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Progress in the Distribution of Standard Time and Frequency, 1963 through 1965

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Abstract

Progress in accurate long distance distribution of standard time and frequency, as reported in the literature from 1963 through 1965, is summarized. Techniques are by VLF, LF, and HF radio propagation, by satellite relay, and by portable clocks. Effects on standard frequency transmissions of variations in VLF propagation with geophysical phenomena are quantitatively understood. VLF and LF transmissions have provided careful, long-term, statistical comparison of remotely located atomic frequency standards. Precision of at least 2 parts in 10^{11} for a 24-hour observation period is possible at 5000 km. The phase of some standard frequency transmitters is routinely steered by VLF at distances up to 5300 km. Global distribution of standard time by VLF to microsecond resolution has been shown feasible. The null beat between two neighboring VLF carriers has been observed to propagate stably enough to mark a particular VLF cycle at 1400 km, and the beat period can be long enough to enable ordinary time signals to mark a particular null beat. Intercontinental time synchronization by microwave pulses has been accomplished via Telstar and Relay II satellites. Accuracy is stated to be several microseconds. Portable cesium clocks have served as global transfer standards with degradation of timing accuracy of only about a microsecond per trip. Results by all the above methods are consistent with each other and with stated accuracies of atomic standards involved.

KEY WORDS: Time, frequency, time signals, standard frequency broadcasts, VLF propagation, portable clocks

PROGRESS IN THE DISTRIBUTION OF STANDARD TIME AND FREQUENCY, 1963 THROUGH 1965

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1. Introduction

The accurate long distance distribution of standard time and frequency is important to the comparison of various national frequency standards, to world-wide oscillator rating and clock synchronization essential for the tracking of space vehicles, to radio navigational aids, to certain communications systems, and to astronomy. Such distribution is now accomplished by terrestrial radio propagation in the very-low frequency (VLF), low-frequency (LF), and high-frequency (HF) bands; by satellite relay; and by the carrying of portable clocks from place to place. This paper surveys the progress in the field as reported in the literature from 1963 through 1965, with occasional comment on matters of special interest falling either earlier or later. Attention is paid to scientific aspects, to limitations of the techniques, and to promising topics for future study.

2. VLF Transmissions (about 10 to 30 kHz)

At the beginning of 1963, the main features of VLF propagation were understood in terms of a waveguide mode theory of propagation (Budden, 1961). An alternative representation in terms of a series of reflected rays is sometimes invoked, but the two representations are equivalent. The main features are attenuation rate, phase velocity, and complex excitation factors for the modes; the principle governing parameters are frequency, ionspheric height, and distance from the source. The influence of certain other parameters, discussed below, was recognized, at least qualitatively. In summary, the attenuation rate is low, that is, 1 to 2 dB per 1000 km, with a broad minimum around 18 kHz (fig. 1). The phase velocity departs from the free space velocity c by several parts in 10^3 depending on frequency and ionspheric height (fig. 2), much as waveguide phase velocity depends on the free space wavelength relative to the guide dimension. The excitation factor for the lowest mode decreases with frequency and with ionspheric height; the excitation factor for the next mode is more slowly varying with these factors and is larger than for the lowest mode at night for the higher frequencies.

By 1963, VLF transmissions had been in use for six years or so as the best method of long distance distribution of standard frequency. A diurnal shift in the phase ϕ of the received signal, caused by the effect on the phase velocity of the day-night change in ionspheric height was the effect of main concern in frequency comparison. A simplified model gives the magnitude of this change at a distance x, as

$$\Delta\phi = (k_2 - k_1)\, x \qquad (1)$$

or, expressed as a time change Δt,

$$\Delta t = \Delta\phi / \omega = (1/v_2 - 1/v_1)\, x, \qquad (2)$$

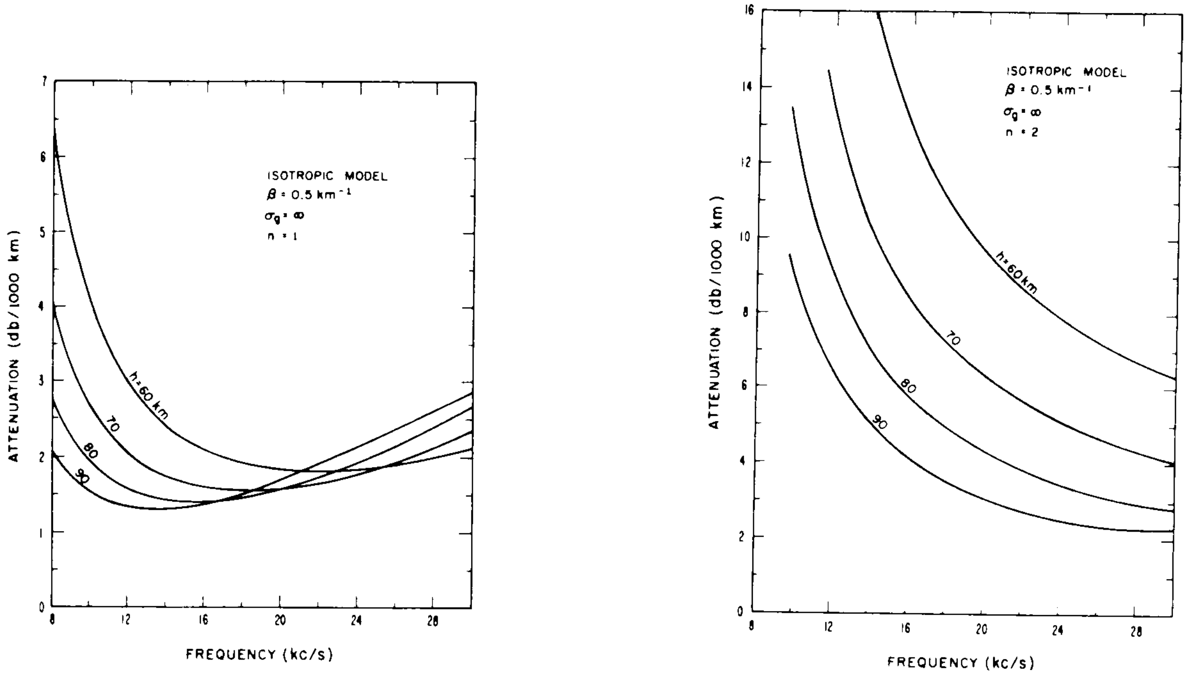

Fig. 1. Attenuation as a function of frequency showing effect of reflecting height (after Wait and Spies, 1964).

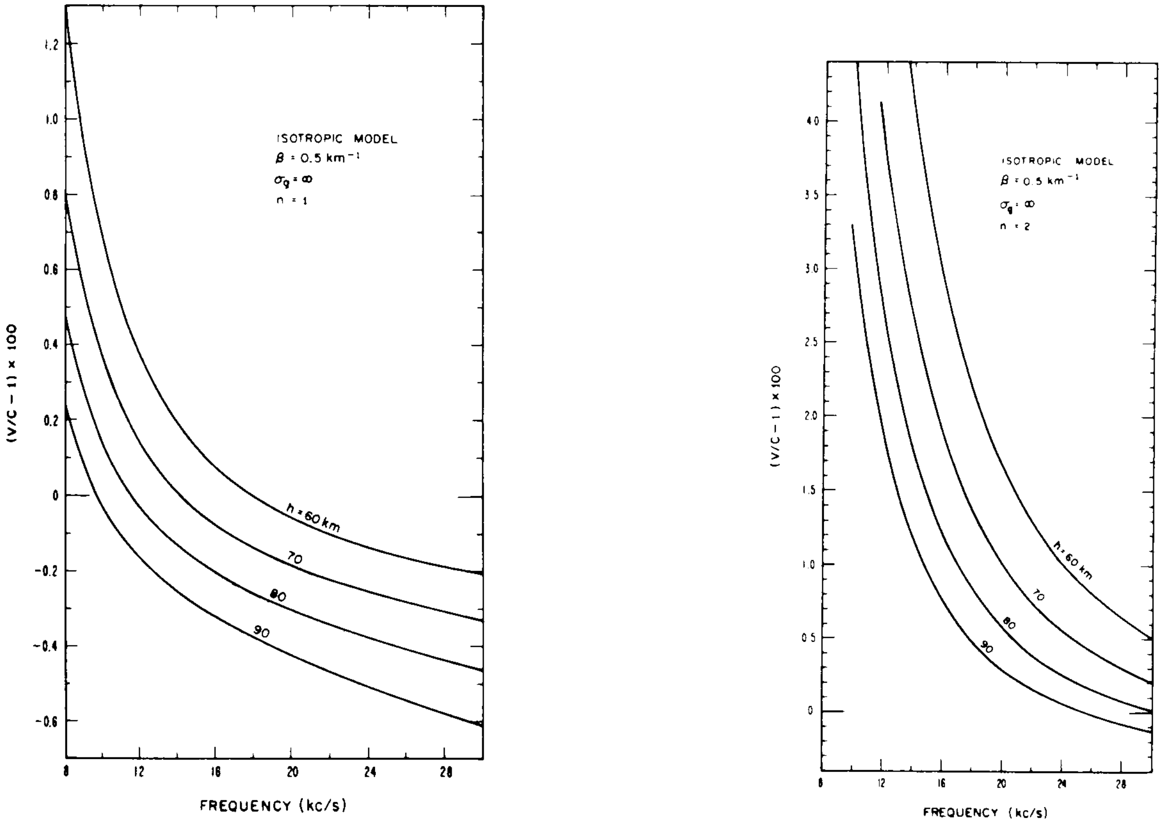

Fig. 2. Phase velocity as a function of frequency showing effect of reflecting height (after Wait and Spies, 1964).

where $\omega = 2\pi f$, f is the frequency, k is the propagation constant $2\pi/\lambda$, v the phase velocity, and the subscripts 1 and 2 refer to path wholly in daylight or in darkness respectively. The shape of the night-day-night transition is roughly trapezoidal as a result of the sweep of the day-night boundary along the path. The uncertainty in the phase shift from day to day, with season, and with ionospheric disturbances, is of central importance in the comparison of frequencies, since the experimenter must know to what extent his observed phase shifts are attributable to the oscillators or to the propagation medium.

Theoretical (Wait and Spies, 1964) and experimental (Watt and Croghan, 1964) understanding of VLF propagation has been considerably refined since 1963. The effect of finite ground conductivity is to increase the attenuation rates, particularly for mode 2, and to decrease the phase velocity slightly for both modes. The earth's magnetic field causes propagation transverse to the field to be nonreciprocal, manifested by lower attenuation for propagation from west-to-east than from east-to-west, but with negligible difference in phase velocity. The influence of an ionospheric electron density exponentially increasing with height, rather than a sharp boundary, has been analyzed (Wait and Spies, 1964).

Variations in the phase of the received wave are dependent on geophysical variations in the parameters. Such variations occur with path length, path direction, day-night conditions over the path, season (Hampton, 1964), and ground conductivity (for example, sea water or arctic ice) along the path. Variations also occur with both general and local ionospheric disturbances such as solar flares, polar cap absorption events (PCA's) sudden ionospheric disturbances (SID's), magnetic storms, and high altitude nuclear blasts (Burgess, 1964; Decaux and Gabry, 1964; Reder, Åbom, and Winkler, 1964; Volland, 1964). Shifts characteristic of these conditions are now recognizable and may be excluded from data used for frequency comparison.

The size of the diurnal shift appears proportional to x from the simple model of (1), but the actual variation has a sizeable superimposed oscillation (fig. 3). The explanation is given in terms of interference between the two lowest modes. The second mode is both excited more and attenuated less at night than in day, and accordingly influences the shift at moderate distances, say less than 5000 km. Beyond 5000 km only the lowest mode persists, and Δt becomes closely proportional to x (Wait, 1963; Blackband, 1964).

An additional result of mode interference is a fading structure on the sunrise and sunset portions of the received phase and amplitude. This structure is associated with the establishment and decay of the second mode at sunset and sunrise, respectively. (Crombie, 1964; Walker, 1965).

With greater understanding has come increased use of VLF for frequency comparison and control. From a study of selected 19.8 kHz data at Boulder from radio station NPM, Hawaii, Brady (1964) demonstrated that precision of frequency comparison could be 2.5×10^{-11} in a 24-hour observation, extending to 3.1×10^{-12} in a 192-hour observation. There was no evidence that propagation conditions rather than oscillator fluctuations were limiting this precision.

Mitchell (1963) and Morgan, Crow, and Blair (1965) have analyzed data on the comparison by VLF for an 18-month period of several atomic frequency standards. Their analyses, essentially similar, do not separate fluctuations due to propagation from fluctuations of the transmitter or from fluctuations associated with each receiving station. Internal consistency of results, however, indicates that propagation effects are not limiting the measurements. Results showed that transmitter fluctuations (rms) were typically 1 part in 10^{10} and receiving station fluctuations (rms),

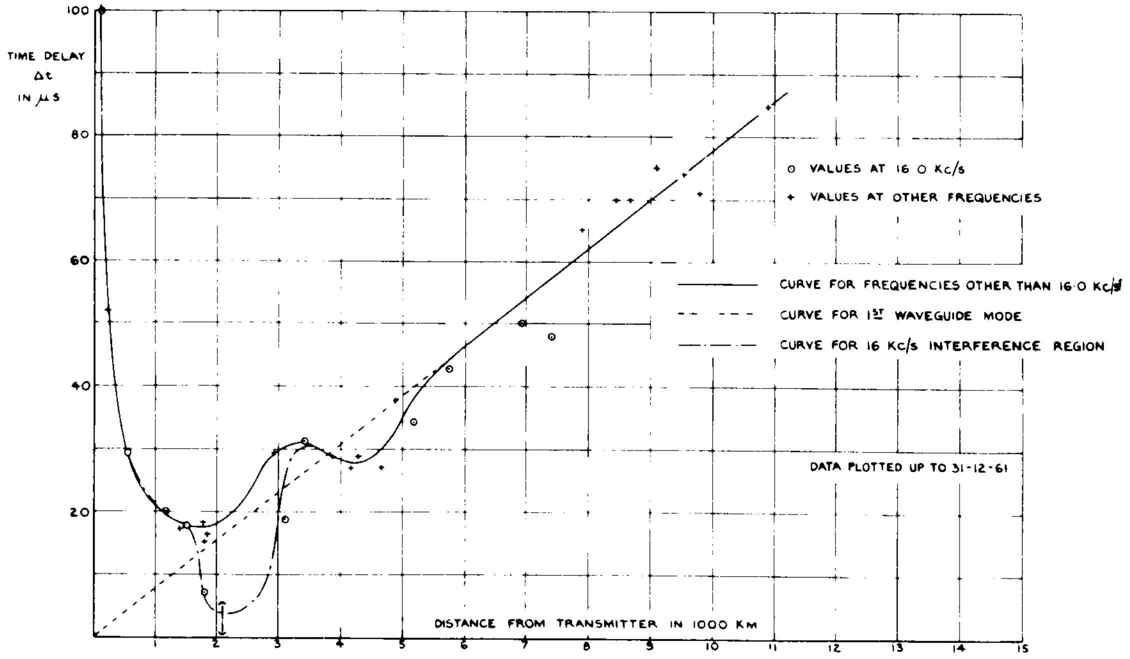

Fig. 3. Variation in diurnal change of transmission time with distance from the transmitter (after Blackband, 1964).

attributed mostly to fluctuations of the atomic standard, ranged from 0.1 to 1.2 parts in 10^{10}. Long term measurements to this precision are therefore possible without limitation by propagation uncertainties.

VLF has been put to routine use in controlling radio stations WWV (fig. 4) and WWVH within a few parts in 10^{11} with respect to the United States Frequency Standard (USFS) at Boulder, Colorado (Blair and Morgan, 1965). Radio station WWVL at 20 kHz, broadcasting since 1963 with about 1 kW radiated power, provides reference signals. In turn, WWVL is controlled in phase with respect to the USFS so that no loss of accuracy will occur between the two.

Time synchronization of widely separated clocks to the order of microseconds may be desirable for some global operations in which events must be referred to a scale of time common to various observers. Looney (1964) has reported on the interest of the U. S. National Aeronautics and Space Administration in VLF time distribution by a two-frequency method. Morgan and Baltzer (1964) have experimentally shown the feasibility of the method at 1400 km.

The positive zero crossings (or other fiducial value of phase) of a received VLF carrier can serve as time markers within a few microseconds as limited by fluctuations in the phase velocity v and corresponding time delay τ, provided the phase delay, $\phi = kx = \omega\tau$, for the path from transmitter to receiver is known.

The "markers," spaced by one VLF period, say 50 μs, may be identified, provided time is established independently at the receiver within one-half VLF period. Interference nulls between two VLF carriers separated by Δf, say 100 Hz, can serve as coarser time markers, as limited by fluctuations in the group velocity v_g, provided also the group delay τ_g from transmitter to receiver is known. These markers, spaced by the beat period $1/\Delta f$, may be identified by conventional

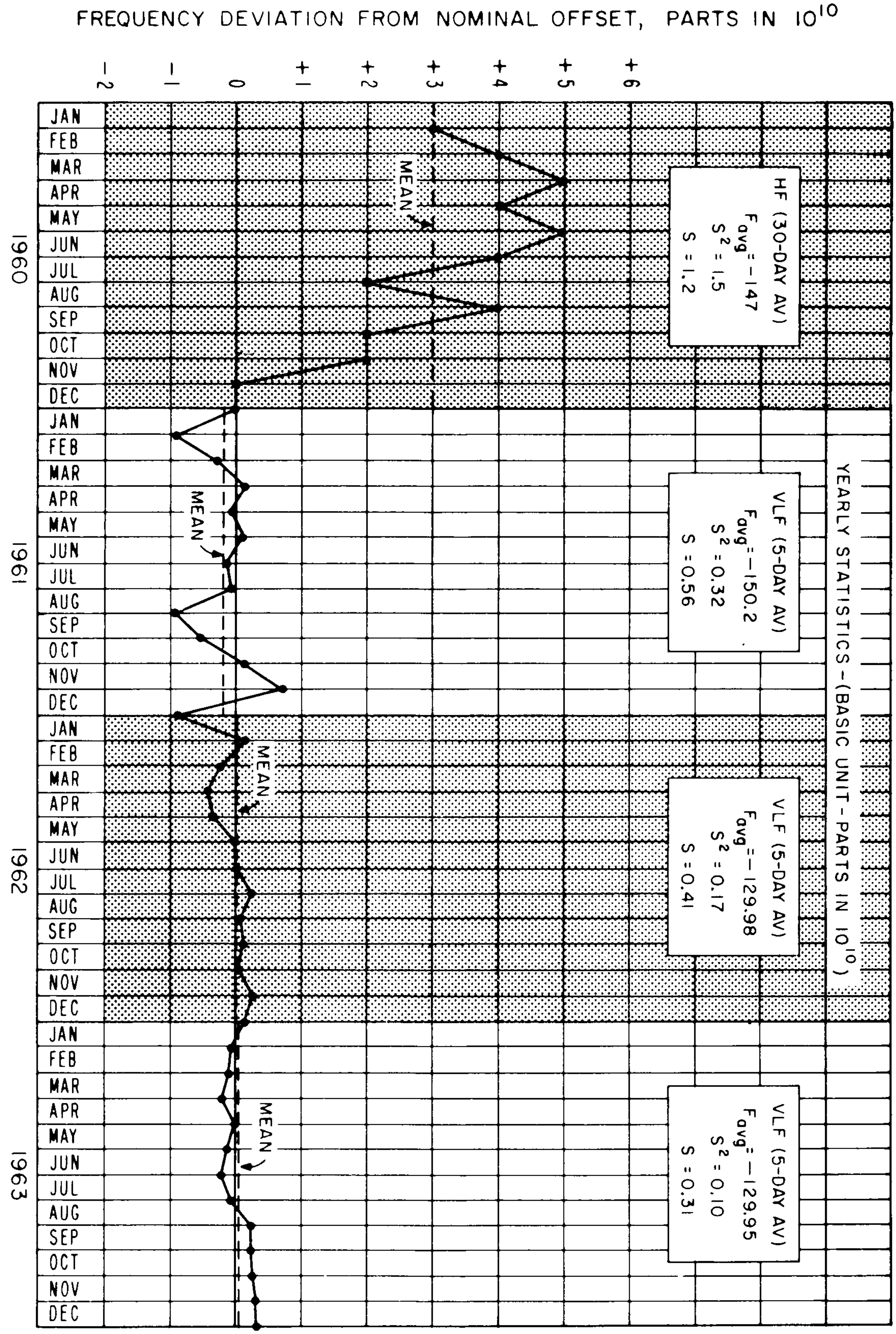

Fig. 4. Improvements in the frequency control of WWV (after Blair and Morgan, 1965).

time signals, which are usually reliable to within one-half of the chosen beat period. The group delay is

$$\tau_g = x/v_g = x\, dk/d\omega = d\phi/d\omega = \omega\, d\tau/d\omega, \tag{3}$$

where $k = 2\pi/\lambda$. If we take $d\omega = \Delta\omega$, the fluctuation in τ_g is

$$\delta(\tau_g) = \frac{\omega}{\Delta\omega}\ \delta(\Delta\tau), \tag{4}$$

where $\Delta\tau$ is the difference in time delay of the two carriers. Morgan and Baltzer (1964) showed that $\delta(\Delta\tau)$ was typically $0.2\mu s$ for averaging times of about two hours, so that $\delta(\tau_g) \simeq 40\ \mu s$ for $\omega/2\pi = 20$ kHz and $\Delta\omega/2\pi = 100$ Hz. Thus the null markers have essentially the required stability. Experimental studies to enable prediction of v and v_g are in progress.

The OMEGA navigation system (Pierce, 1965) is based on the same principle. Absolute (or relative) phase of several VLF carriers from separated transmitters is observed; prior knowledge of v establishes loci of constant phase (or phase difference); and phase ambiguities are resolved by beats. The intersection of two or more loci establishes position; and, as a bonus, the procedure described above may then be used to obtain time.

3. Low Frequency (LF) Transmissions (30 to 100 kHz)

Standard frequency and time signals have been broadcast on WWVB at 60 kHz with 5 kW radiated power since July, 1963. Coverage is satisfactory over the continental U. S. The signals have been used routinely to control radio station WWV at 2400 km distance. Blair and Morgan (1965) report rms phase fluctuations of 0.1 to 0.2 μs during daylight hours. These figures are about three times better than for WWVL reception. The standard deviation of the diurnal phase change is about 1 μs which is slightly better than for WWVL reception. Received time pulses are typically good within 1 ms.

A time tick has been added to the pulsed 100-kHz signals of Loran-C. Johler (1963) reports refinements in calculating the propagation time over a finitely conducting ground of a "tagged-point-in-time" near the leading edge of the pulse. Such effects can influence the propagation time by up to 5 μs at 100 kHz; Johler's theory allows corrections to be applied which will restore the precision to 0.1 μs.

4. High Frequency (HF)Transmissions

The high frequency broadcasts of WWV time signals averaged over 30 days have been successfully used to synchronize remotely maintained time scales to about 1 ms (Newman, Fey and Atkinson, 1963; Bonanomi, Kartaschoff, Newman, Barnes, and Atkinson, 1964). Frequency comparisons, from the rate of change of time difference, were made to an uncertainty of a part in 10^{11}. The method is now surpassed in accuracy and speed by portable clock and satellite techniques.

5. Satellite Relay

Figure 5 shows the basic arrangment of time synchronization by the satellite relay of microwave pulses, which typically may be of 0.1-μs rise time and several microseconds duration. The following notation for instants (epochs) on some common reference scale is used:

A_a: Pulse transmitted by A observed immediately at A.

A_b: Pulse transmitted by A observed at B.

B_b: Pulse transmitted by B observed immediately at B.

B_a: Pulse transmitted by B observed at A.

A'_a: Pulse transmitted by A received and retransmitted at B and then observed at A.

In addition the following intervals are used:

$F = B_b - A_a$: Time difference between the B and A transmissions, equal to the clock difference if A and B are controlled by the clock ticks (positive if A is early).

τ: Pulse propagation time from A to B or B to A (assumed equal).

We here neglect delays in terminal equipment on the ground and in the satellite. These delays may be introduced into the analysis as corrections if necessary.

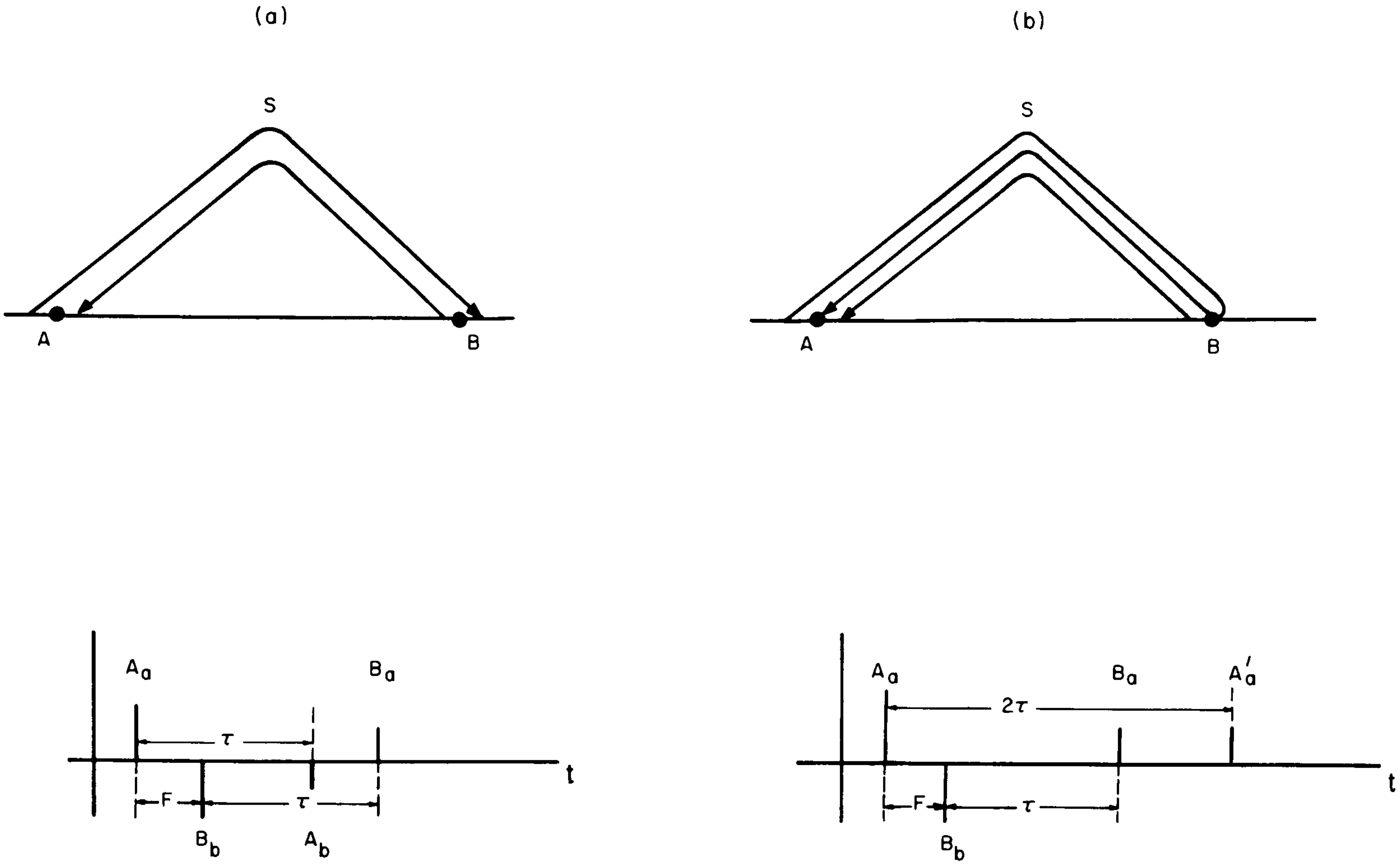

Fig. 5. Time synchronization by satellite relay. For clarity, observations at A are plotted upward and observations at B are plotted downward.

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From fig. 5a we have, from the two one-way transmissions,

$$T_a = (B_a - A_a) = \tau + F \qquad (5)$$
$$T_b = (A_b - B_b) = \tau - F,$$

whence

$$F = \tfrac{1}{2}(T_a - T_b). \qquad (6)$$

Or, from fig. 5b, from a round trip and a one-way transmission we have

$$T_a = (B_a - A_a) = \tau + F \qquad (7)$$
$$T'_a = (A'_a - A_a) = 2\tau ,$$

whence

$$F = T_a - \tfrac{1}{2}T'_a . \qquad (8)$$

Steele, Markowitz, and Lidback (1964) used both methods in their Telstar experiment between Andover, Maine, and Goonhilly Downs, Cornwall, U. K. The uncertainty of synchronization of the Andover and Goonhilly clocks was 1 μs as compared with the pre-satellite degree of synchronism of about 2 ms. Sources of error are the resolution to which the time difference observations T_a , T_b, and T'_a can be made, any possible nonreciprocity of terminal equipment and propagation delays, and effect of the change in τ produced by satellite motion during an observation. In the Telstar experiment, the rate of change of τ was from 1 to 6 μs/s, so that simultaniety of observation within 0.1 s was adequate for errors less than 1 μs.

A similar experiment was reported by the Radio Research Laboratories (1965) of Japan in collaboration with Markowitz of the U.S. Naval Observatory, using the Relay II satellite. Precision of reading the arrival time of pulses on one photograph was about 0.1 μs. The rate of change of τ was 0.03 μs/s, a very low value since Relay II was in synchronous orbit. Time synchronization to 1 μs is anticipated when all data are reduced.

6. Portable Atomic Clocks

Reder, Winkler, and Bickart (1961) reported the first results in transporting Cs clocks by air for time synchronization of remote points. Their uncertainty was about 5 μs. Bagley and Cutler (1964) transported Cs clocks from Palo Alto to Lausanne and return with stops at Washington, Neuchatel, Beltsville, and Boulder, The frequency of the portable clocks was compared directly with frequency standards at the places visited; time was compared within 1 μs, and propagation time of WWV pulses from WWV to Neuchatel was measured to $\pm$ 200 μs, limited mainly by the uncertainty of the pulse arrival time. The frequency comparison was consistent with the stated tolerance of the NBS and LSRH (Laboratoire Suisse de Recherches Horlogeres) Cs standards, and with the value found by the VLF observations of Morgan, Crow and Blair (1965).

Bodily (1965) performed a more extensive experiment, visiting 21 different facilities in 11 different countries (fig. 6). The round trip closure errors of the traveling standards with respect to a known high quality stationary standard were well under one microsecond per day, so that results corrected to the nearest microsecond appear quite valid.

Comparisons of the frequencies of the NPL (National Physical Laboratory), LSRH, NRC (National Research Council, Ottawa), and NBS Cs standards were consistent with the stated accuracies of the standards, and with previous comparisons by HF radio, VLF radio, and portable clocks, where available.

Comparisons between time scales at the Royal Greenwich Observatory, Neuchatel Observatory, U.S. Naval Observatory and NBS were consistent with previous comparisons together with known frequency differences of the standards. Some data are collected in Table I.

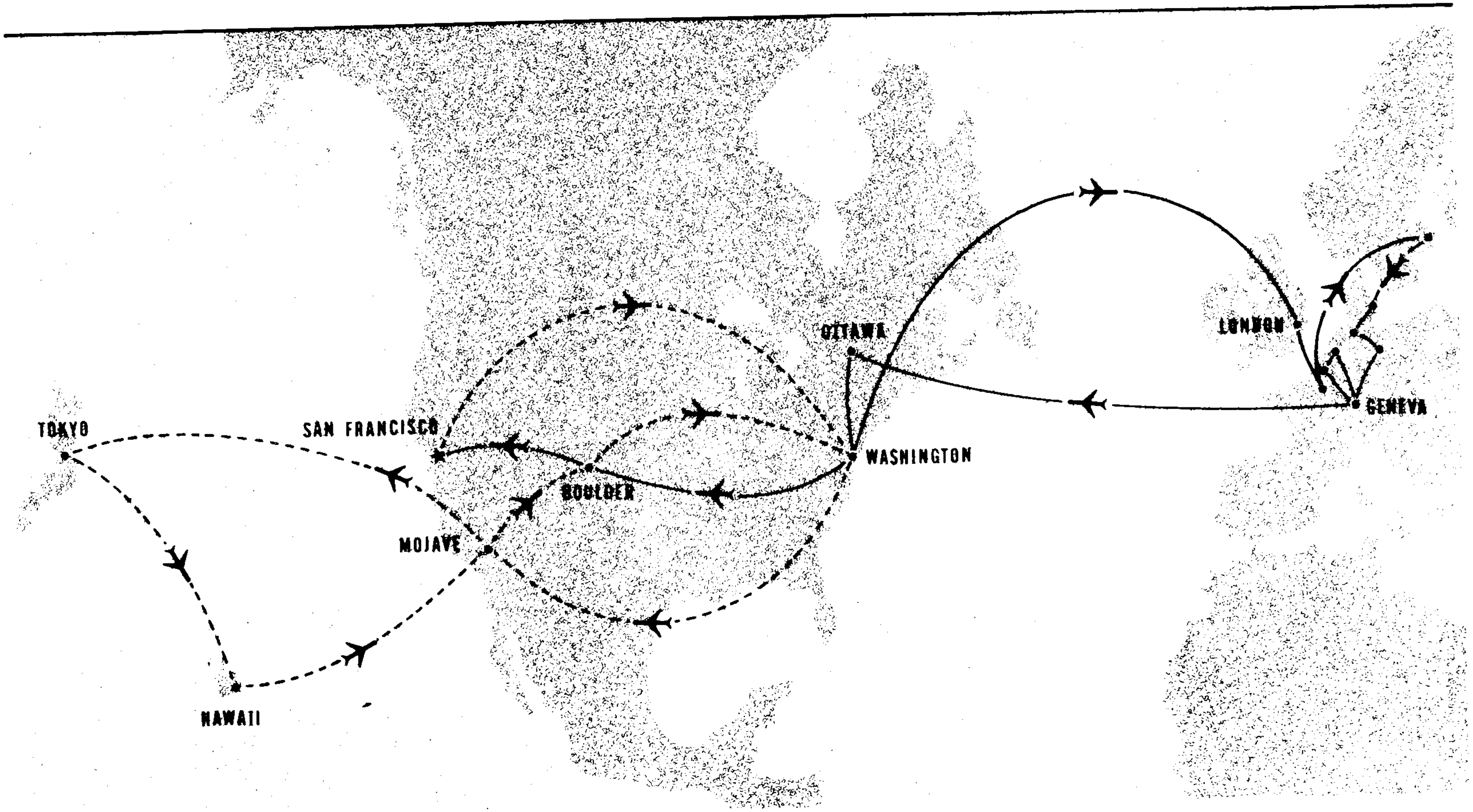

Fig. 6. Precision "atomic" clocks were transported to 11 countries in 35 days to correlate time at 21 facilities (after Bodily, 1965).

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The method has proved accurate and valuable, and no doubt will be used often in the future.

7. Discussion

The status of accurate long distance distribution of standard time is roughly: that instantaneous distribution to terminal stations to at least 1 μs by satellite relay is feasible, that point-to-point distribution at the speed of passenger travel to about 1 μs by portable clocks is feasible, that broadcast by LF pulse to about 1500 km and about 1 μs is in routine operation in those areas served by Loran-C, and that broadcast to all points beyond about 1500 km to several microseconds may be developed. No technique having wide coverage at great distances and accuracy better than about 1 ms is now in regular use.

Accurate long distance frequency distribution to a few parts in 10^{11} in 24 hours is regularly accomplished by VLF broadcast. Any method of time distribution will also calibrate a local frequency standard.

The most severe requirements on accurate long distance distribution of time and frequency will be set by the desire to compare remotely located frequency standards. Needs to calibrate the stability and the absolute frequency of remote oscillators for operational use in tracking, navigation, or ionospheric studies do not now exceed 1 part in 10^{11}. Needs to synchronize remote clocks for operational use to better than 100 μs are not common. Nevertheless, new applications may be found if the capability exists.

Some further study may be fruitfully applied to the geophysical variations in VLF phase so that these fluctuations may be properly identified and corrected for frequency distribution work. Longer averaging, however, may not lead to indefinitely increased accuracy. Either insufficient knowledge of the fluctuation statistics or the tendency for slow fluctuations to be more severe (1/f noise) may hurt the validity of the long-time average. Therefore, we may find a practical limit to the improvement in accuracy.

Further study of differential phase stability at VLF, upon which VLF timing depends, will be fruitful in order to establish its limitations.

Regular time comparisons by satellite relay should be continued as the best method of comparing the rates of important national frequency standards and master clocks.

Two-way VHF transmission using reflection from ionized meteor trails is identical in principle to the satellite relay method of time synchronization. Studies to determine the limitations of this method in accuracy and range are in progress and should be pursued to conclusion.

The question of the distribution of time and frequency standards to operations in space is deserving of scientific study. Limitations by instabilities of propagation from earth through the atmosphere and interplanetary medium should be studied. Corrections arising from relativity should be stated. For example, the second order Doppler effect amounts to 1 part in 10^{12} at 1000 km/hr and the gravitational shift is 1.1×10^{-13} per kilometer of altitude near the surface of the earth.

The future outlook is that the precision and stability of frequency generators may soon increase to a value of 1 part in 10^{14}. The quickest and best way to compare such generators will probably be by satellite relay observation of time drifts to 0.1 μs over 10^{7} μs (100 days) or so.

Global applications of stable frequencies, like the OMEGA navigation system, will be limited by global geophysical effects.

Finally, we can fully expect that ingenuity will eventually find use, especially in space operations, for the full accuracy which can be attained in time and frequency generation and distribution.

Table 1a. Precise time comparisons of certain time standards

Laboratory Pairs	Date	Time Diff. (µ s)	Change (µ s)	Interval (days)	Rate * (x 10^{12})	Ref.
LSRH-NBS	June 6, 1964	1760	-49	273	-2.1	4
	Mar. 5, 1965	1711				
USNO-NBS	Oct. 7, 1963	532†	-190	522	-4.2	6,7
	Mar. 13, 1965	342				4
RGO-USNO	Aug. 27, 1962	2234	3116	911	39.6	5
	Feb. 24, 1965	5350				4

* Assuming no relative time adjustments between scales in the intervals sho

† Assuming zero divergence between USNO and NBS from Apr. 24, 1963 to Oct. 7, 1963.

Table Ib. Precision frequency comparisons of certain time standards. Date and duration of observation are roughly indicated. Entries are in parts in 10^{12}.

Laboratory Pairs	Measurement	Method	1961	1962	1963	1964	1965	Ref.
LSRH-NBS	Freq	A		-51				1
		A		-34				2
		B			-7.3 →			3
		B				-5.1 →		4
	Time	B'				-2.1		4
USNO-NBS	Freq	A		+36				2
	Time	B', D				-4.2		4, 6, 7
RGO-USNO	Time	B', C			+39.6			4, 5
NPL-NBS	Freq	A	+68					1
		A	+55					2
		B			+23 →			4
	Time	-		No available data				-

Methods

A - VLF
B - Portable frequency standard
B' - Portable clock
C - Satellite
D - LF (Loran-C)

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