

VLF Precision Timekeeping Potential

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ABSTRACT

INTRODUCTION

Today, requirements for time synchronizing many remote points to 100 μ s are not uncommon, and tomorrow's needs are almost certain to be in the microsecond region. Recent experiments of Fey and Looney (1), Chi and Witt (2), Rawles and Burgess (3) and the early work of other researchers have shown some possibility of microsecond timing through cycle identification of VLF multiple frequency transmissions. This paper examines the dual carrier synchronization of WWVL from the transmitter outward to receivers at WWVH in Maui, Hawaii, and at a JPL site in Barstow, California.

WWVL TRANSMISSION

During recent years, WWVL has broadcast carriers giving effective difference frequencies of 100 and 500 Hz. The carrier phases of station WWVL are controlled, relative to the NBS master clock at Boulder, Colorado, by the use of portable clocks and a television synchronizing system (4, 5). From theory it is apparent that measurements in the near field of the transmitter, relating the dual frequency zero crossings to the WWVL master-clock pulses, should differ from a far field VLF measurement by one-half cycle.

DUAL FREQUENCY MEASUREMENTS

Three daily phase measurements were made on the records at intervals at least 1 hour apart when the path was sunlit (1,700-2,400 UT). The calibration technique and propagation delay calculation were similar to those of Fey and Looney (1) and employed the equation :

$$t'_d = (\Delta t_2 - \Delta t_1) \left[\frac{f_1}{f_2 - f_1} \right] - \Delta t_2 \quad (1)$$

where

t'_d = fractional part of difference-frequency delay (μ s)

f_1, f_2 = low and high WWVL carriers (Hz)

Δt = phase difference between locally generated f , (φ_c) and received f , (φ_r); $\Delta t_1 = \varphi_{r1} - \varphi_{c1}$; $\Delta t_2 = \varphi_{r2} - \varphi_{c2}$.

The term $f_1/(f_2 - f_1)$ is the so-called magnification factor which essentially dictates the degree of phase control required in VLF timing. We made a study of phase records for the periods and receiving locations shown in Table 1.

TABLE 1. VLF Phase Measurements

Period	Receiving Location	WWVL Signals (kHz)	Frequency Separation (Hz)
Mar-Sept. 1968	Maui, Hawaii	19.9; 20.0	100
Dec. 1968 - Jul. 1969 ..	Maui, Hawaii	20.0; 20.5	500
Dec. 1968 - Jun. 1969..	JPL, Calif.	20.0; 20.5	500

From analysis of phase records during these periods, we computed relative delay times t'_d . The 20.0 and 20.5 kHz relative t'_d data for the period of December 1968 through June 1969 is shown for the Maui data in Figure 1. Because of calibrator non-linearity these determinations are not absolute; however, relatively they indicate positive cycle identification at 500 Hz frequency separation. The JPL data for the same period of time also indicate positive cycle identification. The Maui 100 Hz raw data show no semblance of cycle identification. A running average of both these data, as well as the 500 Hz data, greatly improves the degree of cycle identification, through smoothing by a low-pass-filter effect.

Differential data between the two WWVL carriers, as monitored at WWVL and also received at Maui and JPL, show fluctuations as much as 0.3 to 0.5 μ s. Because of the magnification factor such variation can cause erroneous cycle identification. This demonstrates one of the inherent problem areas of multiple frequency timing, namely, transmitter control of the multiple phases must be stable and unerring within specified limits over long periods of time.

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Åbom and Öhman (7) have made some interesting group-delay measurements from the WWVL transmissions received in Sweden. The WWVL to Stockholm propagation path (7,734 km) crosses Greenland, and attenuation over the ice fields deteriorates the signal-to-noise ratio. To overcome the received phase variations, they determined an average $(t_2 - t_1)$ for a 33-day period early in 1969. To calibrate their WWVL receiver, they developed and employed a symmetrical square-wave synthesizer and transmitted locally-generated 20.0 and 20.5 kHz signals to the receiver loop antenna by means of a wire antenna. Analysis of their data gave an average group delay of 26.055 μs , with an approximate peak variation of $\pm 20 \mu s$.

PROPAGATION DELAY PREDICTIONS

If the propagation delay between a transmitter and receiver is accurately known, resynchronizations of time can be accomplished via VLF signals. The waveguide theory (8) is particularly useful for delay calculations at large distances from the transmitter where one mode is dominant; the hop-theory (9) is more easily used near the transmitter where the ground-

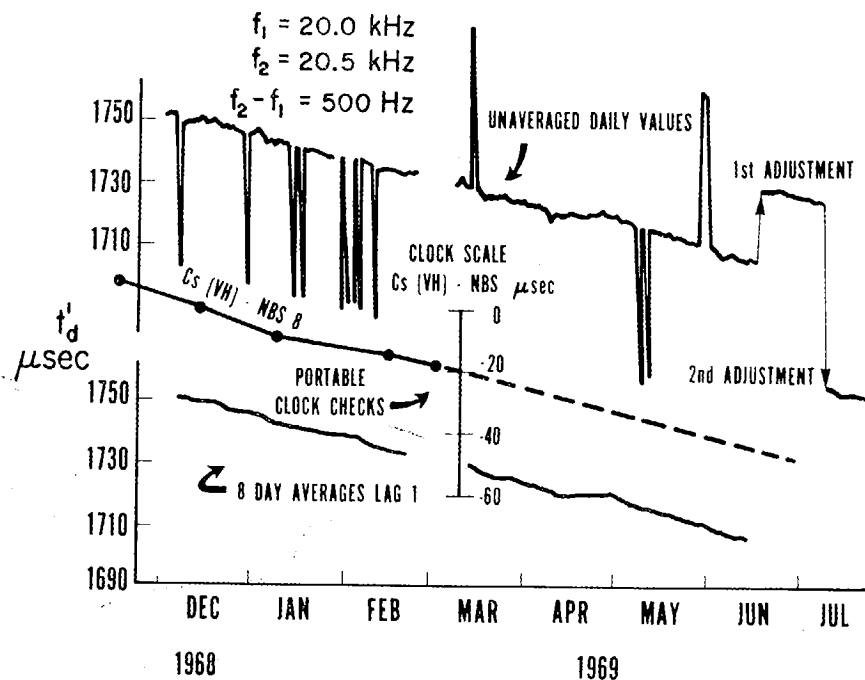


FIG. 1. Relative group delay t'_d for December 1968/June 1969 : Maui Data.

wave and first few hops give an adequate representation. In our results the hop approach has been used and this seems adequate out to about 10,000 km for the daytime profile. Phase-delay calculations have been made at a number of frequencies using the same daytime profile. From any pair of such calculations, we can estimate a theoretical group-delay velocity for the envelope of a signal produced by beating the signals together. Figure 2 shows the result of one such calculation for propagation to the west at frequencies of 20.0 and 20.5 kHz. Calculations, using signals 19.9 and 20.0 kHz, show that decreasing the frequency separation from 500 to 100 Hz caused little effect in the results. A group delay calculation for 20.0 and 20.5 kHz signals propagated to magnetic east gives results very similar to those for propagation to the west.

From theoretical calculations we estimate the group delay from WWVL to Maui to be 17,760 μs and to JPL to be about 4,020 μs . We point out, however, that such predictions have not been evaluated in terms of the experimental data.

RELATIVE TO DELAY IN MEDIUM WHERE $N = 1.0001$
 PROFILE - NORMAL DAY; NUMBER OF HOPS - 10

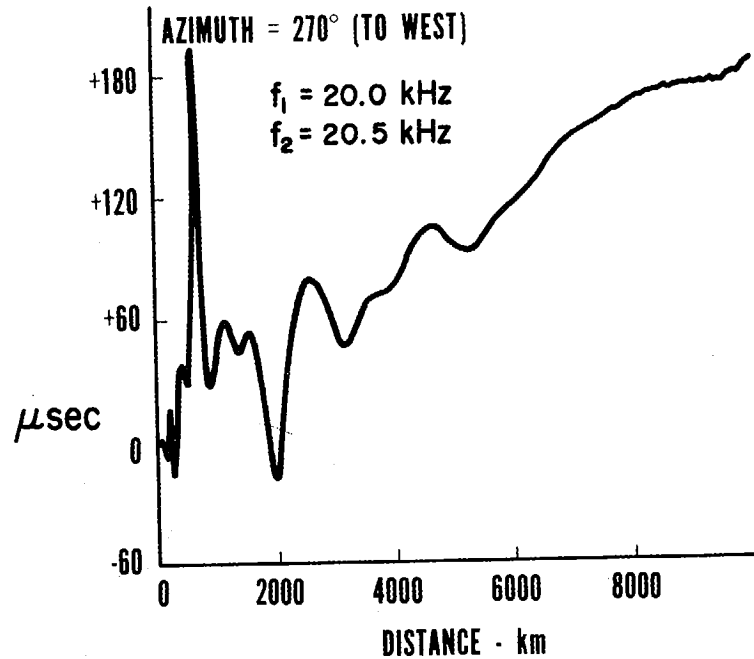


FIG. 2. Theoretical relative group delay for 20.0 and 20.5 kHz as a function of propagation distance to west.

SUMMARY

In any appraisal of the potential of multiple-frequency VLF timing there must be a sense of awareness of the many problem areas inherent in the transmitter/antenna, the propagation medium, and the receiver-clock comparison. The effects are not unique to the 20 kHz region, but apply in varying degrees to the Omega frequencies.

TRANSMITTER CONSIDERATIONS.

In transmitting multiple frequencies for VLF timing, it is imperative that the differential phase between frequency pairs be held to at least several tenths of a microsecond over long periods of time. Theory indicates that it is necessary to make a one-half cycle adjustment in the transmitted phases so that the received far field will be synchronized with the transmitter master clock as related to the near field.

PROPAGATION CONSIDERATIONS.

The problem of determining the propagation delay between antennas of a transmitter and receiver, which is complicated by dispersive effects when multiple frequency transmissions are used, is not easily solved. One approach we suggest is the theoretical delay predictions which include corrections for dispersion and other known influences.

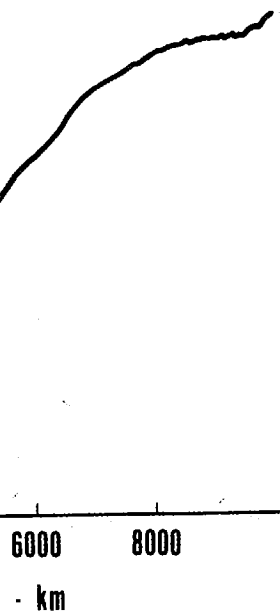
RECEIVER CONSIDERATIONS.

We recommend that the receiver delay be calibrated with a squarewave synthesizer, a time-interval counter, and a whip antenna that permits injection of the calibration signal into the receiver with all elements of the antenna system connected, with the exception of the whip. At this time, it appears that the delay and control problems of both the transmitter and receiver are at least equal in importance to ionospheric effects in VLF timing, with the exception of SID's, diurnal effects, etc. In this regard, a 1,000 Hz frequency separation, giving a magnification factor of 20, should enhance positive cycle identification at a receiving site.

We at NBS are continuing our efforts to exercise closer control over the WWVL transmissions, to relate group-delay predictions of propagating signals to receiving sites with experimental data, and to improve the calibrating, receiving, and analyzing techniques at a local site. We realize the limitations of WWVL, especially its low radiated power which results

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in a low signal-to-noise ratio for reception at great distances. We recognize WWVL as an experimental tool, however, intended to supply some answers to multiple-frequency timing problems, many of which are inherent in a worldwide Omega timing system.

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