Transmitter was "tuned." Most LORAN transmitters have two basic envelope adjustment controls: one controls the near field signal envelope and the other controls the far field signal envelope. Within an hour after arrival at the transmitter, there were some peculiar changes and shifts of wavelets to signal envelope. These shifts at first caused some confusion, as we were attempting to make determinations of the R1 LORAN-C system delay using the local near field of the Seneca transmitter. These system delay measurements were repeated later at the Caribou transmitter in Maine; and they were remeasured a third time with a LORAN simulator upon return to Washington, D.C. by taking a trip to an electromagnetically quiet area near the northwestern corner of Montgomery County, Maryland in late August 1986. See Fig. 21.

System delays measured at the Seneca and Caribou transmitters differ by some 3 microseconds from the system delays measured with the LORAN simulator. Because of the obvious danger of parasitic signal pickup, which could cause the antenna multifilter to be bypassed as well as the fact that with the antenna multifilter the total wideband system delay should be about 19 microseconds as measured using the LORAN simulator, the 19 microsecond values measured with the simulator were adopted.

Departure TOR Measurements.

After these measurements were completed, the van was then driven away from the Seneca transmitter. As it was driven away, measurements were again made in the same manner as was done upon approach. Table 3 gives the departure measurements. The meaning of the columns is the same as for Table 2.

Some comments about Table 3. First, the measurements were made more densely spaced than they were upon approach. This decision was made because on the approach it was noted that at a certain point, the phase of the LORAN wavelets relative to the envelope signal underwent very rapid change at a point about 2.18 Km from the transmitter. Second, the trailing portions of the signal envelope changed very rapidly at this 2.18 Km site. By spacing the measurements more densely, it was possible to determine the region at which this occurred (No. 14 in Table 3). Note that the combined effect of the envelope change with the rapid phase change of the LORAN signal wavelets caused the receiver a certain amount of tracking difficulty. The PC1710 - Seneca value obtained for site No. 14 in Table 3 is 3.86 microseconds, which is almost 2 microseconds different from the other values. Thus, measurements such as these must be made slowly and in small distance increments to allow the receiver to continue to track this phase behavior. We believe this phase shift at site No. 14 may be real and not merely the result of a rapid vehicle motion. The signal was being observed continuously on an oscilloscope as the van was driven away from the Seneca transmitter; and the van was stopped for each time of reception measurement. It appeared that this phase shift at site No. 14 was the result of a rapid shift in wavelet phase over a distance of 100 to 200 meters and that the accompanying fattening and lengthening of the trailing portion of the Loran signal waveform envelope was caused, at least in part, by the onset of dominance of the induction ($1/d^2$) component of the transmitter electric field. The receiver tracking point, during departure was set to track the end of the 9th cycle (measured in wideband) of the filtered narrowband signal waveform (i.e. "8'th" cycle as seen in narrowband). The sudden phase shift at site No. 14 of Table 3 cannot be attributed to the onset of some sort of skywave reception because this close to the transmitter the skywave cannot arrive (for an ionosphere altitude of 75 kilometers) until about 500 microseconds after the beginning of the groundwave pulse.

R1 SYSTEM DELAY MEASUREMENTS

Microseconds

Receiver Delays Marked by manufacturer
Wideband = 15.3
Narrowband = 25.1

At Seneca Transmitter:

Wideband = 16.71
= 16.65
= 16.74

Ave = 16.70 ±0.03

At Caribou Transmitter

Wideband = 15.89

Narrowband = 25.51

Using Loran Simulator

Wideband
Simulator Start - R1 GRP Stop = 19.025
Superimp. GRP Start - R1 GRP Stop = 19.04
Superimp.GRP w/OT 1pps - R1 1pps = 19.10

Narrowband
Simulator Start - R1 GRP Stop = 28.59
Superimp. GRP Start - R1 GRP Stop = 28.76

The above measured system delays are for the R1 System (Austron Receiver II8470 plus delays associated with cabling, multifilter, and whip antenna).

FIG. 21

TABLE 3

LORAN(Seneca, 9960) MAP SCALED MONITORING SITES
12-15 July 1986

DEPARTURE From Seneca Transmitter

	Comment	d Km	PC-R_1 μs	d/(c/n) μs	φ_c μs	φ_t μs	C	PC-Seneca μs
1.	"99.33"	0.008	119.08	0.02	4.98	5.00	9	5.61
2.	"99.33+"	0.010	119.31	0.03	4.98	5.01	9	5.83
3.	"99.33++"	0.018	119.17	0.07	4.95	5.02	9	5.68
4.	"99.36"	0.05	119.25	0.17	4.85	5.02	9	5.76
5	"99.41"	0.13	119.22	0.43	4.58	5.01	9	5.74
6.	"99.46"	0.21	119.10	0.70	4.25	4.95	9	5.68
7.	"99.51"	0.30	119.00	1.00	3.77	4.77	9	5.76
8.	"99.56"	0.38	118.77	1.25	3.28	4.53	9	5.77
9.	"99.81"	0.525	118.26	1.75	2.27	4.02	9	5.77
10.	"100.00"	0.66	118.10	2.17	1.68	3.85	9	5.78
11.	"100.21"	0.91	118.36	3.04	1.09	4.13	9	5.76
12.	"100.50"	1.30	119.42	4.34	0.75	5.09	9	5.86
13.	"100.80"	1.75	120.79	5.84	0.59	6.43	9	5.89
14.	"101.10"	2.18	120.08	7.25	0.50	7.75	9	3.86
15.	"101.19"	2.28	122.26	7.60	0.49	8.09	9	5.70
16.	"101.30"	2.435	122.96	8.13	0.47	8.60	9	5.89
17.	"101.40"	2.63	123.50	8.78	0.45	9.23	9	5.80
18.	"101.46"	2.71	123.81	9.04	0.45	9.49	9	5.85
19.	"101.63"	2.95	124.36	9.84	0.43	10.27	9	5.62
20.	"102.00"	3.50	126.40	11.68	0.40	12.08	9	5.85
21.	"102.29"	3.45	126.43	11.52	0.40	11.92	9	6.04
22	Romulus	3.50	76.00	11.68	0.40	12.08	4	4.87

See notes to Table 2.

TABLE 4

LORAN(Seneca, 9960) PRECISE MONITORING SITES
12-15 July 1986

	Comment	d Km	PC-R_1 μs	d/(c/n) μs	φ_c μs	φ_t μs	C	PC-Seneca μs
1.	Romulus	3.50	76.00	11.68	0.40	12.08	4	4.87
2.	Ovid	4.514	79.17	15.062	0.37	15.43	4	4.69
3.	Reynolds	6.572	86.56	21.932	0.36	22.29	4	5.22
4.	Yale	8.920	94.78	29.765	0.37	30.14	4	5.59
5.	Sweetshill	12.642	97.22	42.185	0.40	42.58	3	5.59
6.	Nicastro	15. 232	115.97	50.828	0.42	51.25	4	5.67
7.	Silver	18.039	125.28	60.194	0.45	60.64	4	5.59
8.	Holiday	21.317	136.06	71.132	0.48	71.61	4	5.40
9.	Waterloo	22.785	141.04	76.027	0.49	76.52	4	5.47

The notes to Table 2 apply except that:

d was computed by means of the Sodano method using the monitor site positions as determined by GPS and the WGS72 transmitter position; and

Corr(C) = 30.00 μs for C=3 and WB;
Corr(C) = 40.00 μs for C=4 and WB.

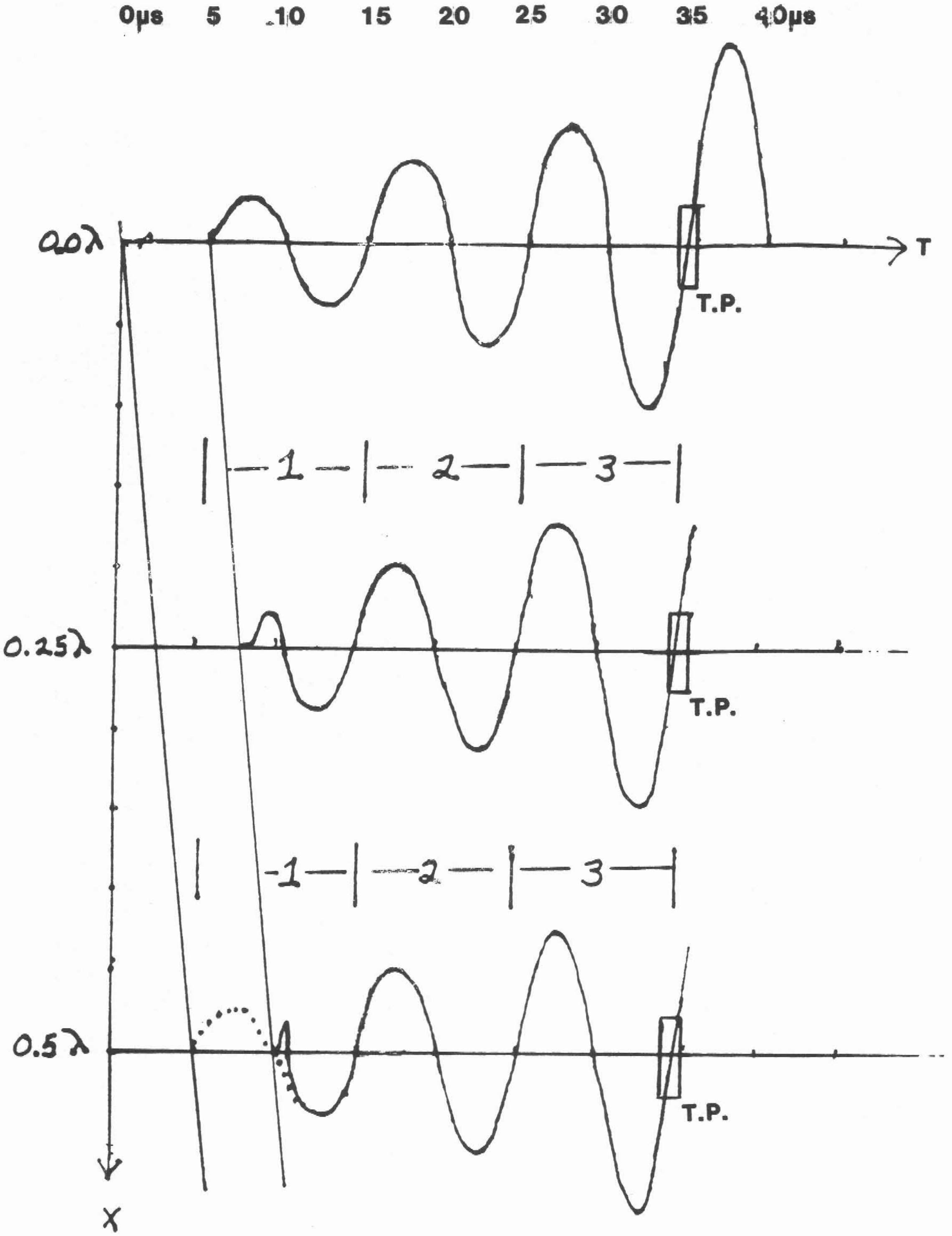

FIG. 22 Note compressed first positive half-cycle that radiates as low level delta-function spike

As can be seen the last column of Table 3, the PC1710 - LORAN(Seneca, 9960) values obtained upon departure from the Seneca Transmitter are consistent with the values obtained upon approach.

Precision Results.

Table 4 gives the values PC1710 - LORAN(Seneca, 9960) obtained at the Precise Position/Benchmark sites in the same manner as Tables 2 and 3. These values are given in the far radiation zone sense.

Fig. 22 shows the sense in which it is said that a LORAN-C transmitter is "on time". The top trace shows the 5 microsecond advanced LORAN near field signal. The bottom trace shows the approximate LORAN signal after it has propagated 1/2 wavelength from the transmitter. Note especially the compression of the first half-cycle of the signal. This compression is a transient dynamic dipole field effect, which produces a low intensity, but high frequency (about 1 MHz) pulse. In addition, as the signal propagates outward towards 1/2 geometric wavelength distance from the transmitter, the following wavelets of the LORAN signal are shifted backwards, or to the left, as is described by NBS Circular 573. The net effect is that the first positive half-cycle is, in effect, compressed into a low level delta-function-like spike and that, beyond 1/2 wavelength from the transmitter, only the negative half-cycle of the first cycle can be seen.

If, as is shown by the dotted extension to the bottom trace on Fig. 22 one pretends that the first positive half-cycle has not been compressed, then by correcting for the light-time (at the 1/2 cycle site), one can extrapolate the far zone radiation signal back to the origin. Thus an ontime LORAN signal in the far radiation zone appears, when extrapolated back to zero geometric distance, to have been emitted at t=0 rather than at its actual near field buildup time t=5 microseconds. Since only the far radiation zone field is used for timing, this apparent t=0 far zone emission time is the sense in which a LORAN transmitter is said to be synchronized. One must only remember that the first positive half-cycle has been compressed and strongly distorted and that only the first negative half cycle can be clearly identified beyond about 1/2 wavelength from a LORAN transmitter.

UTC(USNO-MC) - PC1710 Measurements
(Via GPS Receiver)

DATE & MJD	UTC(USNO MC)-PC1710
12 July 1986 (46623.10)	-8.843 μs
12 July 1986 (46623.93)	-8.932 μs
13 July 1986 (46624.97)	-9.043 μs
15 July 1986 (46626.10)	-9.126 μs
Average:	-8.986 μs

FIG. 23

Using far radiation zone measurements made at the farthest (last six) Precise Position/Benchmark sites given in Table 4, one finds that the average value of PC1710 - LORAN(Seneca, 9960) was +5.552 ± 0.098 microseconds.

Combining this with the average UTC(USNO MC) - PC1710 values obtained from the PC1710 portable clock closures and the GPS timing measurements shown in Fig. 23, one obtains:

UTC(USNO MC) - LORAN(Northeast USA, Seneca, 9960) = -3.43 ± 0.10 μs

at 16:11 UT, 14 July 1986, MJD 46625.674.

The value published for UTC(USNO MC) - LORAN (9960) in Series 4 on 14 July 1986 was:

UTC(USNO MC) - LORAN(9960M) = +1.57 microseconds

This value differs by 5.00 microseconds from the value obtained by this calibration.

Conclusion

Timing calibrations of LORAN-C transmissions have been shown to eliminate accumulated instrumental and bookkeeping errors. Regular periodic timing calibrations every few years, and whenever there may be reason to suspect the existence of systematic timing errors, are highly recommended.

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