PRECISE TIME AND TIME INTERVAL (PTTI) DISSEMINATION VIA THE LORAN-C SYSTEM

by Cyrus E. Potts*

INTRODUCTION

During the last decade the rapid growth of time/frequency technology has brought forth various requirements which have, in some cases, exceeded the capabilities of the available services. Consequently, many new schemes have been proposed, and some implemented, to transfer time and time interval from one geographic location to another. These schemes vary from the physical transportation of precision standards and clocks, to the utilization of electromagnetic emissions from ground-based as well as airborne and earth satellite sources. For economic reasons most of the latter schemes involve the piggybacking of the time service on existing or proposed communications, navigation, or other types of systems. This paper describes PTTI dissemination on one such system, the LORAN-C navigation system. Emphasis is placed on those advantageous characteristics which are of the greatest interest to potential users while at the same time equal time is given to system limitations. At this point in time/frequency technology growth, there is no single system which is a panacea for PTTI user requirements.

BACKGROUND

The LORAN-C Navigation System was conceived as, and primarily serves as, a long-range precision hyperbolic navigation system which

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typically offers users several hundred feet position accuracy at ranges in excess of 1000 nautical miles.[1] However, in recent years improvements to the system have resulted in increased reliability and accuracy and have offered a modem for ancillary uses including range-range mode navigation[2] (both intra- and inter-chain), communications, and PTTI. The ability of the system to be utilized for dissemination of PTTI derives from the excellent long-term stability of the atomic frequency which are used to control the emissions from the individual LORAN-C stations. Cesium beam frequency standards are installed at all LORAN-C stations and provide the fundamental source of timing necessary for both the navigation and PTTI functions. By setting the frequency of the standards to a convenient scale, currently Universal Coordinated Time (UTC), the emissions themselves become a reliable frequency reference, and the pulsed format allows the recovery of epoch information. Since a common frequency source is used at each station, the pulse interval and carrier phase information are coherent.

The LORAN rates assigned to the individual LORAN-C chains serve to identify the transmissions of one chain from another, eliminate mutual interference, and optimize the signal-to-noise ratio for the particular chain geographic configuration. The transmissions are in the form of groups of nine pulses from the master station and eight from the slave station. The leading edge of the transmitted pulse envelope can be approximated by the expression $e(t) = t^2 \epsilon^{-at}$, where α is chosen to maximize the expression for t equal to 65-70 μsecs. Figure 1 illustrates the normalized ideal LORAN-C pulse leading edge for two values of α. By definition, the start of the LORAN-C pulse is that point which precedes the third to fourth RF cycle zero crossing by 30 μsecs. This third to fourth cycle zero crossing is also the normal receiver phase tracking point, since it usually yields the maximum signal-to-noise ratio without skywave contamination. Phase coding of the individual

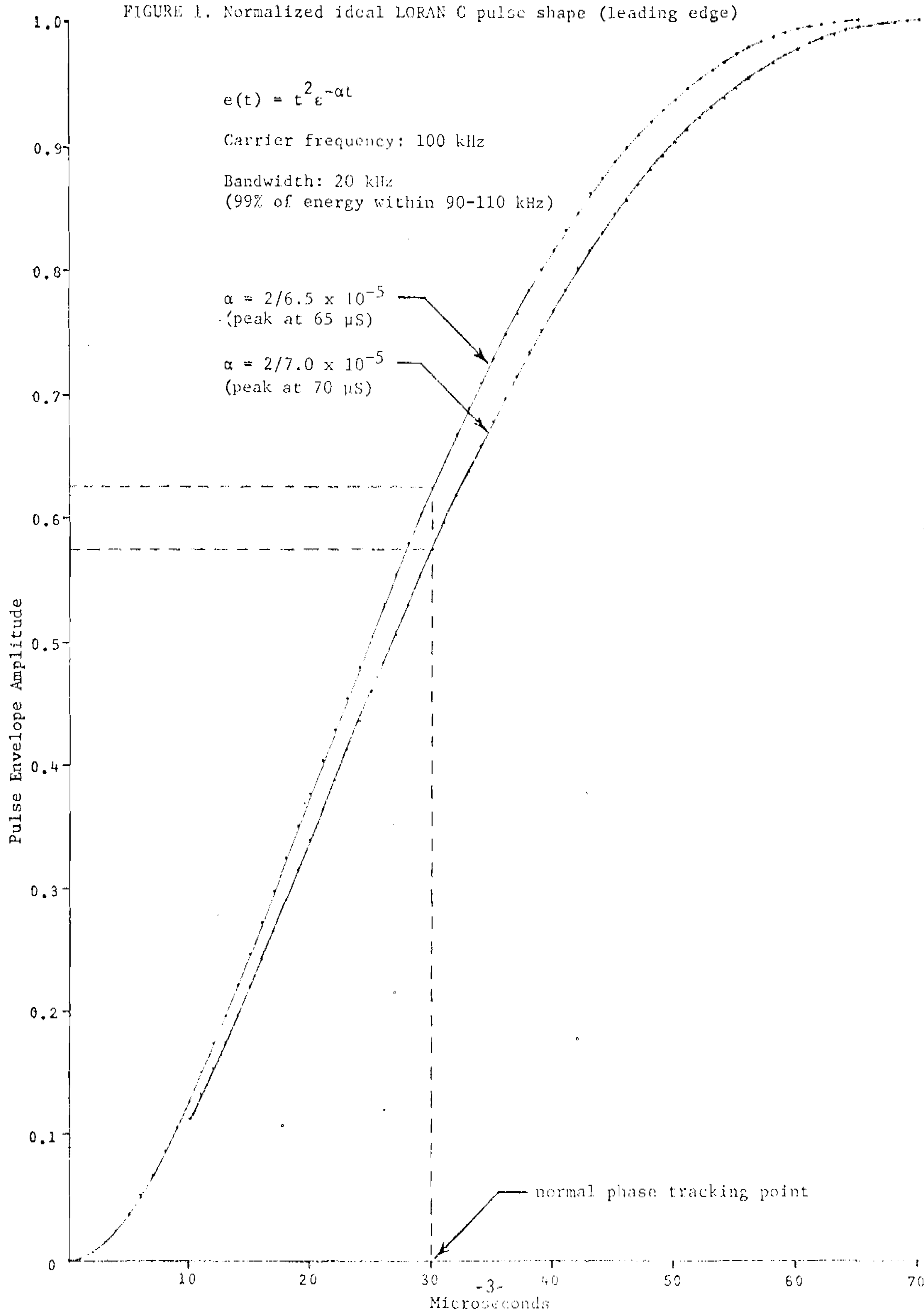


FIGURE 1. Normalized ideal LORAN C pulse shape (leading edge)
e(t) = t²ε^(-αt)
Carrier frequency: 100 kHz
Bandwidth: 20 kHz
(99% of energy within 90-110 kHz)
α = 2/6.5 x 10^-5
(peak at 65 μS)
α = 2/7.0 x 10^-5
(peak at 70 μS)
normal phase tracking point
Pulse Envelope Amplitude
Microseconds
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
10
20
30
40
50
60
70

-3-

FIGURE 1

pulses within a pulse group is employed to reduce skywave and other interference. Positive phase code means the first RF cycle starts in a positive direction. Negative phase code is 180° in opposition to positive phase code. The pulse group format and phase code format are illustrated in Figure 2.

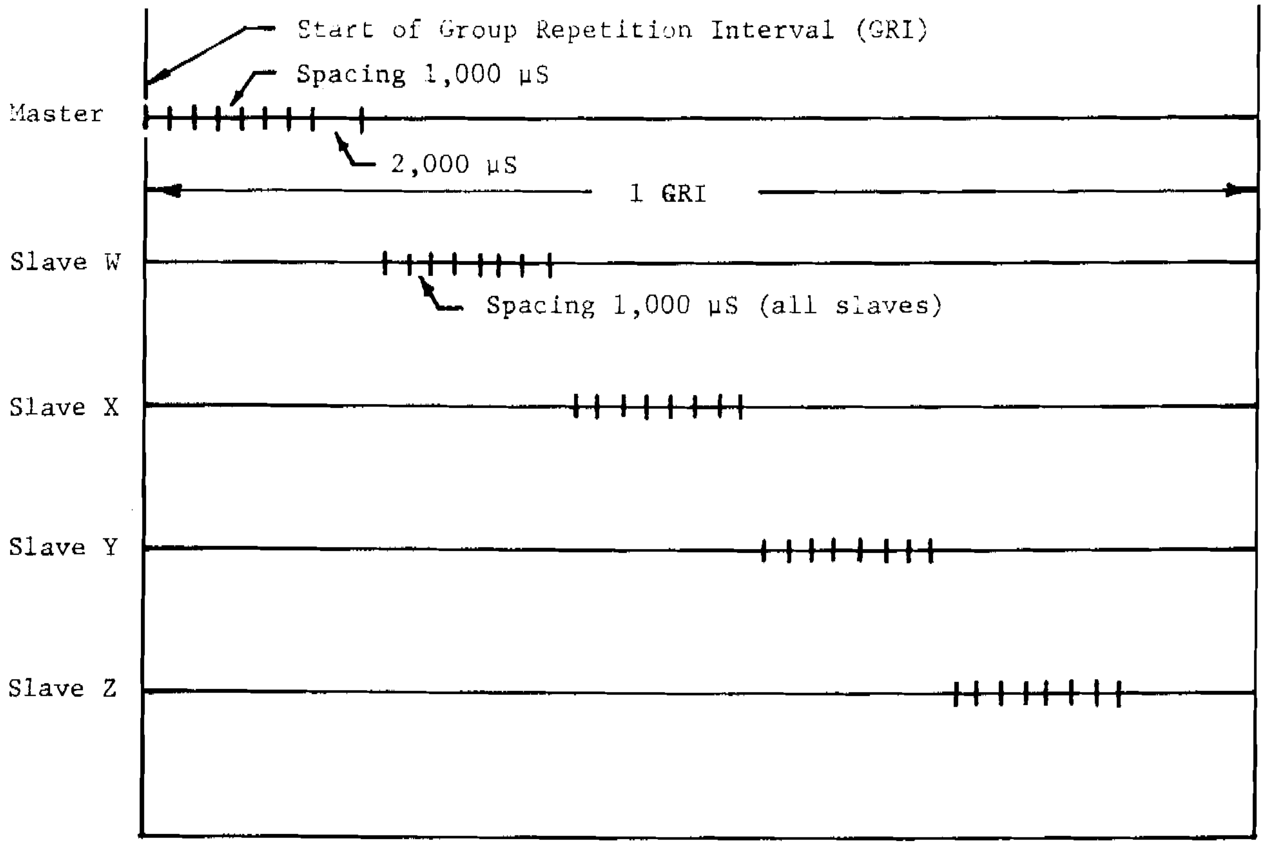
The master station blinks the ninth pulse to indicate that one or more of the chain legs are unusable for navigation. The ninth pulse is blinked in the Morse code for the character R (·—·) followed by one, two, three, or four dots (·) indicating unusability of the X, Y, Z, or W legs, respectively. The blink interval is twelve seconds. The slave stations blink their first two pulses; on for 0.25 seconds, off for 3.75 seconds (approximate) to indicate that their respective legs are unusable.

There are eight LORAN-C chains at present, all located in the Northern Hemisphere. Table I lists the pertinent data for all LORAN-C stations and reflects recent changes.

TIMING A LORAN-C CHAIN

LORAN-C chains are timed by synchronizing the transmissions of the master station to the U. S. Naval Observatory master clock. No special procedures are required at the slave stations, since they are already synchronized to the master station to fulfill the navigation requirement. Since most LORAN basic and specific rates are not submultiples of one second, there is only periodic coincidence between the LORAN pulse groups and a Universal Time Second (UTS, a second on the Universal Time Scale). For example, coincidence occurs every 3 seconds for rate SHO but only once every 999 seconds for rate SS1. Table II illustrates the basic and specific LORAN rates, and the period between coincidences for the rates. Because of the typically long baselines between stations, LORAN rates L and H are not used in the LORAN-C system. To provide knowledge of specific coincidences for the chains

PULSE GROUP FORMAT



PHASE CODE

	1st GRI	Alternate GRI
Master	+ + − − + − + −	+ + + + + − − +
Slave	+ − − + + + + +	+ − + − + + − −

Figure 2. LORAN C Pulse Group and Phase Code formats.

TABLE I. LORAN C STATION INFORMATION

CHAIN	RATE	STATIONS	EMISSION DELAY(μS)	POWER(kW)
U. S. EAST COAST	SS7	M Carolina Beach, N.C.		1,000
		W Jupiter, Fla.	13,695.48	400
		X Cape Race, Newfoundland	36,389.56	2,500
		Y Nantucket Is., Mass.	52,541.27	400
		Z Dana, Ind.	68,560.68	400
MEDITERRANEAN	SL1	M Simeri Crichi, Italy		300
		Y Targabarun, Turkey	32,273.28	300
		Z Estartit, Spain	50,999.68	300
NORWEGIAN SEA	SL3	M Ejde, Faroe Is.		400
		W Sylt, Germany	30,065.69	400
		X Bo, Norway	15,048.16	300
		Y Sandur, Iceland	48,944.47	1,500
		Z Jan Mayen, Norway	63,216.20	300
NORTH ATLANTIC	SL7	M Angissoq, Greenland		500
		W Sandur, Iceland	15,068.10	1,500
		X Ejde, Faroe Is.	27,803.80	400
		Z Cape Race, Newfoundland	48,212.80	2,500
NORTH PACIFIC	SH7	M St. Paul, Pribiloff Is.		400
		X Attu, Alaska	14,875.30	400
		Y Port Clarence, Alaska	31,069.07	1,800
		Z Sitkinak, Alaska	45,284.39	400
CENTRAL PACIFIC	S1	M Johnston Is.		400
		X Upolo Pt., Hawaii	15,972.44	400
		Y Kure, Midway Islands	34,253.02	400
NORTHWEST PACIFIC	SS3	M Iwo Jima, Bonin Islands		3,000
		W Marcus Island	15,283.94	3,000
		X Hokkaido, Japan	36,684.70	400
		Y Gesashi, Okinawa	59,463.34	400
		Z Yap, Caroline Islands	80,746.78	3,000
SOUTHEAST ASIA	SH3	M Sattahip, Thailand		400
		X Lampang, Thailand	13,182.87	400
		Y Con Son, South Vietnam	29,522.12	400
		Z Tan My, South Vietnam	43,807.30	400

TABLE II. BASIC AND SPECIFIC RATE AND COINCIDENCE INFORMATION.

BASIC AND SPECIFIC RATES: (pulse group repetition interval in microseconds)

Specific \ Basic	S	SH	SL	SS
0	50,000	60,000	80,000	100,000
1	49,900	59,900	79,900	99,900
2	49,800	59,800	79,800	99,800
3	49,700	59,700	79,700	99,700
4	49,600	59,600	79,600	99,600
5	49,500	59,500	79,500	99,500
6	49,400	59,400	79,400	99,400
7	49,300	59,300	79,300	99,300

PERIOD OF TIME BETWEEN UTS AND LORAN RATE COINCIDENCES: (in seconds)

Specific \ Basic	S	SH	SL	SS
0	1	3	2	1
1	499	599	799	999
2	249	299	399	499
3	497	597	797	997
4	31	149	199	249
5	99	119	159	199
6	247	297	397	497
7	493	593	793	993

in operation, null ephemeris table has been devised by the U S Naval Observatory (USNO). As an initial arbitrary epoch, all LORAN-C master stations are assumed to have transmitted their first pulse at $00^h\ 00^s$, 1 January 1958. The periodic coincidences are thus computed from this epoch and are tabulated in null ephemeris tables, covering a full year, which are published by the USNO in Time Service Announcement, Series 9.

When a master station is synchronized to UTC, special equipment is installed in order to ensure the PTTI reliability. This equipment includes multiple cesium standards, redundant rate generation and time-of-day devices, and sufficient battery power to withstand extended power failures. Only a catastrophic failure would prevent the station from knowing its correct transmission time. Even in that event, the slave stations or system monitor could direct the repositioning of the master transmissions. The special equipment also allows the master station to transmit an additional pulse, once per second (1 pps), which a user within range may utilize to recover or maintain time. This 1 pps transmission is inhibited during the time that it is coincident with the master's normal pulse group. User techniques will be addressed later in this paper.

The transmissions from timed LORAN-C chains are monitored by special Time Monitor Stations within the prime coverage area. The readings taken by these stations are forwarded to the USNO, correlated, and then published by the USNO in Daily Relative Phase Values, Series 4, which is available upon request.

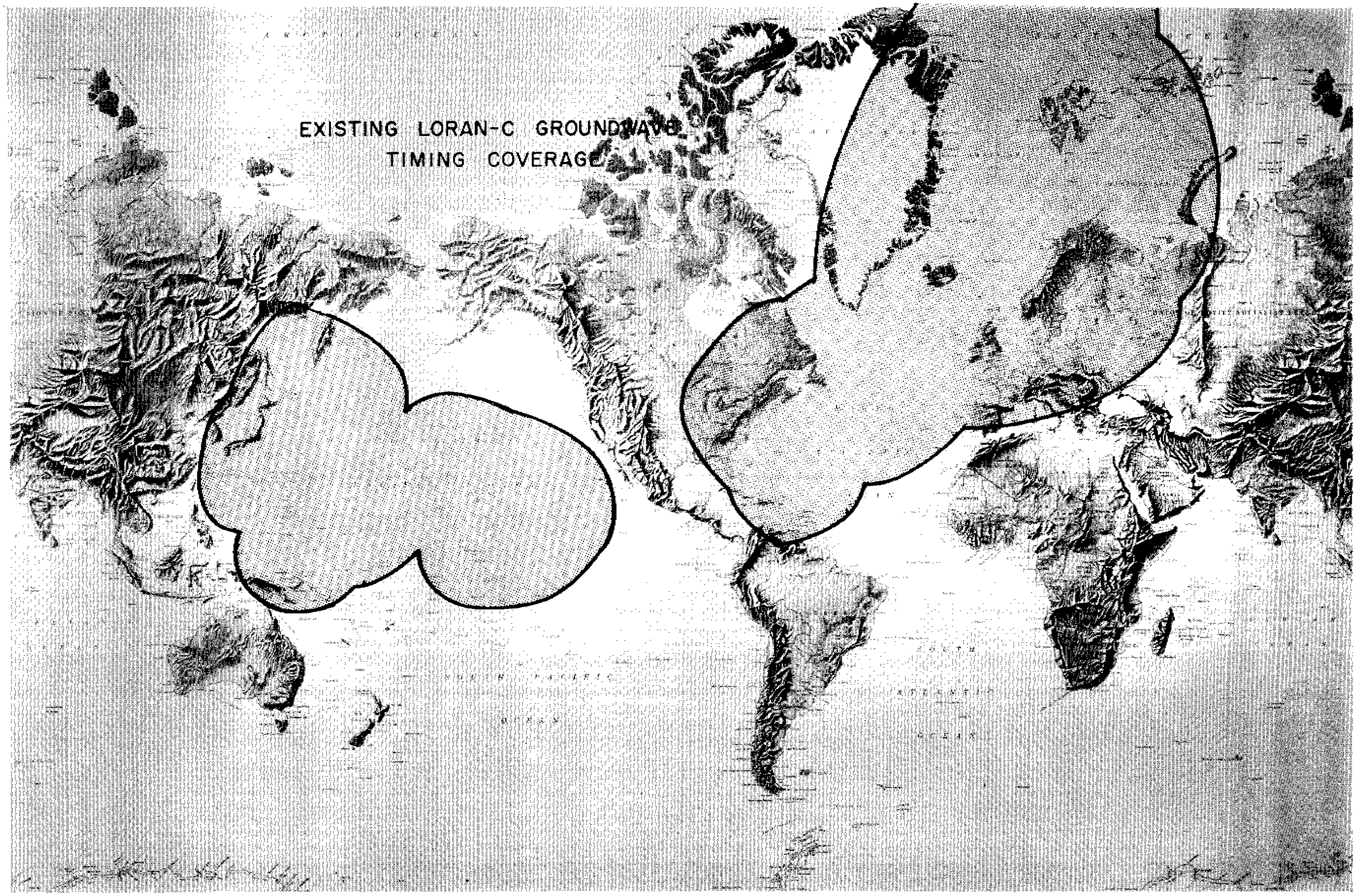
COVERAGE

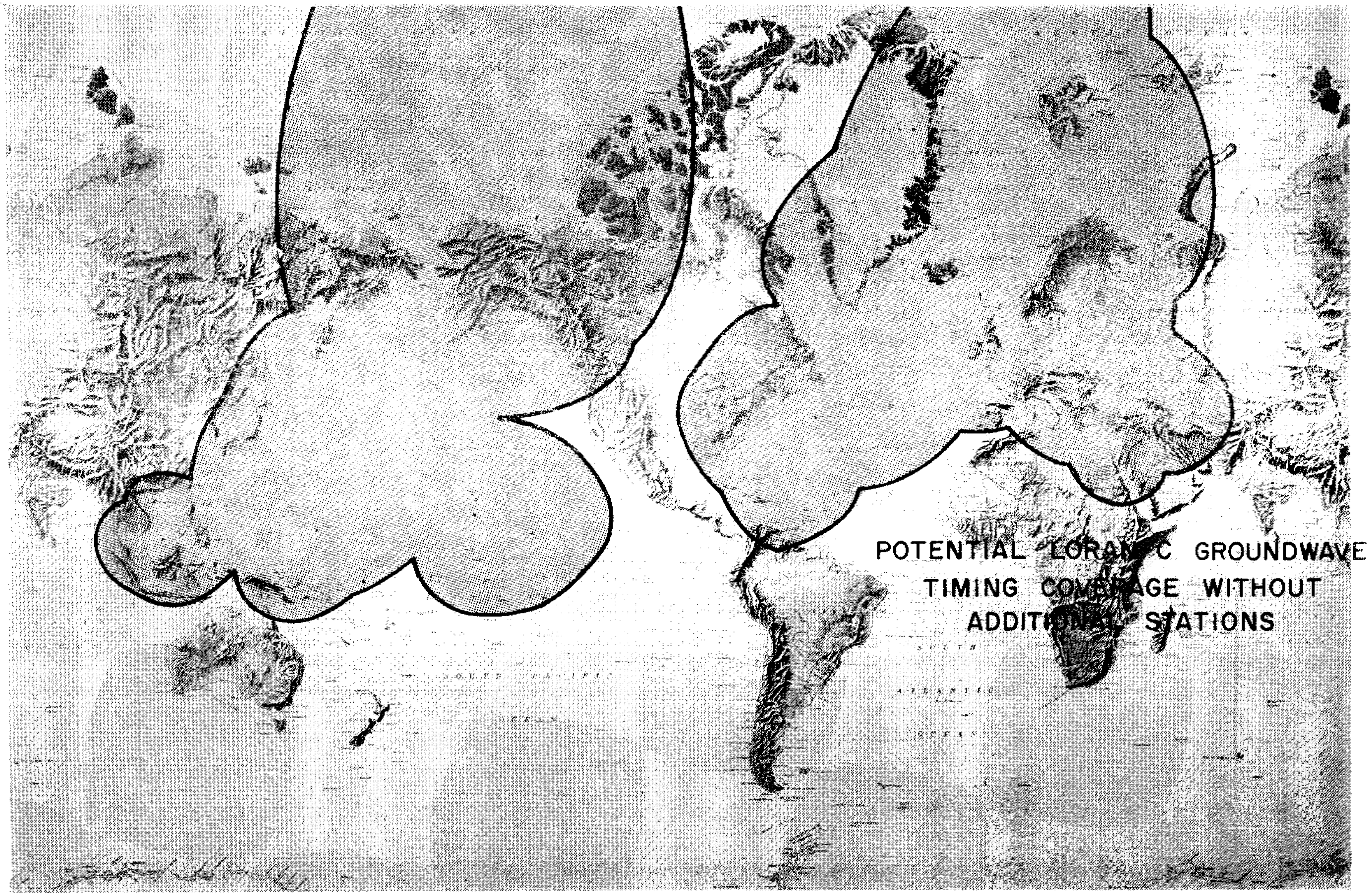
It is always difficult to exactly define limits of coverage for electromagnetic emissions, since many variables are involved (e.g., receiver sensitivity, atmospheric noise condition, propagation conditions, conductivity, local noise and interference, etc.). Figure 3 illustrates the approximate groundwave coverage which is presently available from the four LORAN-C chains which have been permanently synchronized to the USNO master clock. These chains are: the U. S. East Coast, the Norwegian Sea, the Northwest Pacific, and the Central Pacific. Permanent synchronization is synonomous with having the special equipment installed at the master station. One additional chain, the Mediterranean, has been synchronized since July 1969 on a temporary basis in support of NASA's APOLLO missions. Another chain, the North Atlantic, is synchronized "de facto" since it operates in conjunction with time chains on either side of it. The daily values for these two latter chains are published by the USNO in addition to those for the permanently synchronized chains. Thus, the existing groundwave coverage for PTTI is considerably extended, if these two chains are included. Figure 4 illustrates the groundwave coverage which will be available when the remaining chains are timed. These two chains, the Southeast Asia and the North Pacific, are presently useful for relative PTTI on an intrachain basis since the operating frequency is on the UTC scale.

USER INSTRUMENTATION AND TECHNIQUES

Shapiro[3,4] has covered instrumentation methods in considerable detail and no effort will be made to duplicate that work. Instead, simple block diagrams and descriptions will be used to illustrate the types of instrumentation and techniques which may be used to recover PTTI from the received LORAN-C transmissions. Kramer[5] has all ready furnished details of receiver design and construction.

Previously, it was noted that an additional pulse, transmitted once per second, was available from timed master stations for those users within groundwave range. To utilize this pulse, an equipment configuration similar to that shown in Figure 5 is suggested. The band


EXISTING LORAN-C GROUNDWAVE
TIMING COVERAGE


POTENTIAL LORAN C GROUNDWAVE
TIMING COVERAGE WITHOUT
ADDITIONAL STATIONS

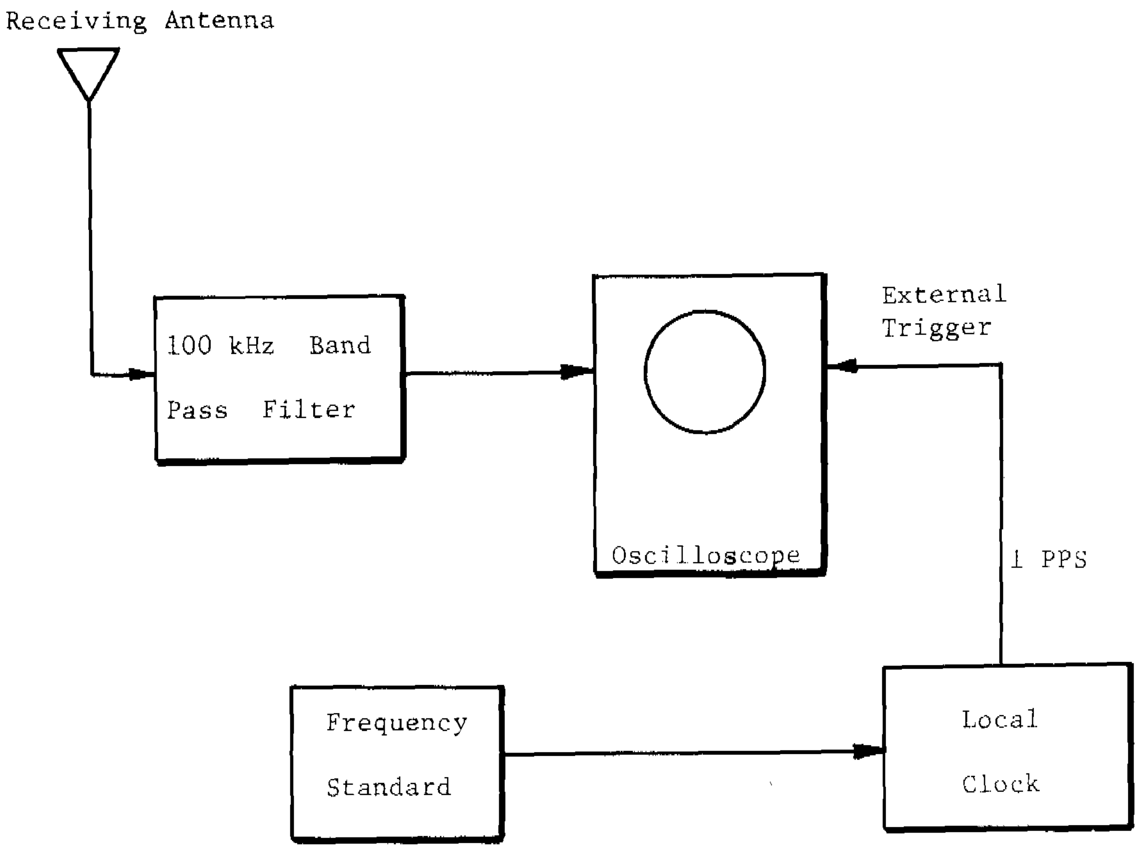


Figure 5. Instrumentation for utilization of the 1 PPS transmission from timed master stations.

The ultimate precision achievable is obtained by utilizing all of the pulses within the pulse groups transmitted from a single station. This provides the maximum information rate and the maximum signal-to-noise ratio for a given user location and equipment configuration. The equipment required is illustrated in Figure 6. The receiver contains not only signal processing circuits but also a phase-locked loop and digital circuitry to provide output triggers which are synchronized to the received LORAN-C carrier phase. The local frequency standard and clock are then used as inputs to a LORAN rate generator which is synchronized to the LORAN-C ephemeris table. The outputs of the LORAN rate generator and receiver are then used to start and stop (respectively) a time interval counter. At this point, depending on exact equipment configurations, the user has a choice of information (a counter reading update) at the rate of once every Group Repetition Interval (GRI), once every second, or once every Time Of Coincidence (TOC). The precision remains the same for all cases the differences lie in the digital circuitry involved. The counter reading again represents the sum of the propagation and emission delays between the LORAN-C station and the user's location, any receiving systems delays, the published correction for the LORAN-C chain, and the user's clock must initially be correct to within plus or minus one-half of the LORAN repetition interval in order to eliminate any ambiguity. User costs for this type PTTI recovery range from $7,000 to $10,000, assuming commercial procurement.

FREQUENCY CONTROL

One of the fringe benefits of phase-locking a local frequency standard to the received LORAN-C groundwave carrier phase is that the local standard does not have to exhibit good long-term stability on its own. Indeed, one may use a good quality crystal oscillator and take advantage

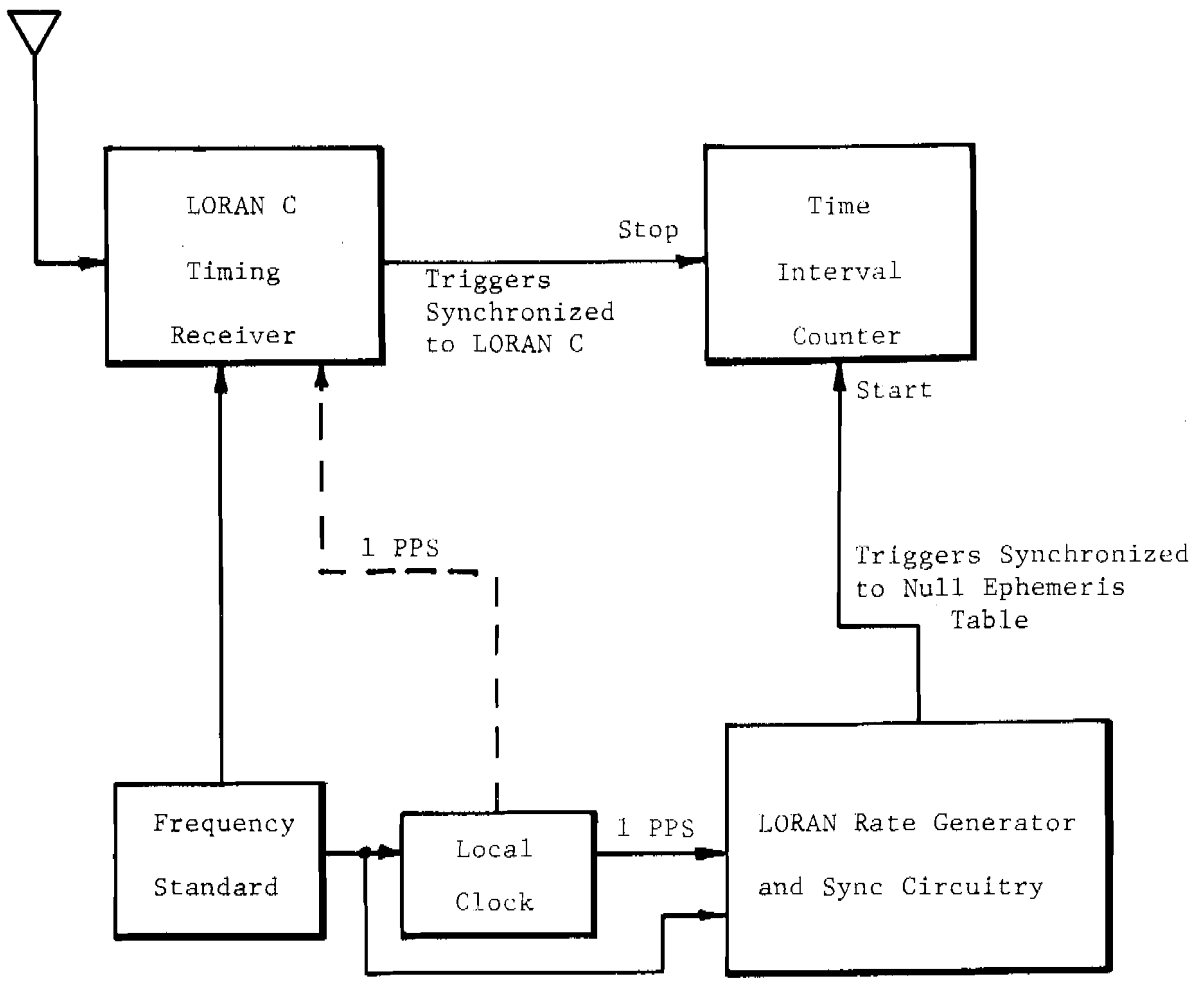


Figure 6. Instrumentation for utilization of the pulses within the LORAN C pulse groups.

of the excellent short-term stability while enjoying the excellent long-term stability of the cesium standard installed hundreds of miles away. This is possible since the groundwave at 100 KHz exhibits negligible diurnal shift. Stone[6] has demonstrated the success of this technique. In-house schemes may be employed at costs of less than $100, while commercial equipment is available in the range of $500 to $1,000, depending on optional accessories desired. Since the frequency of the LORAN-C chain is traceable to either the U. S. Naval Observatory or the National Bureau of Standards, the local standard output may be used to calibrate other equipment. It should not be necessary to point out that it may also be used to drive a precision clock.

The frequency of the radiated carrier at LORAN-C master stations is nominally maintained within $\pm 2 \times 10^{-12}$ with respect to UTC. It is typically within $\pm 1 \times 10^{-12}$, and on several occasions chains have been within 1×10^{-13} for a period of months. Although the slave stations operate in what is termed the "free running mode" (i.e., active phase-locked synchronization to the master received phase is not maintained and corrections necessary to maintain the required navigation synchronization are inserted as incremental phase steps), the frequency of the slave cesium standards is rigidly maintained within $\pm 5 \times 10^{-13}$ with respect to the master station standard in order to minimize the necessary phase corrections. Consequently, a user who phase-locks his local standard to the received carrier phase from a slave station is in fact (for periods in excess of one day) phase-locked to the master carrier as well; and the frequency of the received slave carrier may be considered identical to that of the master station frequency standard.

PRECISION

Pakos[7] has given a great deal of attention to the error budgets involved in LORAN-C timing from the user's standpoint. That work will not be repeated here, but can be summarized quite readily. Pakos' one sigma error estimates of the different error sources are·

- System error, $\sigma_{SE} = 3.0\ \mu sec$
- User prediction error, $\sigma_{PE} = 0.1\ \mu sec$
- Groundwave propagation anomoly (over land), $\sigma_{PA} = 0.2\ \mu sec$
- Slave synchronization error, $\sigma_{SS} = 0.05\ \mu sec$
- UTC tolerance,* $\sigma_{UT} = 2.0\ \mu sec$
- User measurement error, $\sigma_{ME} = 0.1\ \mu sec$

Using these values, one can calculate that two users who wish to synchronize to each other (but not to UTC) and who are within groundwave range of the same master station may expect an rms error of 0.35 μsec. On the other hand, a user who wishes to synchronize a clock to UTC using a slave station could expect an rms error of 3.6 μsec. However, if the user was willing to wait a day to remove the UTC error and had been visited once by a portable clock (to remove prediction and system errors), he could expect the rms error to be reduced to 0.27 μsec. The best use under the error estimates given by Pakos would be made by one who used a master station for synchronization, waited a day to remove the UTC error, had been visited once by a portable clock, and whose propagation path from the master station was over seawater. In this case the rms error would be the measurement error, 0.1 μsec. The advantages of a single portable clock visit to the user's site to "calibrate" the receiving system are quite obvious.

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*This is really an uncertainty figure and does not relate to the operational UTC tolerance held by the chains.

Analysis of the data contained in the USNO's Daily Relative Phase Values, Series 4, is quite revealing. The data was processed in the following manner: First, the daily values were plotted with intentional (announced) time steps removed. The resultant curves were then partitioned to segregate periods of operation free of frequency or other adjustments. Then a linear regression was performed on the data to determine frequency offset and the degree of correlation. Next the slope and mean value were removed and the standard deviation was calculated. The results are as indicated in Table III. Further analysis of the results reveal an expected value of 0.35 μsec for 2,832 samples (days). This effectively represents approximately eight years of data. On the basis of these results Pakos' one sigma error estimate for the UTC tolerance would appear to be excessive. If we stipulate that the system error can be removed by calibration (work has already begun), then one of the two major error sources is removed and the other is reduced to a value commensurate with the remaining factors in the error budget. Returning for a moment to the case of the user who wishes to synchronize to UTC using a slave station (rms error previously reported as 3.6 μsec), recalculating the rms error using the new estimate for σ_{UT}(0.35) and assuming σ_{SE} equals zero, we find that the rms error is now calculated to be 0.43 μsec. Recall that this user has not been visited by a portable clock and does not know the chain correction for the day of measurement. This recalculated rms error agrees well with the author's experience in field measurements.

SKYWAVE USE

Thus far, only groundwave coverage and precision have been mentioned, although LORAN-C skywaves offer an excellent modem for PTTI dissemination if slightly degraded accuracy is acceptable. An offsetting advantage lies in the fact that time recovery from LORAN-C

TABLE III. RESULTS OF ANALYSIS OF PUBLISHED LORAN C DAILY RELATIVE PHASE VALUES

CHAIN	PERIOD	NO. OF DAYS	$\sigma(\mu S)$	R*
U. S. EAST COAST	FEB 1, 1968 - JAN 15, 1969	349	0.89	.90
	JAN 16 - MAR 30, 1969	74	0.18	†
	MAR 31 - AUG 25, 1969	148	0.38	.96
	AUG 26 - NOV 1, 1969	67	0.19	.98
	NOV 2 - DEC 12, 1969	42	0.11	.99
	DEC 13, 1969 - FEB 12, 1970	62	0.28	†
	FEB 13 - JUL 7, 1970	145	0.40	.98
	AUG 8 - SEP 17, 1970	41	0.08	1.00
	SEP 18 - NOV 18, 1970	62	0.12	†
NORTH ATLANTIC	JAN 1 - JUL 2, 1970	181	0.40	.96
	JUL 3 - NOV 18, 1970	140	0.30	†
NORWEGIAN SEA	OCT 15, 1968 - MAR 30, 1969	168	0.49	.94
	MAR 31 - NOV 14, 1970	279	0.43	.98
	NOV 15, 1969 - JAN 20, 1970	67	0.29	.97
	JAN 21 - APR 12, 1970	82	0.27	.99
	APR 13 - JUL 30, 1970	109	0.35	.96
	JUL 31 - NOV 18, 1970	111	0.28	.99
MEDITERRANEAN SEA	NOV 1, 1969 - FEB 12, 1970	104	0.40	†
	FEB 12 - JUN 16, 1970	124	0.33	.92
	JUN 24 - OCT 3, 1970	102	0.39	.96
	OCT 4 - NOV 19, 1970	47	0.20	.90
CENTRAL PACIFIC	FEB 11 - MAR 31, 1970	49	0.17	†
	APR 13 - MAY 26, 1970	44	0.30	.94
	MAY 27 - JUL 19, 1970	54	0.15	.87
	JUL 20 - NOV 17, 1970	121	0.45	.97
NORTHWEST PACIFIC	(NOT ANALYZED)			

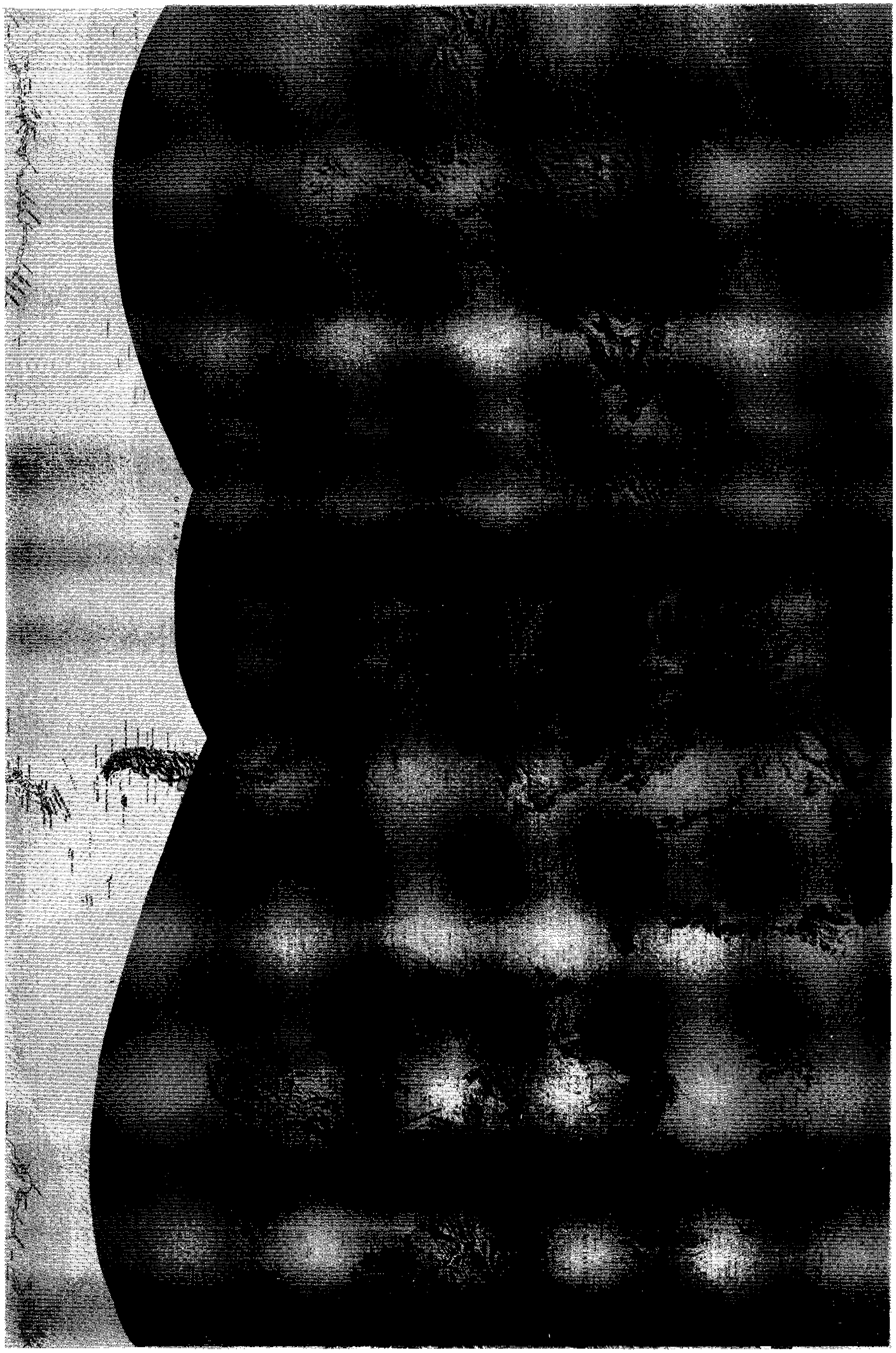
*R is the linear regression correlation coefficient. Computer program failure to yield the correct value due to the very small slope involved is signified by †. An R = 1.00 indicates a perfect fit of the data points to the linear expression.

skywaves is readily achievable at thousands of miles using both one hop and multi-hop propagation modes. In many instances these measurements may be carried out with visual receiving equipment at very low cost.[8] A single visit to the user's site with a portable clock to calibrate propagation delay can reduce the error budget to within an order of magnitude equal to that available with groundwaves. Where poor signal-to-noise ratio and interferring signals are a problem, special equipment may be employed to recover the LORAN-C pulse.[9] The maximum precision is achieved when a single propagation path is used and the observations are made at the same time each day. Figure 7 illustrates the potential skywave coverage, which is effectively the area north of 40° south latitude.

The National Aeronautics and Space Administration (NASA) is currently conducting a year long study of LORAN-C skywave stability, after some initial brief tests which resulted in synchronization capabilities on the order of several microseconds. More data and investigation are required to fully understand and take advantage of the ultimate potential of LORAN-C skywaves for PTTI dissemination. Nevertheless, skywaves may be utilized without correction practically worldwide, with accuracy in the 50-μsec region.

PRESENT OPERATION

Timed LORAN-C chains are currently held to a $\pm$ 15 μsec tolerance with respect to UTC through a coordinated arrangement between the U.S. Coast Guard and the U. S. Naval Observatory. Two types of corrections are employed to maintain this tolerance. They are infrequent step adjustments in the time of transmission of the chain, usually on the order of 10 μsecs or less and always announced in advance; and infrequent C-field adjustments to the operating cesium beam frequency standard at



the master station, usually on the order of 1×10^{-12}. Although the tolerance is ± 15 μsecs, the daily relative phase values are published to 0.1 μsec. If the requirement were presented, the tolerance could be reduced to $\pm$ 5 μsecs almost immediately.

FUTURE OPERATION

Recently the Department of Defense approved a proposal to implement UTC synchronization on all of the existing LORAN-C chains. At the time this program is implemented, it should be entirely possible to further reduce the tolerance to $\pm$ 1 μsec, although some investigative work is required. Improvements in the time monitor and master station equipment and measurement techniques should provide substantial reductions in the user's error budget. A burgeoning interest in LORAN-C timing should produce lower costs for commercial LORAN-C timing equipment. Studies of skywave stability should yield quantitative information to facilitate one hop and multi-hop propagation delay prediction and to produce a better model of the ionosphere.

LORAN-C PTTI USERS

It is worthy of mention to note the diverse interests and techniques which have or are utilizing LORAN-C PTTI; to wit, NASA's Manned Space Flight Network, intercontinental surveying, aerial mapping, long baseline interferometry, missile ranges, propagation studies, commercial peddlers of time, instrument calibration, communications, power companies for frequency control, and international bureaus and observatories for the maintenance and dissemination of the International Atomic Time Scale.

CONCLUSIONS

LORAN-C provides an excellent medium for the dissemination of PTTI on a continuous basis in both groundwave and skywave modes. User costs are not excessive and they vary, depending on the mode of propagation chosen and precision required. Expansion of the present system to all chains will enhance the coverage already available. At the same time, spectrum conservation and cost effectiveness are both achieved, since the system already exists to fulfill a separate (although related) requirement.

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