PATH DELAY CORRECTIONS FOR LORAN SIGNALS

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ABSTRACT

In November 1973, an experiment was initiated to explore the possibility that measurements of the Loran pulse location relative to the phase of the carrier could be used to infer path delay corrections. The Applied Physics Laboratory was joined in this effort by the U.S. Naval Observatory and the Defense Mapping Agency. Measurement of the transit time of the Loran-C wave between a site at the U.S. Naval Observatory and 10 field sites were made in the summer of 1975. The instrumentation and the results of the test are described along with statistical estimates of the precision of measurement and of the quality of the data. The precise nature of the transmitted signal and the precision of time recovery is inferred from the data. Status of the development of a path delay correction is also described.

INTRODUCTION

APL is conducting a research program including a field test for the U.S. Air Force and the Defense Advanced Research Projects Agency to determine the validity of one facet of the theory of ground wave propagation at 100 kHz. The theory indicates that if proper account is taken of group and phase velocities in the propagation of pulses of the Loran-C radio navigation service, then geodetic position could be computed by using the vacuum speed of light and the times of arrival of the pulse and the carrier. Specifically, the goal is to determine if an analytic function can be developed for operational use which relates secondary phase factor to envelope to cycle difference (ECD) so that geodetic position can be computed accurately and in real time.

The field test was conducted in the eastern United States using the East Coast Loran-C chain and required two identical sets of precision equipment, one in a mobile test van and the other at a fixed site at the U.S. Naval Observatory

(NAVOBSY). The van occupied 10 field sites during the course of the test. See Fig. 1. The positions of all sites were precisely surveyed by the Defense Mapping Agency Topographic Center (DMATC) using the Navy Navigation Satellite System and are located on ray paths from Loran-C stations through NAVOBSY. The collected data include very accurate measurements of the Loran-C ground wave phase and pulse envelope times of arrival at the 10 fixed sites and simultaneously at NAVOBSY.

APL was assisted in this test by NAVOBSY and DMATC. In addition to the satellite survey, DMATC computed all required geodetic distances. NAVOBSY executed time transfers on each test day using low noise cesium beam clocks. The APL development effort includes measurement system definition, assembly and checkout of equipment, acquisition and analysis of field test data, and a final report documenting the test and incorporating pertinent test results. Currently, APL is performing analysis of field test data.

TEST DESCRIPTION

The test instrumentation is shown functionally in Fig. 2. Two identical systems were designed and assembled, one for the van and one for the NAVOBSY site. Referring to Fig. 2, the Loran-C signal is inputted to a fixed gain tuned receiver via a wide-band variable attenuator. The purpose of the wide-band attenuator is to standardize the Loran-C pulse amplitude as seen by the tuned receiver without distorting the signal waveform or causing a phase shift which varies with signal strength. At least 3 dB of attenuation always remains in the attenuator to minimize mismatch effects between the antenna and the input to the tuned receiver. The output of the tuned receiver is adjusted by the wide-band attenuator to give a Loran-C pulse amplitude of 0.5 volt at the positive peak of the fifth cycle (i.e., with positive phase code). The receiver output connects to an analog-to-digital converter, which digitizes wave samples at sample points on the Loran-C pulse. Sample triggers open a sample and hold circuit at the input of the analog-to-digital converter, and the converter then digitizes the analong voltage at the output of the sample and hold circuit to 13 bits pulse a sign bit. Data sampling was done as shown in Fig. 3. Only the first pulse of each group was sampled and a total of 32 voltage measurements were taken on each of these pulses. The first 16 were at 2.5 microsecond intervals, and the second 16 were at 7.5 microsecond intervals. The sample triggers are generated by sample gates. Timing of the sample gates is derived from a group repetition interval (GRI) preset counter. The phase of the preset counter can be adjusted in plus or minus 0.1 μs time intervals by phase slewing circuitry. The phase of the GRI counter is adjusted such that the sample triggers, displayed on one channel of an oscilloscope, must nearly match the desired sample points on the Loran-C pulse which is displayed on a second channel of the oscilloscope. The precision timing for the GRI preset counter, and also for a Universal Time Coordinated (UTC) clock, is derived from a low noise Cesium beam frequency standard.

The digitized Loran-C pulse waveforms, along with a synchronous output from the UTC clock and fixed data input information stored in digiswitches, are formatted by a digital formatter and stored on computer-compatible digital magnetic tape. The tape block size, i.e., the number of eight-bit characters written in one continuous block, is 512. This number of characters allows for point values from seven Loran-C pulses, a UTC clock time, and the input information stored in the digiswitches to be stored on each tape block in a standardized format.

DATA ANALYSIS

One segment of the data consists of 32 measurements of voltage on each of 12,000 pulses. These data are obtained in 20 minutes of recording in the East Coast Loran-C chain. Simultaneous recordings consisting of three consecutive 20 minute segments were made at the NAVOBSY site and each van site, both of which are accurately located on the ray path from a transmitter. The location of all the sites along with the distance between them and the Loran-C stations are presented in Table 1. Pairs of these simultaneous recordings along with the distance between them permit analyses of propagation effects experienced by the pulse during its travel from one site to the other.

Measurements of the pulse made at individual sites were analyzed in several ways. The statistics of the raw measurements on individual pulses were computed as well as the statistics of the averages computed for 50 pulses and for 700 pulses. Statistics of edited data were also computed. By "edited" we mean that all the measurements on each pulse are rejected and the pulse is not counted if any of the measurements on the pulse are more than two standard deviations different from the mean value of that measurement based on the raw data. Of the 12,000 pulses measured in a 20 minute recording, editing threw out 1180 to 5500 pulses depending on the character of the noise.

Figures 4 and 5 are two-dimensional histrograms of two adjacent measurements on the leadingedge of the pulse 2.5 microseconds apart. The first of the two adjacent measurements, Q, is in quadrature with the carrier and the second, I, is in phase. I is plotted as the abscissa and Q as the ordinate. The histogram is generated by considering each pair of Is and Qs to be coordinates of a point in the plane and counting how many points lie in each cell of preselected size. The cell size is 0.0032 volts for Figure 4 and 0.0210 volts for Figure 5 which correspond to 0.017 and 0.365 microseconds of phase respectively. It is very clear that the data are not normally distributed. If they were, we would expect 5 data points to be outside a 16 by 16 cell square centered on Figure 5, whereas the actual number is 215. The probability that this would happen by chance for a normal distribution is less than 10^{-30}.

These histograms can be considered to be phasor diagrams which show the frequency with which the terminus of the electrical vector falls in each cell. The angle of the vector determinable therefrom with respect to the vertical is the error in phase with respect to the phase track point.

The histograms can also be considered a representation of the input to a third cycle phase tracking loop which has no loop closure. Superimposed on the figures are editing windows equivalent to ± 0.102 microseconds for Fig. 4 and ± 1.82 microseconds for Fig. 5. The effect of accepting only data that falls within the window is clearly beneficial since many data outside the window individually would cause large disturbances to the phase tracking loop.

The output of a phase tracking loop is estimated by averaging 700 contiguous edited pulses. Such a tracking loop in the East Coast Chain would have a time constant of about 9 seconds if all of the group of eight pulses were used each GRI. The standard deviation of the estimated output was computed for all first 20-minute segments of data. These results are presented in Table 2. The standard deviations of the differences between the output of such tracking loops at van and NAVOBSY are also presented in Table 2.

We also estimated the standard deviation of the measurement of propagation time between van and NAVOBSY using the averages of the 20 minute edited data segments for all sites as single samples. This standard deviation is 4.8 nanoseconds which includes the deviations due to distance, weather or residual noise.

These same 20-minute averages were used to construct an analytic model of the transmitted Loran-C pulse. Assuming that the pulse is formed by modulation of a 100 kHz carrier, the measured data can be represented over the data span by an equation of the form

$$L(t) = I(t) \sin \omega t + Q(t) \cos \omega t$$

where $L(t)$ is the loran pulse (non-propagating)

$I(t)$ is the sine modulation

$Q(t)$ is the cosine modulation, and

ω is the 100 kHz circular frequency

The functions $I(t)$ and $Q(t)$ were chosen to be 10th degree polynomials in t, computed such that the energy in the $Q(t)$ modulation over the data span from 10 to 70 microseconds was a minimum. These polynomials represent the data with negligible error, typically the standard deviation is one millivolt about mean errors which are less than 28 microvolts. These models were normalized to the same energy at the field sites and at NAVOSBY and used to plot the $I(t)$ and $Q(t)$ functions observed at both sites. Figures 6 and 7 are samples of these plots.

Refer to Figure 6. This figure is an example of those cases in which very little change in the modulations has taken place over the path. We can say, therefore, that what we have measured as the transit time of the pulse (e.g. based on 3rd cycle zero crossing) is indeed the transit time. However, consider Figure 7. Considerable change has taken place in the $Q(t)$ modulation. In this case, it is clear that measurement of the time of arrival of the third cycle zero crossing at both van and NAVOBSY does not produce the transit time. This problem is highlighted in Table 3 which shows the time of zero crossing near 30 microseconds corresponding to the modulation of Figures 6 and 7. Note that the difference between the third cycle zero crossing at the van site at Wilmington and NAVOBSY is about 28 nanoseconds whereas between NAVOBSY and Dexter it is about 240 nanoseconds.

For those cases where the wave form has not changed, the displacement of the envelope at the van with respect to the envelope at NAVOBSY is determined by the difference between group transit time and phase transit time. For the other cases, group and phase transit times have so far refused to be identified. Analysis is continuing in the hope of resolving this problem.

CONCLUDING REMARKS

Analysis of the measurements made on the first pulse of groups of eight in the East Coast Loran-C chain indicate that, over the short term, i.e., 1 hour, these transmitted pulses are very stable. Averages of 700 contiguous pulses exhibit standard deviations between 5 and 40 nanoseconds relative to the mean of the pulses observed during one hour, provided the pulses averaged are limited to those accepted by the editing procedure. This observation applies to all the distances over which the observed pulses were transmitted, a wide variety of weather conditions, and man-made interference. The same statistics apply to the measurement of the transit time of the pulse over the distances used in the test. In a related paper presented by Dr. Klepczynski at this meeting he indicates a probable error of 29 nanoseconds in making clock transfers over the distances of the test. It should be possible therefore to coordinate time by Loran-C to well under a microsecond.

The Loran-C stations transmit both amplitude and phase modulation of the 100 kHz carrier. Over paths which did not substantially modify the phase modulation, both group and phase arrival times can be identified. When the phase modulation is substantially modified over the path, we have not yet discovered a consistent estimator for group or phase arrival times.

During the extensive analyses which have been under way since the first of last July (i.e., July 1975), nothing has been discovered which definitively rules out the eventual accomplishment of our goal, which is to relate group and phase velocities to the vacuum speed of light. We expect to achieve this goal when the propagation of the phase modulation is finally understood.

ACKNOWLEDGEMENT

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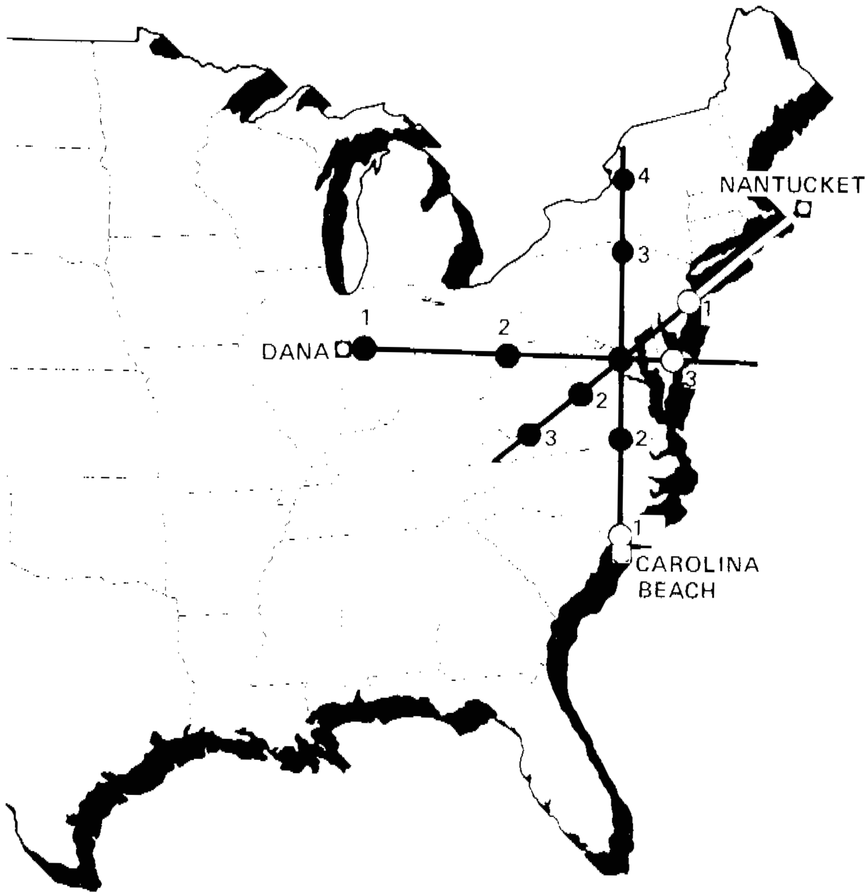

Fig. 1 LOCATIONS OF FIELD TEST SITES

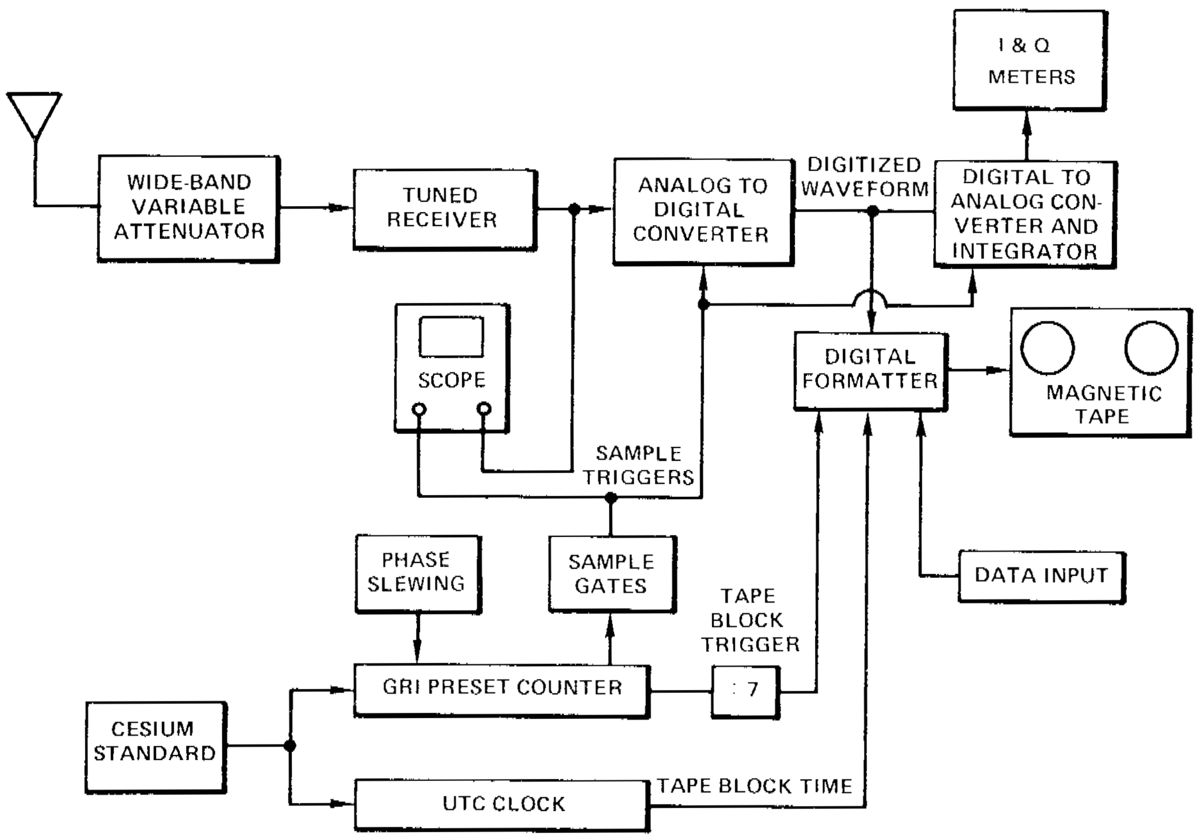

Fig. 2 GROUP/PHASE MEASUREMENT SYSTEM

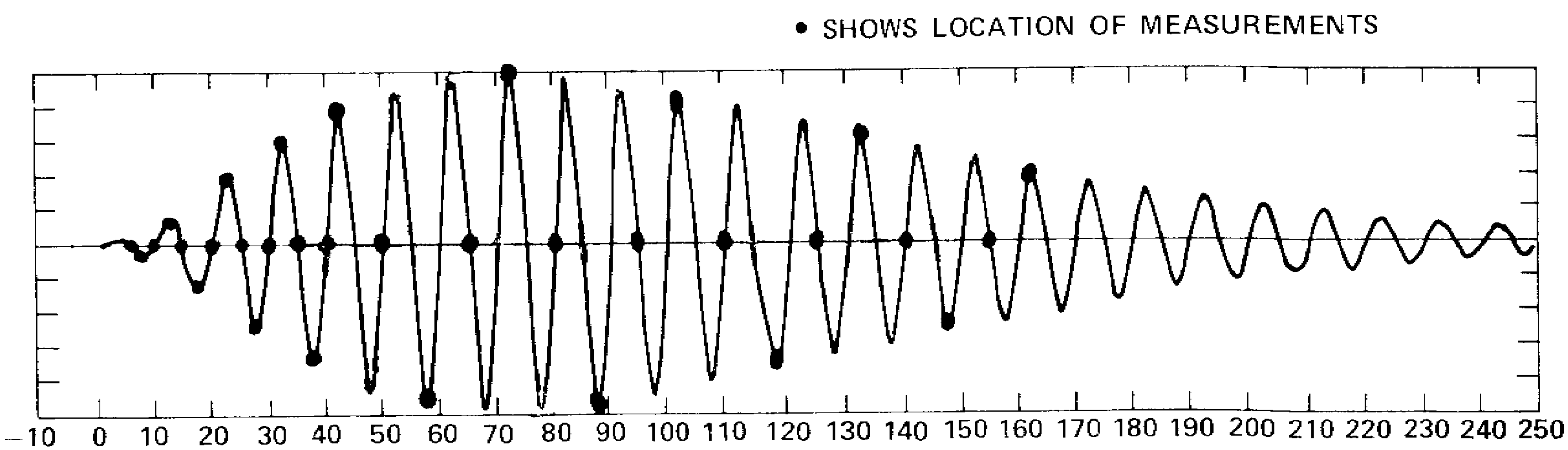

Fig. 3 VOLTAGE MEASUREMENTS ON LORAN PULSE

QUADRATURE, Q

PHASE, I

LOWER Q = -0.4702 LOWER I = 2.4853 INC - 0.0323

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	[illegible]	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	3	0	1	0	0	0	0	[illegible]	0	0	0
0	0	0	0	0	0	0	0	0	1	1	6	5	3	5	1	0	1	0	0	0	0	[illegible]	0	0	0
0	0	0	0	0	0	2	2	3	1	3	8	11	14	10	8	1	3	2	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	2	12	22	24	31	32	25	18	5	7	0	1	0	0	0	0	0	0
0	0	0	0	0	1	2	7	10	39	60	77	78	85	48	43	24	8	5	0	0	0	0	0	0	0
0	0	0	0	1	1	4	10	27	63	126	152	198	195	130	103	46	21	3	5	1	0	0	0	0	0
0	0	0	0	0	1	4	15	51	99	188	306	356	314	251	181	103	38	6	3	0	0	0	0	0	0
0	0	0	0	0	3	4	15	54	128	278	361	425	381	342	294	156	56	16	8	1	0	0	0	0	0
0	0	0	0	0	0	5	15	45	108	212	310	381	378	392	277	119	70	19	7	1	1	0	0	0	0
0	0	0	0	0	0	2	15	32	73	149	190	218	262	264	166	100	33	19	5	5	0	0	0	0	0
0	0	0	0	1	0	3	13	23	63	113	119	140	165	154	77	49	25	6	2	3	0	0	0	0	0
0	0	0	0	0	0	1	8	11	27	47	60	71	95	61	43	23	21	4	2	0	0	0	0	0	0
0	0	0	0	0	0	2	3	5	22	27	38	49	49	28	23	5	3	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	5	9	15	22	20	25	13	13	2	2	2	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	1	3	3	10	15	5	7	3	0	3	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	2	2	6	5	2	0	0	0	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

OUT Q = 1 OUT I = 1

NO. OF POINTS = 12048 AVG Q = -0.0003 AVG I = 2.9054

Q	0	0	0	0	4	9	23	68	180	487	1076	1916	2522	2340	1533	956	474	255	129	51	19	3	3	0	0	0
I	0	0	0	0	2	6	31	104	269	650	1246	1688	2009	2000	1736	1253	633	292	84	33	11	1	0	0	0	0

Fig. 4 HISTOGRAMS OF IN-PLACE AND QUADRATURE DATA TAKEN AT DANVILLE, IN. Q AND I (AT BOTTOM) ARE ONE-DIMENSIONAL HISTOGRAMS

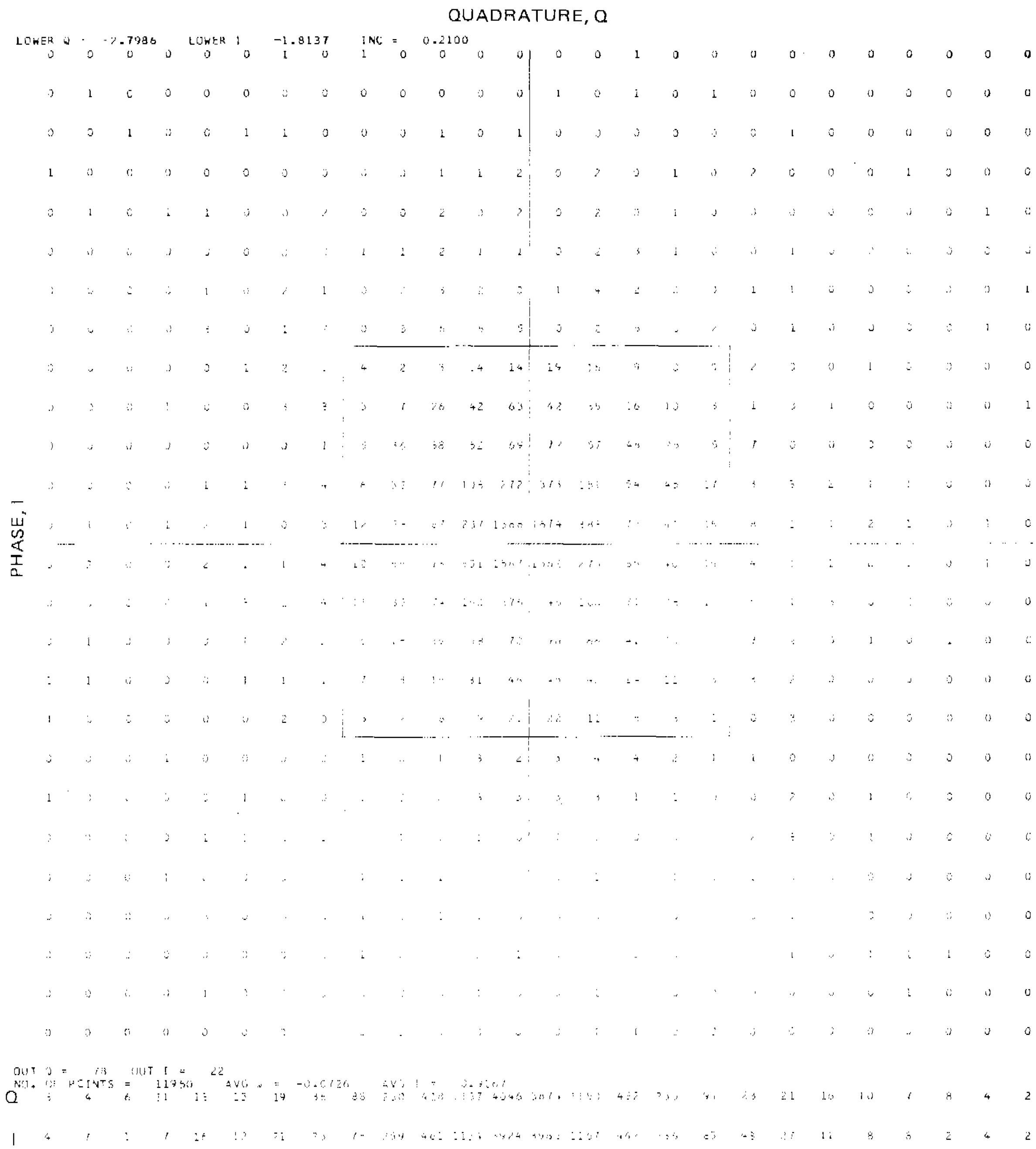

Fig. 5 HISTOGRAMS OF IN-PHASE AND QUADRATURE DATA TAKEN AT BLUEFIELD, WV. Q AND I (AT BOTTOM) ARE ONE-DIMENSIONAL HISTOGRAMS

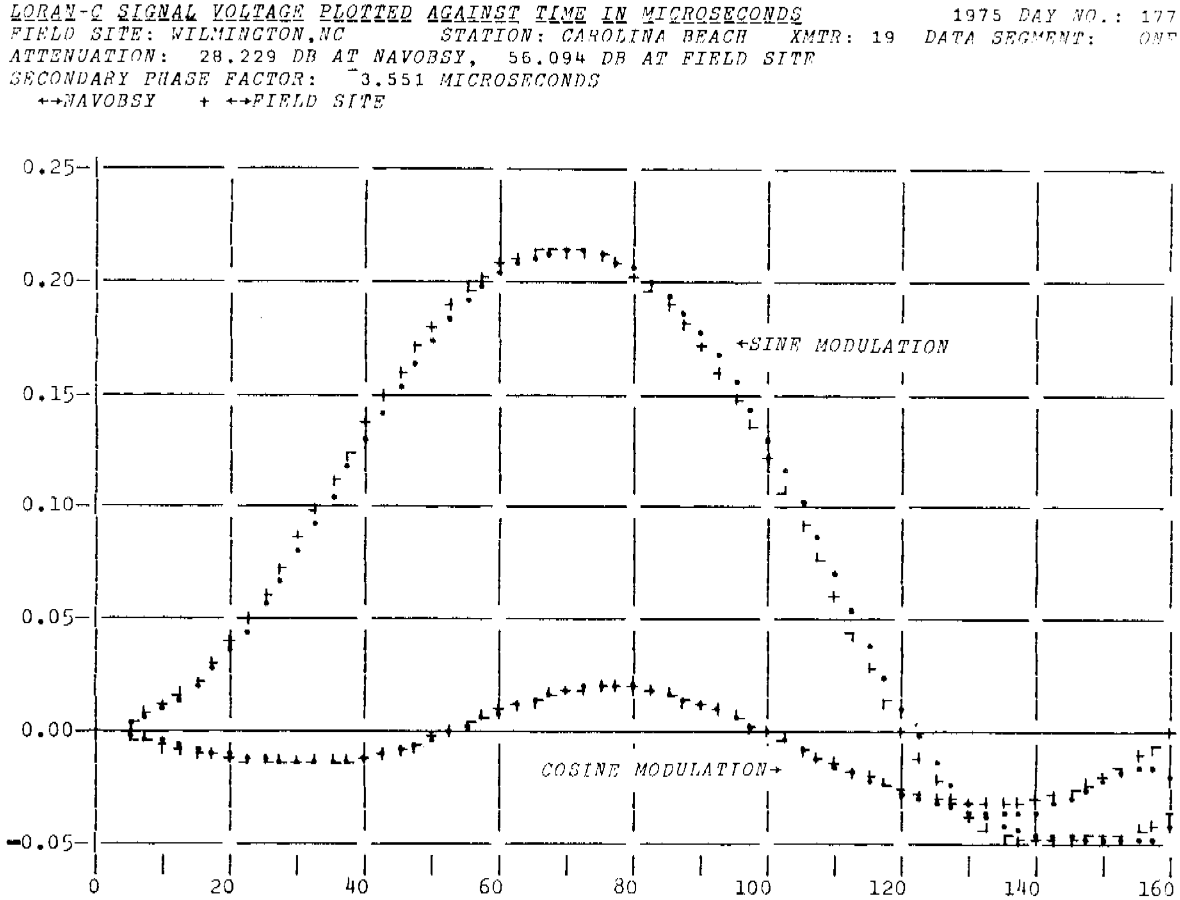

Fig. 6 LORAN-C SIGNAL VOLTAGE PLOTTED AGAINST TIME IN MICROSECONDS: 1975 DAY NO. 177

LORAN-C SIGNAL VOLTAGE PLOTTED AGAINST TIME IN MICROSECONDS 1975 DAY NO.:
FIELD SITE: DEXTER,NY STATION: CAROLINA BEACH XMTR: 19 DATA SEGMENT:
ATTENUATION: 28.393 DB AT NAVOBSY, 8.755 DB AT FIELD SITE
SECONDARY PHASE FACTOR: 4.222 MICROSECONDS
. ←→NAVOBSY + ←→FIELD SITE

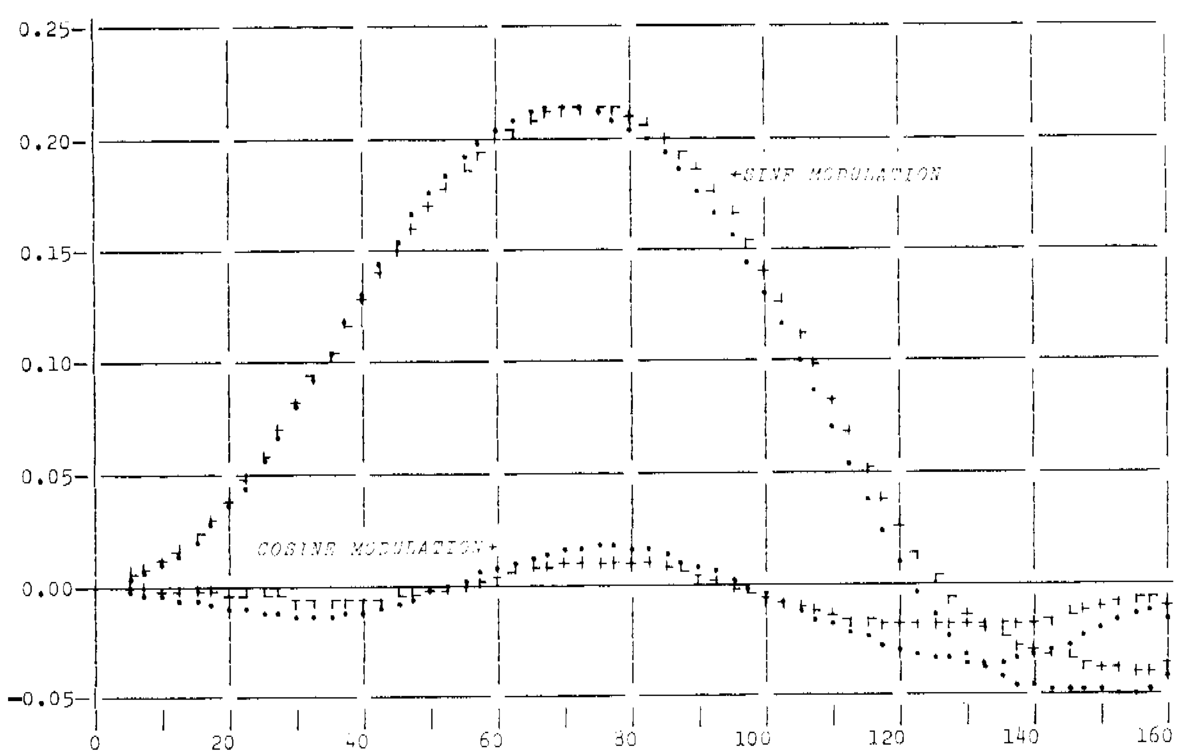

Fig. 7 LORAN-C SIGNAL VOLTAGE PLOTTED AGAINST TIME IN MICROSECONDS: 1975 DAY NO. 181

Table 1

DISTANCE FROM LORAN-C STATIONS TO TEST SITES IN METERS

Test Sites	Station	Distance
Wilmington, NC	Carolina Beach	23572.074
Emporia, VA	Carolina Beach	293343.813
Towanda, PA	Carolina Beach	867731.246
Dexter, NY	Carolina Beach	1113945.864
Danville, IN	Dana	85946.204
Marietta, OH	Dana	526905.326
Georgetown, DE	Dana	1053516.979
Toms River, NJ	Nantucket	384345.877
Grottoes, VA	Nantucket	827589.501
Bluefield, WV	Nantucket	1063424.588
NAVOBSY	Carolina Beach	544243.957
NAVOBSY	Dana	903083.427
NAVOBSY	Nantucket	657576.077

Table 2

STANDARD DEVIATIONS IN MICROSECONDS OF AVERAGES OF
700 PULSES DURING THE FIRST 20
MINUTES OF RECORDING AT EACH SITE

Van Site	XMTR	Van	NAVOBSY	Van-NAVOBSY
Wilmington, NC	Carolina Beach	.005	.010	.006
Emporia, VA	Carolina Beach	.005	.008	.005
Towanda, PA	Carolina Beach	.023	.016	.027
Dexter, NY	Carolina Beach	.008	.010	.013
Danville, IN	Dana	.005	.027	.027
Marietta, OH	Dana	.008	.026	.023
Georgetown, DE	Dana	.022	.022	.029
Toms River, NJ	Nantucket	.011	.040	.038
Grottoes, VA	Nantucket	.015	.012	.022
Bluefield, WV	Nantucket	.024	.010	.021

Table 3

TIME OF ZERO CROSSINGS IN THE PULSE TRANSMITTED FROM CAROLINA BEACH

Day	Test Site	Time of Zero Crossing (μsec)				
177	Wilmington	20.3274	25.2266	30.1417	35.0691	40.0045
		20.3272	25.2269	30.1422	35.0697	40.0048
		20.3259	25.2260	30.1416	35.0693	40.0047
	NAVOBSY	20.3380	25.2486	30.1706	35.1021	40.0389
		20.3401	25.2493	30.1705	35.1016	40.0384
		20.3354	25.2479	30.1705	35.1020	40.0386
181	NAVOBSY	20.3299	25.2497	30.1772	35.1124	40.0526
		20.3326	25.2465	30.1756	35.1156	40.0607
		20.3224	25.2368	30.1667	35.1071	40.0527
	Dexter	19.9644	24.9466	29.9347	34.9229	39.9074
		19.9657	24.9511	29.9394	34.9260	39.9083
		19.9524	24.9419	29.9332	34.9215	39.9046

QUESTION AND ANSWER PERIOD

LCDR. POTTS:

Cy Potts, Coast Guard.

I have several brief questions. First of all, I would like to know what type of distribution you saw in the data. Did it approach a normal distribution?

MR. ROLL:

It was a normal contaminated by the sporadic interference -- impulsive stuff. It was clearly not a normal distribution as a whole.

LCDR. POTTS:

Were the synchronization adjustments made by the stations removed from the data?

MR. ROLL:

There were no synchronization adjustments made during the data runs by cooperation of the chain commander.

LCDR. POTTS:

And how did you handle interference, synchronous and near-synchronous?

MR. ROLL:

There were four notch filters which were tuned to the NSS frequencies and were nailed down. We had no other problems other than NSS.

DR. REDER:

Is it out of the question that the cosine modulation which you saw was introduced by the propagation media? Has a measurement been taken close to the transmitter site?

MR. ROLL:

One of the measurements, the one at Wilmington, North Carolina is only 25 kilometers; it is there, and it has not substantially changed after 500 kilometers.

DR. REINHARDT:

Victor Reinhardt, Goddard Space Flight Center.

You mentioned that the scatter for short-term data taking was 30 nanoseconds. Did you take any data with respect to diurnal variations?

MR. ROLL:

Data were taken with respect to diurnal, but have not been analyzed. We have several hours reporting on a sunset, during sunset, at both ends of the path where the terminator crosses the path. We have that data, but it has not been analyzed.