CALIBRATED VLF PHASE MEASUREMENTS:
SIMULTANEOUS REMOTE AND LOCAL MEASUREMENTS OF 10.2-kHz
CARRIER PHASE USING CESIUM STANDARDS

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ABSTRACT

An investigation of spatial irregularity of VLF phase due to nearby objects and terrain is discussed. It is shown that the phase is regular to the microsecond accuracy of the instrumentation, and that a grounded steel tower in close proximity to a whip antenna will not affect the phase measurement. However, antennas coupling to trees may cause an anomalous phase shift.

INTRODUCTION

During the past ten years, increased use has been made of VLF phase measurements for navigation, time dissemination, and frequency distribution. Additional techniques have been proposed, such as differential OMEGA, in which a local monitor is used to calibrate a given area. In differential OMEGA, errors are not caused by overall phase fluctuations over the long propagation path, but are introduced only insofar as the local phase is irregular, or as phase fluctuations are decorrelated within a local area. Differential OMEGA and similar techniques thus place high requirements on the spatial regularity of phase and the constancy of phase measurements to the local environment. The purpose of this study was to investigate local phase regularity and immediate environment through the use of two matched equipments.

A generalized block diagram of the receiving instrumentation is found in Figure 1. The output of a cesium frequency standard is fed through a phase shifter into appropriate synthesizing equipment to develop a 10.2-kHz injection signal to be fed into the front end of the antenna system. The antenna system consists of a ten-foot vertical whip and appropriate coupler.

Signals were fed into a Tracor 599R receiver modified to four-minute time constants. An internal commutator was used to select the remote stations to be tracked, and also the local calibration signal which was inserted on an otherwise unused segment of the OMEGA commutation pattern. The receiver output was then recorded on analog recorders. Prior to commencement of the task, the equipment was assiduously checked in the laboratory not only to determine adequate function in the equipment, but also as part of an evaluation of Tracor 599R receivers. The remote equipment was then transferred from the laboratory into a station wagon and installed in as nearly the same relative component position as possible.

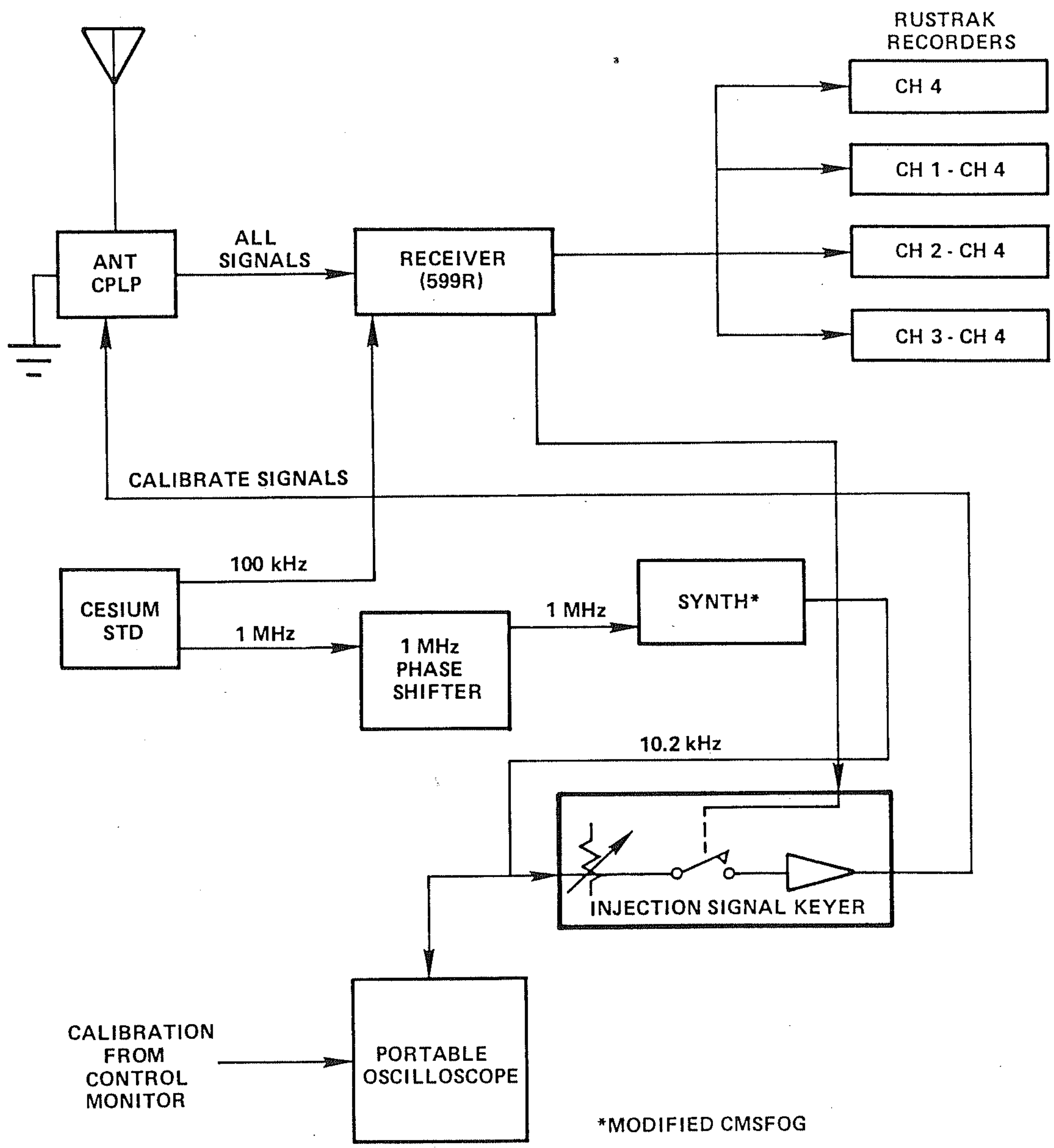


Figure 1. Block diagram of receiving instrumentation.

One of the receivers was left at the Naval Electronics Laboratory Center (NELC) for the duration of the tests. This receiver was operated from a ten-foot whip. Signals were fed from the antenna coupler at the base of the antenna through approximately 70 meters of coaxial cable to the receiver's location. This receiver operated from commercial power and was rack mounted, together with a second Tracor being used for measurements at 13.6-kHz and being served from the same coupler. The Tracor phase measurement output was then recorded using a multipoint analog recorder.

The remote receiver was operated from lead acid batteries, using a ten-foot whip mounted atop the station wagon roof. Recordings were made on four Rustrak dc recorders of one percent accuracy.

The experimental procedure consisted of parking the station wagon at a point outside the laboratory near the room housing the fixed receiver. The epoch as presented on the 10.2 kHz calibration of the output from the fixed receiver was then fed over approximately 30 meters of twin-ax to the station wagon. There the fixed epoch was compared with the epoch from the remote receiver and the phase shifter adjusted until coincidence was achieved. The phase calibration signals on remote and local receivers were thus matched to within a few tenths of a microsecond; the difference being due entirely to the differences in propagation velocity in cable lengths between the local receiver and the remote calibration receiver. The calibration procedure was conducted before each day of monitoring and again at the conclusion of each day of monitoring.

After calibration, the equipment was operated continuously as the vehicle was driven to a variety of receiving sites. Typically, the coordinates of the sites were determined from local topographic maps at a scale of 1:24000. Although the whip antenna was normally tied back during transit, the receiver was usually able to track signals even at freeway velocities, although serious quadrature error may sometimes have occurred. Once a recording site was reached, the antenna was elevated and 15 to 20 minutes were then allowed for the phase measurements to stabilize. The measurements were then made, strip-chart recorders marked, antennas tied back, and the vehicle was driven to the next site. Data was generated by two different means. In the first, the exact measurements were compared with simultaneous measurements made at the laboratory. Secondly, all records were reveiwed and compared for similarity. It was found that in most instances, the remote record exhibited behavior similar to the fixed record within the five minutes preceding movement from the remote site. In this case, the period for similar records was chosen, usually ranging from five to ten minutes. The entire period was then averaged, and the result used as the effective value. This latter approach apparently reduced experimental scatter, and is therefore the method employed to obtain measurements cited herein.

After the first two days of field monitoring, it was determined that there was a little leakage between the 10.2-kHz injection generator and the antenna system on the vehicle. The leakage was corrected; the data from the first two days of monitoring have been retained if the relative amplitude readings were not less than 10 decibels. Under these conditions, the phase perturbation would be negligible.

The test may be divided conveniently into two parts. The first part, the spatial regularity of phase was studied by conducting various measurements throughout the San Diego area. The second part consisted of a detailed investigation of the phase shift associated with antenna siting adjacent to a tree and a tower.

PART I: SPATIAL REGULARITY OF PHASE

General

It is important to note that there are several potential causes for spatial irregularity of phase and that the present study was designed especially to note only those associated with possible terrain or local environmental factors. Phase may vary irregularly from point to point due to imperfect spatial correlation of temporal variations; that is, long-term averages might vary regularly, but short-term test results exhibit scatter. Effects of the spatial decorrelation of temporal variations are best investigated by long-term measurements at a few fixed receiver sites rather than by the methods described herein. Phase may also vary irregularly as a function of distance from a transmitter if the propagation structure is due to several waveguide modes. This structural irregularity is expected to be the dominant irregularity at short distances from transmitters and may be significant up to several thousand kilometers or more at night.

Site Descriptions

The measurements to determine the spatial regularity of phase were designed to take maximum advantage of the extremely varied topography of San Diego County. Measurements were made from sea level to an elevation of 6000 feet and from the coast to the desert. Measurements were made on coastal bluffs, plains, promontories, in valleys, and in foothills. Weather conditions were generally sunny, although fog was sometimes experienced near the coast, and patches of snow remained on the ground at higher elevations.

The topography of the eastern sites is especially noteworthy. Mt. Laguna is on a ridge line running approximately north-south. An escarpment to the east is particularly abrupt, falling over 2000 feet in the first mile and over 4000 feet in the first four miles. The site at Ocotillo is located in the desert and separated from the ridge line by about one wavelength. Accordingly, if reflections off the escarpment were significant, the measurements at Ocotillo would probably be perturbed. The site at Devils Wash was located at the foot of the escarpment, at the 1000-foot contour level.

Several measurements were made in the immediate vicinity of NELC on Point Loma, a promontory separating San Diego Bay from the Pacific. Point Loma is approximately one mile wide and 400 feet high. Measurements were taken on the top and both sides of Point Loma. Additional measurements were made near the coast at Camp Pendleton and Imperial Beach. In general, every effort was made to obtain data from diverse geographic conditions. A description of the sites is given in Table 1. Data used to determine the spatial regularity of phase included only those sites at least 30 meters from trees, power lines, and other structures.

Table 1
Sites.

Sites	Location		Elev	LOP			Site Description (Remarks)
	Latitude Deg Min	Longitude Deg Min	(Feet)	TR	HK	FP	
Cabrillo	32°40.26′	117°14.44′	405	209.275	142.114	130.380	Exposed promontory overlooking Pacific Ocean. No power lines. Unknown antenna 100 meters south.
Pt. Loma	32°42.96′	117°15.62′	300	209.304	142.127	130.305	Adjacent to large tree; 8 ft from high-voltage power line.
Sunset Cliffs	32°43.80′	117°15.33′	25	209.360	142.094	130.308	Cliff overlooking Pacific. No power line.
NELC No. 1	32°42.52′	117°14.67′	365	209.311	142.119	130.318	Poor location adjacent to building.
NELC No. 2	32°42.53′	117°14.67′	360	209.311	142.120	130.318	60 ft further from building than site 4 above.
Harbor Drive	32°43.68′	117°12.73′	5	209.223	142.231	130.195	Next to bay; clear location.
Shelter Island	32°42.49′	117°13.84′	5	209.268	142.163	130.281	Clear location surrounded by water on three sides.
Wooded Area	32°42.97′	117°14.70′	310	209.318	142.123	130.308	Residential area surrounded by trees, no power lines nearby.
Warner	32°42.96′	117°14.66′	305	209.316	142.124	130.306	Open site in residential area.
Mt. Laguna	32°52.32′	116°24.69′	6050	206.815	144.822	127.724	Southeast edge of mountain near top. Visibility 100 miles to N, E, and S. Some snow on ground nearby.
Ocotillo	32°44.14′	115°59.62′	390	205.415	146.084	126.840	Small desert community.
Devils Wash	32°43.63′	116°03.78′	1000	205.626	144.861	127.046	Good site just entering foothills.
Laguna Site No. 2	32°48.62′	116°30.70′	4085	207.086	144.481	128.118	
Glencliff Camp Ground	32°48.01′	116°29.97′	3810	207.040	144.438	128.102	In clear area.
Imperial Beach	32°36.05′	117°07.73′		208.880	142.438	130.210	
Camp Pendleton	33°36.18′	117°24.27′		210.147	141.864	129.793	

Results

Phase measurements were obtained by driving to the various sites in the San Diego Area and simultaneously measuring the phase at the sites and at NELC. The phase measurements, amplitude readings, and times for daytime readings taken on Trinidad, Hawaii, and Forestport from the remote sites together with the simultaneous phase measurements recorded at NELC are contained in an informal technical note describing the experiment.[1]

Assuming that there are no spatial irregularities of phase and that the true prevailing propagation velocity is used to define the circular line of position (LOPs), then the phase from any transmitter received at the remote site (ϕ_R) should equal

$$\phi_R = \phi_N + (LOP_R - LOP_N)$$

where ϕ_N is the phase at NELC and LOP_R and LOP_N are the 0.9974 range-range LOPs at the remote site and at NELC, respectively. Since the maximum separation from NELC was less than four wavelengths, the typical error due to dispersion would be about 0.1 cec even if the true prevailing relative velocity was several parts in 10^4 from the assumed v/c = 1.0026. Discrepancies in ϕ_R may then be interpreted as position errors or timing errors due to irregularities, instrumentation, etc. The discrepancies are tabulated in Reference 1. The overall rms discrepancy for sites appropriately removed from trees and other objects was 2.3 cec (2.3 μs). The discrepancies can be compared with estimated experimental errors.

The sources of expected experimental magnitudes are estimated in Table 2. The summation of the experimental error contributions is especially dependent on the S-curve error per channel. S-curve error arises through leakage or other nonlinearity in the phase-tracking circuitry of each phase-tracking channel. The amount of S-curve error depends on the actual phasing of the tracking channels within the receiver. Synthesized error estimates thus depend on the number of active phase-tracking channels as shown in Table 3. With four tracking channels active (references and signal on both NELC and remote receivers), the most likely experimental scatter would thus be about 1.8 cec rather than the 2.3 cec actually obtained. However, the reference phase at NELC was not changed during the experiment and thus at most three channels were active, while at least one contained an unknown bias. In practice, the received signal phase is fairly repeatable from day to day, and hence the signal channels for each of the various stations will also tend to reflect bias rather than scatter if diurnal change is not important. Further, the injection phase to the remote monitor was varied only infrequently and hence might have tended to contribute as either a bias or scatter. Accordingly, although the best estimate for the experimental rms should be computed allowing for four S-curve errors, it is likely that the actual experimental conditions may have produced significant biases and scatter, indicative of only one or two active tracking channels. Table 4 shows statistics computed for phase measurements on each

[1]Naval Electronics Laboratory Center Technical Note 1778, *Calibrated VLF Phase Measurements,* by E. R. Swanson, R. H. Gimber, and J. E. Britt, December 4, 1970. (Note: NELC technical notes are informal documents intended primarily for use within the Center.)

Table 2
Expected Errors.

Estimated Variation (cec)	Quasimaximum Variation (cec)	Source of Error
0.5	0.7	Noise
0.7	1.0	Field recorder nonlinearity
0.1	0.2	NELC recorder nonlinearity
0.4	0.5	Field reading
0.1	0.1	NELC reading
0.2	0.2	Phase variation with amplitude
0.5	0.7	Time synchronization between NELC and remote
0.1	0.1	Map coordinates
0.7	1.0	S-curve receiver tracking error per channel

Table 3
Synthesized Error Estimates.

No. of Active Tracking Channels	Estimated Scatter (cec)	Estimated Maximum Bias due to S-curve
4	1.8	0
3	1.6	1
2	1.5	2
1	1.3	3

of the individual remote signals unaffected by trees or other objects. Apparently, the rms errors differ significantly between the various stations, presumably depending on biases in the reference channels and bias generated by nearly constant phase measurement at NELC. The standard deviations confirm the expected behavior. The phase of Hawaii and Forestport remained relatively constant at NELC throughout the experiment and hence the scatter should reflect primarily S-curve error in tracking signals with the remote monitor and, to a lesser extent, whatever scatter may have been introduced by changes in the injection phase for the remote monitor. Thus, for Forestport and Haiku, the estimated scatter would be between 1.3 and 1.5 cec which is greater than the actual scatter of 1.1 cec. The discrepancy may be due to pessimistic error estimates for noise effects and strip-chart timing errors on Hawaii and Forestport. The noise and timing esti-

Table 4
Experimental Errors (cec).

Statistic	Transmitter		
	Trinidad	Haiku	Forestport
RMS	2.0	3.3	1.1
Bias	0.4	3.2	0.3
Scatter (Standard Deviation)	2.0	1.0	1.1

mates were nominal and may be expected to be pessimistic for the relatively clean and constant Hawaiian and New York signals and somewhat optimistic for Trinidad. The 2.0 cec observed scatter for Trinidad is indeed slightly larger than the 1.5 or 1.6 cec which should be expected due to the effects of diurnal variation on two tracking channels and possible scatter due to injection changes on the remote reference. Of course, to some extent, individual station differences may also be due to some variation on the S-curve errors of the particular receiver channels. Nonetheless, the typical scatter (1.5 cec is essentially equal to that predicted by the error analysis, while the details of the analysis tend to confirm the error model. The error model may also be extended to predict a quasimaximum likely error of about 7 cec, which is indeed greater than any observed discrepancy. It is therefore concluded that irregular phase variations due to terrain features must be less than about one cec (one microsecond) on 10.2-kHz OMEGA signals during the day.

PART II: PHASE SHIFT ASSOCIATED WITH ANTENNA SITUATED ADJACENT TO TREES AND TOWERS

Reception Near a Tree

As was mentioned earlier, phase fluctuations may occur in a local area because of an irregular local environment. A phase shift near a tree can be assumed to be the result of tree movement and not the propagation path to the given area.

Measurements for the tree experiment were made in the neighborhood of a 60-foot eucalyptus tree in the vicinity of NELC. Distances from the tree ranged from an open area 500 feet from the tree to directly beneath the tree where the branches nearly touched the antenna. Two smaller trees were also within 100 feet of the tree, and a five-foot chain-link fence was approximately 100 feet from the tree. Measurements made at 94 feet and closer to the tree were between the tree and Hawaii, while partially in the shadow with respect to Trinidad and Forestport. For the 90 minutes during which the measurements were taken, the weather conditions were a heavy overcast with sprinkles.

Equivalent Circuit

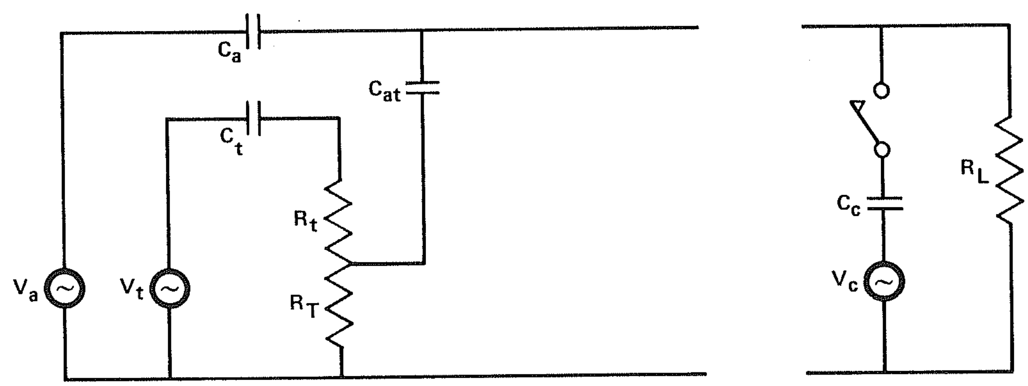
An equivalent circuit was used as a model for the effects of the tree on the antenna, as can be seen in Figure 2. V_a is the induced voltage in the whip antenna caused by an electric field (E = electric field strength) and is by definition

$$V_a = E\, h_a \cos\theta$$

where h_a is the effective height of the antenna at an angle of θ with respect to the electric field. If the effective height of the tree is $6h_a$, then the voltage induced in the tree is

$$V_t = 6V_a$$

This approximation is reasonable if the effective height of the tree is close to half its physical height. The loss resistance typically dominates the radiation resistance, while at the same time the input reactance is mostly capacitive and much larger than the resistive term. For the present case, the loss resistance and radiation resistance are assumed negligible and are not shown in Figure 2.



V_a = Incoming signal to antenna

C_a = Input coupling

V_t = Incoming signal to tree

C_t = Input coupling to tree

R_t, R_T = Resistance of tree

C_{at} = Coupling of tree to antenna

V_c, C_c = Internally generated frequency standard injected into antenna

R_L = Load resistance

Figure 2. Equivalent circuit for the tree experiment.

The coupling of the antenna to the tree will be distributed over the height of the antenna. It is difficult to say exactly how the leaves, branches, moisture, and other features of the tree effect its capacitance, but it seems clear the capacitance will increase in regions near the tree. A resistive term will be introduced in the coupling of the antenna to the tree since the resistance of the tree is nonzero. For the purposes of our circuit, the antenna was assumed to be coupled to the tree at the ten-foot level of the tree, so $R_t = 5R_T$. The resistance of the tree (1.5K Ω/six feet for dc) was determined by driving nails six feet apart into the tree and measuring the resistance across the nails.

With the superposition principle and a look at Figure 2, it is clear that the signal applied to the load is the sum of the component signals from the antenna and the tree. It is anticipated that a phase shift will occur when the phase component from the tree differs from that of the antenna. Clearly, the phase from the antenna (ϕ_a) is -90°. The phase injected from the tree should be a function of the coupling of the tree to the antenna, the effective resistance in the coupling of the tree to the antenna, and of the coupling of the tree to the signal. C_{at} should be small at large distances from the tree, reaching a maximum under the tree. For small values of the effective coupling resistance, there is a potential for the phase component from the tree to reach -180°. Assuming that the signal injected from the tree is much greater than that from the antenna, a phase shift of as much as 90° is possible. The signal from the tree may be dominate if C_c is much greater than C_a.

Results of the Tree Experiment

The results of the tree experiment are tabulated in Reference 1 and the phase readings are normalized to readings taken at 94 feet in Table 5. As can be seen in Figure 3, the phase shift is substantial in regions near the tree, while at the same time there is up to an 80 percent reduction in amplitude. Although the phase readings are not entirely reliable for amplitude readings below 5 dB, the phase on the three transmitters appears to be equally affected for reception near the tree.

Comparing the results that the model predicts with the observed data requires assigning values to the different components in the circuit. As an approximation for an antenna directly under the tree, the following values were estimated:

$R_L = 56\text{k}\ \Omega$

$V_t = 6V_a$

$C_t = 200$ pF (assume 35-ft. whip has 150 pF) $X_t = 75\text{k}\Omega$

$R_t = 15\text{k}\ \Omega$

$R_T = 3\text{k}\ \Omega$

$C_a = 25$ pF $X_a = 600\text{k}\ \Omega$

$C_{at} = 250$ pF $X_{at} = 60\text{k}\ \Omega$

Since C_{at} is much greater than C_a the signal from the tree will be dominant. The signal at V' then will be

$$V' \approx 6V_a \sqrt{75^2 + 18^2} \cdot 3 \approx V_a/4 \text{ advanced } 76^\circ$$

Our model predicts both the observed drop in amplitude and the phase shift in the proper direction. Admittedly, the model was developed to fit the data and admittedly, it is an oversimplification to assign lump values to a distributed circuit, but it should be noted that the assumptions of circuit values are not unreasonable and that the model does account fairly well for the phenomena observed.

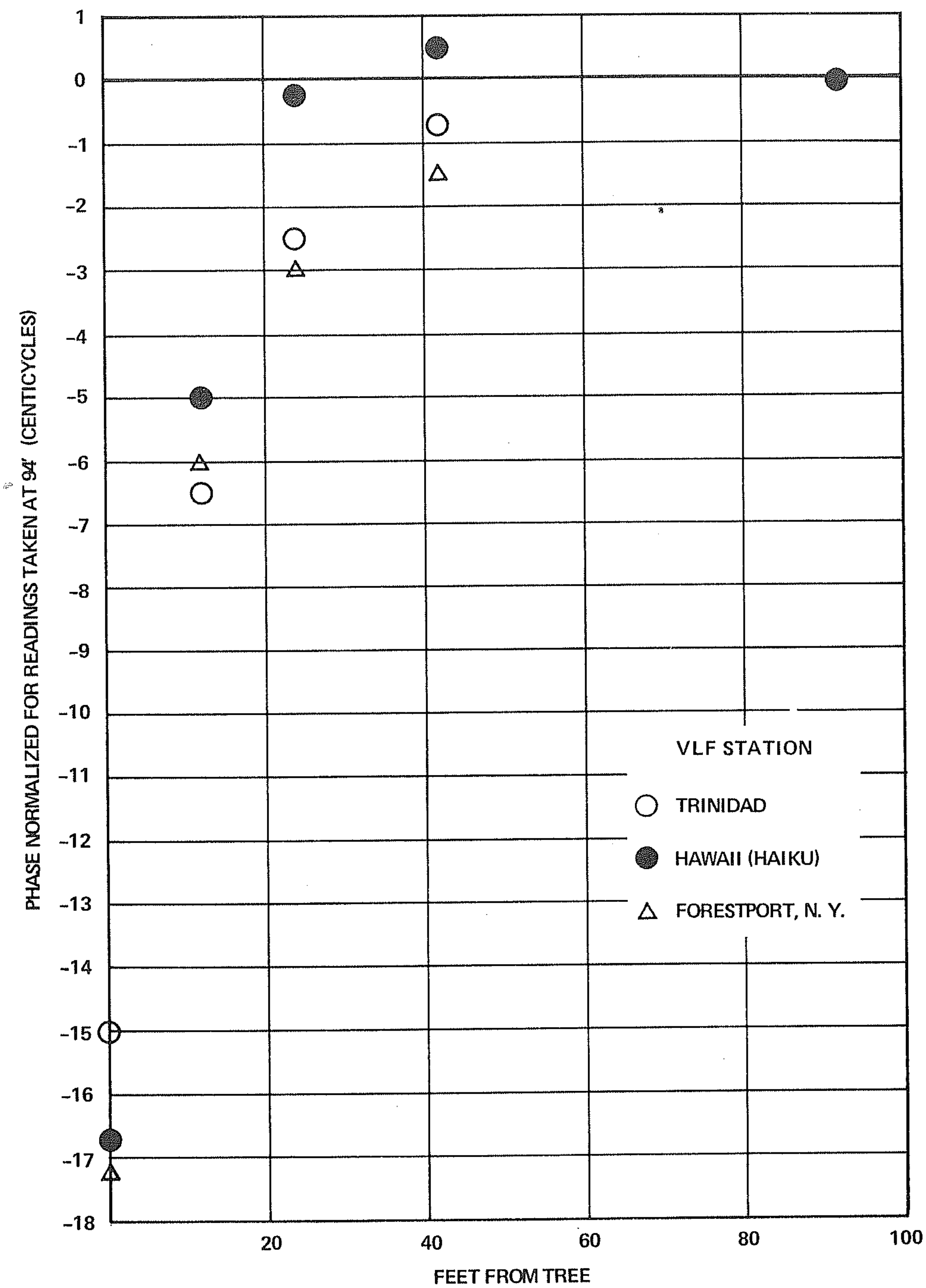


Figure 3. Phase shift versus distance from a 60-foot Eucalyptus tree (10.2 kHz).

Table 5
Phase Shift (cec)
(Normalized to Readings at 94 Feet).

TR	HK	FP	Distance From Tree
0.0	0.0	0.0	94 feet
-0.7	0.5	-1.5	42 feet
-2.5	-0.2	-3.0	24 feet
-6.5	-5.0	-6.0	12 feet
-15.0	-16.7	-17.3	Beneath tree

Measurements were also taken at three residential sites within 300 feet of one another. Warner (Site 9) was a clear area free of trees and power lines. Pt. Loma (Site 2) was adjacent to a large tree and eight feet from a high-voltage power line. The wooded area (Site 8) was completely surrounded by trees. The wooded area and Warner were on the same street while the site called Pt. Loma was around the corner from them. As can be seen from Table 6, those sites in close proximity to trees showed a substantial phase shift, while the open site at Warner, in the same vicinity as the two near trees, showed no corresponding phase shift.

Table 6
Tree Experiment
(LOP Errors for Hawaii).

Site	Date	Time	Amp	Raw Error (cec)	Bias Error (cec)	Remarks
Pt. Loma	March 24	1856	18	-11.4	-13.9	Adjacent to large tree.
	March 25	1719	16	- 8.7	-11.2	
Wooded Area	March 24	2243	12	-17.8	-20.3	Surrounded by trees.
Warner	March 25	1702	25	1.9	- 0.6	Clear area.

Reception Near a Tower

Signal behavior in the vicinity of a metal tower may be computed using the same equivalent circuit as was employed in analyzing the effects of being in the proximity of a tree (Figure 2). For a tower, the internal resistance will be negligible while the resistance between the effective point of antenna coupling and ground will usually be zero or infinite, depending upon whether the tower is perfectly grounded or ungrounded. The circuits of Figure 4 may thus be used to approximate Figure 2 for grounded or ungrounded towers.

From Figure 4, it is clear that no phase shift will occur at the receiver input as long as the reactance of the coupling capacitance between the tower and the antenna dominates the receiver input impedance. However, the amplitude may be significantly affected: If the tower is ungrounded, the signal will be enhanced; if grounded, the signal will be reduced.

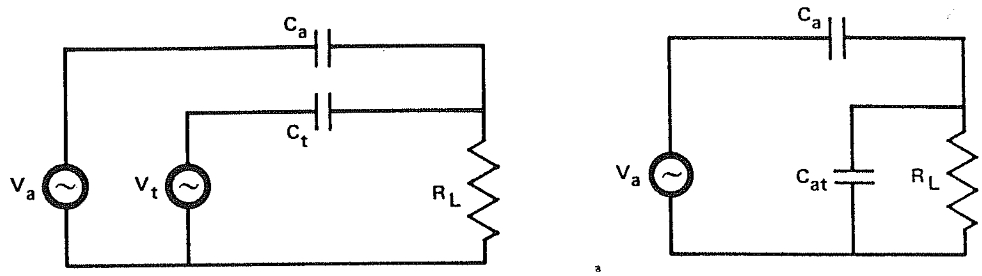


Figure 4. (a) Circuit for ungrounded tower; (b) circuit for grounded tower.

Measurements taken near a 100-ft grounded tower at NELC are given in Table 7. The measurements show no significant phase shift.

Table 7
Phase Shift Near Tower.

Trinidad		Haiku		Forestport		Difference (cec)			
Tower	Ref	Tower	Ref	Tower	Ref	TK	HF	FP	Feet from Tower
θ	θ	θ	θ	θ	θ				
77	76	46	45	72	73	1	1	-1	130
78	76	46	45	74	74	2	1	0	70
78	77	46	45	75	74	1	1	1	30
82	81	47	45	75	75	1	2	0	18
87	85	47	45	77	75	2	2	2	7

Reception Near Objects

The foregoing discussion of reception near trees and towers may be generalized to reception on a whip antenna near any object. The important considerations are (1) the capacitative coupling between the antenna and the object, and (2) the self-induced voltage on the object in the coupling region. Since both the coupling capacitance and the induced voltage depend on the size of the object, a convenient rule for siting antennas might be to provide separation from nearby objects equal to or greater than one-half their height. In practice, ordinary care in siting antennas should be more than adequate to avoid detrimental coupling.

It is particularly noteworthy that the experimental results can be explained by a simple model using direct coupling, rather than a more complex model using reflections such as might be expected at higher frequencies. Anomalous phase shift will thus be equal on all signals received at the same frequency independent of the station azimuths and local geometry. Accordingly, phase difference measurements made for navigational purposes will be unaffected no matter how close the receiving antenna is placed to other objects. (Assuming, of course, that adequate signals are available for phase tracking.) However, timing information obtained from various stations using an improperly sited antenna will be consistent, but incorrect.

The coupling model should also be applicable to the analysis of antenna performance on ships, buildings, or near various other structures. If the electrical parameters of the structure remain constant, then coupling is immaterial for normal navigation providing only that signals are adequately received. For timing, calibration of the antenna would be necessary if coupling was significant. Slow variation of the electrical parameters of a nearby structure would be unimportant for hyperbolic navigation but potentially unacceptable for timing. Fast variations, such as might occur on a ship due to roll or vibration causing intermittant electrical connections between various masts and guys, could cause rapid anomalous phase shift at the receiver which would appear as noise.

III. INTERPRETATION OF RESULTS

Application to Timing

The experimental results can be applied directly to assess possible local effects on timing accuracy using OMEGA. Timing accuracies have been parenthetically inserted in previous discussions by noting that one centicycle at 10.2 kHz can be interpreted as corresponding to about one microsecond. As previously noted, the effect of terrain irregularities is thus less than one microsecond. However, trees or structures may cause significant timing error if the receiving antenna is very poorly sited. If trees or structures introduce timing errors, the same error will be introduced on all 10.2-kHz OMEGA signals, and thus redundant measurements will not improve timing. Poor antenna siting is, however, usually easy to avoid.

The experiment also shows that OMEGA provides a means of providing accurate relative time between moderately separated sites.

Application to Navigation

The experimental results are also applicable to assessment of navigational errors and, in particular, evaluation of differential OMEGA, rendezvous accuracy, or relative positioning. Basic hyperbolic OMEGA navigation will include errors due to local phase irregularities. As a result of this experiment, local phase irregularities on 10.2-kHz OMEGA signals are negligible during the day.

The performance of differential OMEGA and the relative accuracy of OMEGA are especially dependent on local phase irregularities and decorrelation of phase fluctuations between two separated sites. As the experiment reflects errors of either type, the results obtained imply no significant limitation of differential accuracy due to local terrain features, antenna siting, or the decorrelation of phase fluctuation over the spatial extent of the experiment. In particular, in the absence of complicated signal structure due to propagation by various modes, it is unlikely that rms differential phase errors on circular lines of position in a differential system could be larger than one centicycle over spatial separations in the range 0 to about 100 km.

CONCLUSIONS

OMEGA phase measurements using whip antennas are unaffected by local terrain features to the experimental accuracy of about one centicycle. No anomalous phase shift is introduced by trees or towers unless the receiving antenna is placed sufficiently close so that significant capacitive coupling can occur. If phase measurements are taken adjacent to trees or within a forest, the anomalous phase shift will be the same for all OMEGA signals at the same frequency, and hence will not affect hyperbolic navigation. However, consistent through erroneous time estimates could occur.

ACKNOWLEDGEMENTS

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