Distribution of Standard Frequency and Time Signals

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Abstract—**This paper reviews the present methods of distributing standard frequency and time signals (SFTS), which include the use of high-frequency, low-frequency, and very-low-frequency radio signals, portable clocks, satellites, and RF cables and lines. The range of accuracies attained with most of these systems is included along with an indication of the sources of error. Information is also included on the accuracy of signals generated by frequency dividers and multipliers.**

Details regarding the techniques, the propagation media, and the equipment used in the distribution systems described are not included. Also, the generation of the signals is not discussed.

I. INTRODUCTION

THE DISTRIBUTION of standard frequency and time signals (SFTS) with the highest accuracy over long distances has become increasingly important in many fields of science. It is essential for the tracking of space vehicles, worldwide clock synchronization and oscillator rating, international comparisons of atomic frequency standards, radio navigational aids, astronomy, national standardizing laboratories, and some communication systems. Methods used include use of high-frequency (HF), low-frequency (LF), and very-low-frequency (VLF) radio transmissions, portable clocks, satellites carrying a clock or a transponder, and RF cables and lines.

This paper will review these distribution systems and some of their limitations and also indicate some promising techniques for future study. Recent advances [1] in the distribution of SFTS will be included, but they will not always be specifically pointed out. Information will be included on the accuracy of SFTS signals generated by frequency dividers and multipliers. Details regarding the techniques, the propagation media, the equipment involved in the distribution systems described, and the generation of the SFTS are not included.

The definition of the terms *stability*, *precision*, and *accuracy* as used in this paper are essentially the same as those given in another paper [2].

II. DISTRIBUTION BY RADIO SIGNALS

A. Distribution by HF and VHF Signals (3 to 300 MHz)

At present there are about 15 standard HF and time-signal broadcasting stations [3], [4] operating in the allocated bands between 2.5 and 25 MHz. Table I lists them along with certain characteristics, such as location, carrier frequencies and power, period of operation, carrier offset, etc. The characteristics of the HF and VHF stations that broadcast standard frequency and time signals [3] in additional frequency bands are given in Table II. Many of these stations participate in the international coordination of time and frequency and are identified in the tables. The signal emission times of the coordinated stations are within 1 millisecond of each other and within about 100 ms of UT2; their carrier frequencies are maintained as constant as possible with respect to atomic standards and at the offset from nominal as announced each year by the Bureau International de l'Heure (BIH) [4]. The fractional frequency offset in 1966 was -300 parts in 10^{10}, and this value is to be used in 1967.

The long and widespread experience with standard HF and time signals, and their present world-wide use, underlines their importance to a large body of users. There are international organizations, such as the International Radio Consultative Committee (CCIR) [5], the BIH [4], and the International Scientific Radio Union (URSI) [6], [7], that are concerned with many aspects of their operation and utilization, such as reduction of mutual interference, broadcast accuracy, synchronized emission times, etc. For instance, the CCIR not only publishes information on signals but also is engaged in a study program designed to improve the services and uses of the present stations.

A technique employed by NBS to improve the transmitted accuracy of the frequencies of WWV[1] and WWVH was to use the received signals of WWVB (60 kHz) and WWVL (20 kHz) at these stations to remotely control them [8]. The NBS atomic standards are located at Boulder, Colo., and the transmissions of WWVL and WWVB, which stations are located about 50 miles away, are remotely phase-controlled by means of a VHF phase-lock system [9] connected between them and the atomic standard at Boulder so that their transmitted frequency accuracy is essentially that of the NBS standard. Because of the high received frequency accuracy of LF and VLF signals, it was thus possible to improve the frequency control of WWV and WWVH. Later, the carrier frequencies and time signals of WWV and WWVH were phase-locked to the received signals of WWVL and WWVB, so that they might be used to obtain time (epoch) [42].

The received accuracy of the HF time interval and epoch signals depends on many factors, such as the averaging time, the length of the radio path from transmitter to receiver, the condition of the ionosphere, whether the path is partially in light and darkness or not, the frequency used,

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[1] WWV was located at Beltsville, Md., until December 1, 1966, and is now at Ft. Collins, Colo. All references in this paper are to the Beltsville location.

TABLE I

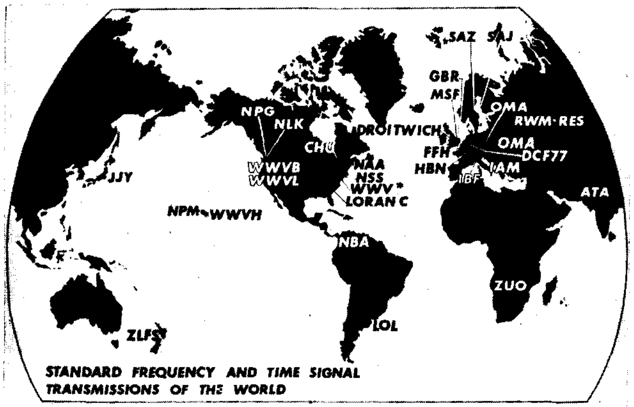
CHARACTERISTICS OF STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS IN THE ALLOCATED BANDS

Station				Carrier				Time Signals			Operation	
Call sign	Approximate location	Latitude Longitude	Coordination	Frequencies MHz	Power kW	Offset $\times 10^{-10}$	Accuracy $\times 10^{-9}$	Modulation 1 Hz	Duration Minutes	100-ms Steps	Days Week	Hours Day
ATA	New Delhi India	28° 34′ N 77° 19′ E		10	2		20	yes	continuous		5	5
FFH	Paris France	48° 59′ N 2° 29′ E		2.5	0.3		2	yes	10/20	yes	2	8 1/2
HBN	Neuchatel Switzerland	46° 58′ N 6° 57′ E	yes	5	0.5	−300	0.1	yes	5/10	yes	7	24
IAM	Rome Italy	41° 52′ N 12° 27′ E		5	1		0.5	yes	10/15	yes	6	1
IBF	Turin Italy	45° 3′ N 7° 40′ E		5	0.3		0.1	yes	35/60	yes	6	1 1/3
JGZAR	Tokyo Japan	35° 42′ N 139° 31′ E		0.02	3		0.5	yes	continuous	yes	5	2
JJY	Tokyo Japan	35° 42′ N 139° 31′ E	yes	2.5; 5; 10; 15	2	−300	0.5	yes	continuous	yes	7	24
LOL	Buenos Aires Argentina	34° 37′ S 58° 21′ W	yes	5; 10; 15	2	−300	20	yes	4/60	yes	6	5
MSF	Rugby United Kingdom	52° 22′ N 1° 11′ W	yes	5, 5; 5; 10	0.5	−300	0.1	yes	5/10	yes	7	24
OMA	Prague Czechoslovakia	50° 7′ N 14° 35′ E		2.5	1		1	yes	15/30	50 ms	7	24
RWM-RES	Moscow U.S.S.R.	56° 37′ N 36° 36′ E		5; 10; 15	20		5	yes	10/120	*n* × 10 ms	7	19
WWV	Fort Collins Colo.	40° 41′ N 105° 2.5′ W	yes	2.5; 20; 25 5; 10; 15	2.5 10	−300	0.02	yes	continuous	yes	7	22 1/2
WWVH	Hawaii U.S.A.	20° 46′ N 156° 28′ W	yes	2.5 5; 10; 15	1 2	−300	0.1	yes	continuous	yes	7	22 1/2
WWVL	Fort Collins Colo.	40° 41′ N 105° 3′ W		0.02	1.8	−300	0.02				7	24
ZLFS	Lower Hutt New Zealand	41° 14′ S 174° 55′ E		2.5	0.3		50				1	3
ZUO	Johannesburg South Africa	26° 11′ S 28° 4′ E	yes	10	0.25	−300	0.5	yes	continuous	yes	7	24
ZUO	Olifantsfontein South Africa	25° 58′ S 25° 14′ E	yes	5	4	−300	0.5	yes	continuous	yes	7	24

TABLE II

CHARACTERISTICS OF STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS IN ADDITIONAL BANDS

	Station			Carrier				Time Signals			Operation	
Call sign	Approximate location	Latitude Longitude	Coordination	Frequencies kHz	Power kW	Offset $\times 10^{-10}$	Accuracy $\times 10^{-9}$	Modulation 1 Hz	Duration Minutes	100-ms Steps	Days Week	Hours Day
CHU	Ottawa Canada	45° 18′ N 75° 45′ W	yes	3330 7335 14670	0.5 3 5	−300	5	yes	continuous	yes	7	24
DCF77	Mainflingen Germany	50° 1′ N 9° 9′ W		77.5	12			yes		200	6	6
	Droitwich United Kingdom	52° 16′ N 2° 9′ W		200	400		10				7	18–20
GBR	Rugby United Kingdom	52° 22′ N 1° 11′ W	yes		300 40	−300	0.1	yes	4/5	yes	7	22
HBG	Prangins Switzerland	46° N 6° E		75	20		0.02	yes	continuous	yes	7	24
Loran-C	Carolina Beach N. C.	34° 4′ N 77° 55′ W		100	300		0.05		continuous	50	7	24
MSF	Rugby United Kingdom	52° 22′ N 1° 11′ W	yes	60	10	−300	0.1	yes	5/10	yes	7	1
NAA	Cutler Me.	44° 39′ W 67° 17′ W	yes	17.8	2000 1000	−300	0.05				7	24
NBA	Balboa Canal Zone	9° 4′ N 79° 39′ W	yes	24	300 30	−300	0.05	yes	continuous	yes	7	24
NPG-NLK	Jim Creek Wash.	48° 12′ N 121° 55′ W	yes	18.6	1200 250	−300	0.05				7	24
NPM	Lualualei Ha.	21° 25′ N 158° 9′ W	yes	26.1	1000 100	−300	0.05				7	24
NSS	Annapolis Md.	38° 59′ N 76° 27′ W	yes	21.4	1000 100	−300	0.05				7	24
OMA	Podebrady Czechoslovakia	58° 8′ N 15° 8′ E		50	5		1	yes	23 hours/day	50	7	24
RWM-RES	Moscow U.S.S.R.	55° 45′ N 37° 33′ E		100	20		5	yes	40/120	$n \times 10$	7	21
SAJ	Stockholm Sweden	59° 20′ N 18° 3′ E		15×10^4	0.06		0.1				1	2
SAZ	Enkoping Sweden	59° 35′ N 17° 8′ E		10^5	0.1		5				7	24
VNG	Lyndhurst Australia	38° 0′ S 145° 12′ E		5425 7515 12005	0.5 0.5–10 10		1			yes	7	24
WWVB	Fort Collins Colo.	40° 40.5′ N 105° 2.5′ W		60	13		0.02	yes	continuous	200	7	24
ZUO	Johannesburg South Africa	36° 11′ S 28° 4′ E		10^5	0.05		0.5		continuous	yes	7	24



*WWV moved to Ft. Collins, Colorado, December 1, 1966

Fig. 1.

etc. [10]. In general, higher accuracies of received frequency and time interval are associated with longer averaging times, *with all daylight or all darkness on the radio paths*, a quiet ionosphere, and the highest useful HF frequency. For example, the HF broadcasts of WWV, averaged over a 30-day period, were used to compare to about 1 ms three atomic time scales, two of them separated from each other by about 2400 km [11], and from the third by about 7400 km [12].

From studies made in Japan and Sweden, the one-sigma standard deviation of a single HF time measurement was found [13] to vary from about 0.01 ms at short distances to about 0.5 ms at distances around 18 000 km. This is in good agreement with results [10] obtained in the U. S.

Frequency comparisons to a few parts in 10^{10} were made between Boulder, Colo., and Washington, D. C., using the HF time signals of WWV averaged over a period of 30 days [14], [8]. When short-term (one second to one hour observing time) frequency measurements are made, the fluctuations may vary [15] from a few parts in 10^8 to a few parts in 10^7. The limit of received accuracy at HF is set by the propagation medium regardless of the length of the observation period.

Figure 1 shows the locations of the standard frequency and time transmitters of the world.

B. Distribution by LF Transmissions (30 to 300 kHz)

There are about seven stations broadcasting standard frequency and time signals in the LF band, with transmitted frequency and time interval accuracies ranging from 0.2 to 50 parts in 10^{10}. (See Tables I and II.) Experiments [13] have shown that the time signals of HBG (75 kHz) may be received with a precision of 0.1 ms at distances of 1000 km, and the phase of the ground wave is typically stable to about ± 2 μs at 500 km.

The received frequency and phase accuracy is much better at LF than at HF because of the higher stability of the propagation medium. For instance, the rms phase fluctuations of WWVB (60 kHz) as received at distances of 2400 km were 0.1 to 0.2 μs during the daytime and around 0.6 μs at night [8]. Each measurement was averaged over a 30-minute period. Within the ground-wave range, the Loran-C stations at 100 kHz provide signals with high stability at the receiver. At Washington, D. C., the signals from the Cape Fear Loran-C Station (Table II) were used to measure time interval to a precision of about 0.1 μs and to make frequency comparisons to about one part in 10^{12} in one day [16]. Others have reported similar results [17]. Sources of error in using Loran-C signals included identification of the wrong RF cycle in the pulse (3rd one usually used) and uncertainty in propagation delays.

C. Distribution by VLF Transmissions (10 to 30 kHz)

There are about eight VLF stations broadcasting standard frequency and time signals with transmitted accuracies of a few parts in 10^{11} or better. Tables I and II list them and their main characteristics.

Of all the radio transmissions available, those at VLF have proven to be the best for the accurate distribution of standard frequencies over large areas of the world [18]–[22]. They have been in use for over a decade [18] but have been widely used for this purpose only during the last five or six years.

Atomic frequency standards in different countries have been continuously intercompared by means of VLF transmissions ever since they first became available [20], [23]–[29]. As a result of greater understanding of VLF propagation and the improvements in the accuracy of the atomic standards and the VLF receiving equipment, frequency comparisons over long distances with precisions better than one part in 10^{11} are now possible. For example, an analysis of data on the comparison by VLF for an 18-month period of several widely separated atomic frequency standards [25], [26] indicated that long-term precisions of this order are realizable. Although the analyses did not separate the fluctuations due to the propagation medium from those due to the transmitter or receiving system, the internal consistency of results indicated that the propagation effects were not limiting the measurements. Short-term VLF frequency measurements of NPM (19.8 kHz), Hawaii, were made [30] at Boulder, Colo., with precisions ranging from 2.5×10^{-11} (24-hour observing time) to 3.1×10^{-12} (8-day observing time).

Time signals on VLF transmissions of NBA (18 kHz) using a pulse technique provided a received precision [31] of about one-half millisecond in Washington, D. C. The limiting factor is the low signal-to-noise ratio as set in the wideband receiver required for reproducing the pulse.

Another more promising technique, devised at NBS [32], [14], [34], uses two or more alternately transmitted closely spaced carriers; its feasibility has been shown for distances of about 1400 km [34] and 2400 km [38]. It is based on the same principle as the proposed Radux-Omega Navigation System [33]; however, the NBS VLF time distribution system was developed independently. The positive zero crossings of the received VLF carrier may serve as "time markers" if they are phase-locked to a local signal. Their accuracy is limited by the phase fluctuations. At, say, 20 kHz, these "markers" are separated by 50 μs and may be identified by use of the interference nulls produced by a second nearby carrier which is also phase-locked. The ambiguity of identification of these nulls will be the period of the beat between the two wider-spaced carriers (if more than two are used). Coarser time markers are obtained by either a third closer-spaced carrier or conventional time signals or both. As in all timing systems using radio transmissions, both the phase and group delays of the signals must be known in order to synchronize widely spaced slave clocks to the transmitter or to each other. This is necessary because the dispersion in the propagation medium will cause the phase and group velocities to be different.

The National Aeronautics and Space Administration has reported interest in this VLF time distribution system for use at its satellite tracking stations [35]. Further investigations of its utility as a worldwide accurate time distribution system are underway at NBS [36] and elsewhere [37], [38]. Another similar system for VLF distribution of time signals has been reported [39], [40]. It has been studied theoretically, but as yet no field tests have been made.

The Omega Navigation System [41] is based on the same principle as the above-mentioned multiple carrier VLF timing system, and if it is placed into operation with eight stations as planned, it will be possible to distribute time with it to any point on the globe. The received time (epoch) accuracy has not yet been established.

A recent method that may be used to maintain widely spaced clocks in synchronism, after they have been set together by other methods (such as portable clocks), is to use the received phase of WWVL (20 kHz). These signals have been phase-locked [9] to the controlling NBS standards at Boulder, which in turn are held at nearly constant phase with respect to the NBS-UA time scale [42]. By observing the daily change between a zero crossover of the 20-kHz signal and a suitable time signal from the local clock, it is possible to keep the local clock correct to within a few microseconds.

Recent results [27] on the comparisons of atomic frequency standards by VLF gave values approaching those obtained with portable clocks, as shown in Table III(a). From this study and others [30] it is concluded that the stability of the propagation medium at VLF for paths up to 7500 km may be around two or three parts in 10^{12}. Apparently the limit of the stability of the medium has not been reached yet during times of quiet ionosphere.

Sources of error in using VLF for frequency comparisons include: 1) undetected loss of one cycle of the received signal during diurnal phase-shifts, 2) phase-jumps in the receiver synthesizer, 3) variations in the phase of the transmitted signals [9] due to the antenna system, 4) phase variations introduced by the receiving antenna, 5) lack of knowledge of the stability of the propagation medium, 6) occurrence of sudden phase anomalies (SPA) on the path, and 7) mode interference in the region between the useful ground-wave range and out to about 2500 km from the transmitter.

Sources of error in time comparisons include all of the above-mentioned factors and the lack of knowledge of the phase and group velocities in the given radio path.

III. Distribution by Portable Clocks

The most accurate method of distributing standard frequency and time over great distances to individual users, in wide use today, is by use of portable clocks, a technique first proposed [10] by NBS in 1959. Following this proposal, the first set of experiments of transporting cesium clocks [43] by air, to test the possibility of synchronizing remote slave clocks, were begun in 1959. Some preliminary measurements were made in 1960 [44], [45], but the final results were reported [46] in 1961. These results were that the slave clocks were synchronized to about 5 μs.

Another experiment conducted in 1963, in which a quartz clock was transported by air, produced similar results. It was reported that a time closure of about 5 μs was obtained in the comparisons of the portable clock with the standard before and after being transported [47].

A recent series of "flying clock" experiments was undertaken in 1964 in which atomic clocks were flown by commercial airlines to several countries to intercompare the various standards [48]–[50]. The results are shown in Table III(a) which also includes some comparisons of the same standards using VLF radio transmissions [25]–[27]. The frequency and time of the portable clocks were compared directly with those of the standards in the laboratories visited. Frequency comparisons were made to uncertainties of a few parts in 10^{12} and time comparisons to about one microsecond.

Sources of error relating to portable clocks include: 1) undetected changes in the clock during transit, 2) undetected phase-jumps in the frequency dividers, and 3) environmental effects on the rate of the clock, such as shock, vibration, voltage, and temperature changes, etc.

IV. Distribution by Satellites

Two experiments in the use of satellites to distribute time have been reported. In the first one, the satellite Telstar was used to compare clocks at Andover, Me., and Goonhilly Downs, Cornwall, U. K. [51], [52]. The clocks were compared to a precision of about 1 μs.

The second experiment made use of Relay II to compare [53], [54] clocks in Kashima, Japan, with those at Mojave, U. S. The precision of determining the arrival time of pulses on a photograph was about 0.1 μs, but it was believed there were systematic errors of around 1 μs.

Sources of error in these measurements include the nonreciprocity of the propagation paths used, lack of simultaneity of the time of the observations at each end of the paths, and resolution of the pulse arrival time.

V. Distribution by Transmission Lines and Cables

Many distribution systems use telephone lines or coaxial cables to carry the SFTS between two points; for example, between a distribution amplifier and a transmitter, between the transmitter and the antenna, or between locations several miles apart from one another.

TABLE III

(a) Frequency Comparisons in Terms of an Arbitrarily Selected Standard (NBS)

(Unit is 1×10^{-12})

	VLF			Portable Clocks†		
References Year	Mitchell [25] 1961–1962	Morgan et al. [26] 1961–1962	Crow et al. [27] 1965	Bagley and Cutler [48] 1964	Bodily [49] 1965	Bodily et al. [50] 1966
CNET		+245*	−8			−12
FOA			+4		+6	−2
LSRH	−51	−34	+2	+7	−5	+2
NPL	+68	+55	−9		+23	−2
NRC		+164*	+5		+5	−3
PO						+15
PTB					+34	−14
RRL			−2		0	+2
USNO		+36	+37	−5**		−2**

* Standard was changed some time after these measurements were made.

** Not the same standard that was used with the VLF comparisons.

† The last measurement made each year was used here. For convenience, the values given here are rounded off to the nearest unit of 1×10^{-12}.

(b) Time Comparisons in Terms of an Arbitrarily Selected Standard (NBS)

(Unit is $1 \mu s$)*

References Year	Bodily [49] 1965	Bodily et al. [50]** 1966	Time Change ΔT	UT or A Time
CNET	−242	−142 +358	+100	UT-2
FOA	−883	−868 −368	+15	UT-2
HBN	+1353	+389 +889	+964	A
NPL	+705	+296444† +496944	+295739	A
NRC	+6‡	+352† +200852	+346*	A
PO	−752	−160 +340	+591	UT-2
RGO	+5019	−437 +63	−5456	A
RRL	+1001	+977 +1477	−24	UT-2
USNO	−342	+420 +80	−76	UT-2
WWV	−481	+492 +8	−11	UT-2
WWVH	−231	−494 +6	−363	UT-2

* For convenience, the values are arbitrarily rounded to the nearest microsecond.

** The lower figures for each station are, to the nearest μs, as reported by Bodily et al. [50]; the upper figures are adjusted to take account of retardation of 500 μs in time of NBS-UA standard on April 15, 1966.

† A −200-ms adjustment of other time scales which occurred during the period between measurements was subtracted.

‡ Clock was set by portable clock.

Laboratories Involved in Comparisons

CNET—National Center for Commun. Studies, Bagnieux, France
FOA —Swedish Nat'l Defense Institute, Stockholm, Sweden
LSRH—Laboratoire Suisse de Recherche Horlogere, Neuchatel, Switzerland
NBS —National Bureau of Standards, Boulder, Colo.
NPL —National Physical Laboratory, Teddington, England
NRC —National Research Council, Ottawa, Canada
PO —Paris Observatory, Paris, France
PTB —Phys.-Tech. Bund., Braunschweig, Germany
RGO —Royal Greenwich Observatory, Herstmonceux Castle, England
RRL —Radio Research Laboratory, Tokyo, Japan
USNO—U. S. Naval Observatory, Washington, D. C.

*Note added in proof (1970):

The value of 346 μsec for NRC in Table III(b) should be 17 μsec. [See Mungall, A. G., et al., "Atomic Hydrogen Maser Development," Metrologia, Vol. 5, No. 3, p. 93 (1968).]

A. Distribution by Telephone Lines[2]

Underground telephone lines are used to carry a 10-kHz signal, derived from a hydrogen maser, from the Naval Research Laboratory to the Naval Observatory (both in Washington, D. C.) and back, a distance of about 10 miles each way [55]. Using 10-kHz amplifiers with bandwidths of 1 kHz, the fractional frequency changes introduced by the amplifiers and the 20-mile telephone wire loop were about 1×10^{-12}, averaged over 24 hours. This was determined by comparing the signal sent around the loop with that as transmitted.

A similar system, using a 1-kHz signal with outside telephone lines part of the way, was found to have diurnal phase shifts due to the daily ambient temperature cycle [56]. The relationships were determined between 1) the phase shift and the temperature change, 2) a change in the dc line resistance and the temperature change, and from these was found 3) the resistance change versus phase shift, in ohms per microsecond equivalent phase change. The latter was used in the design of an automatic phase corrector introduced into the line so that a change in the dc resistance of the line would provide the error signal to the phase corrector. A reduction of a 30-μs phase shift to a 1-μs phase shift, averaged over 5 hours, was attained on the 46-mile (round-trip) line. Averaged over 48 hours, the phase shift was still 1 μs, which represents a long-term fractional frequency stability of about 6 parts in 10^{12}.

Sources of error in the received signals include pickup of stray signals on the line and environmental effects on the group and phase-delay of the line.

B. Distribution by Coaxial Cables

Measurements of phase variations [57] on 163 km of coaxial cable between Birmingham and London, England, revealed changes of from 4 degrees to 7 degrees on signals sent completely around the loop at 1 kHz. This would cause time errors of about 20 μs at the receiver on this particular coaxial cable. The authors did not state whether the cable was underground or not.

A few limited measurements at the NBS [58] on 1000 feet of RG-58/U coaxial cable indicated that during periods of rapid temperature changes, there are significant phase and frequency changes. This was observed several times with the cable outside in the open sunlight. An increase in temperature caused a decrease in phase delay in the cable. This work is being extended to include other cables and other environmental conditions and also their effects on timing pulses.

Sources of error are the same as for the telephone lines.

VI. FREQUENCY SYNTHESIZERS

An important function in the distribution of SFTS is the synthesis of other frequency (and time) signals from the standard frequency, each of which still retains the accuracy of the standard. Two common devices that are important in this process are (a) frequency multipliers, and (b) frequency dividers.

A. Frequency Multipliers

The phase variations occurring in vacuum-tube-type frequency multipliers were investigated in Japan [59], and the investigation included theoretical as well as experimental work. It was reported that the prime causes of the phase fluctuations in the multipliers were the temperature variations of the tuned circuits. Other factors included the fluctuations in the filament and plate supply voltages and the number of multiplier stages. The exact effects of tube noise, especially at low frequencies, were not determined.

For averaging times of 10 seconds, the fractional frequency fluctuations, $\Delta f/f$, were about one part in 10^{11} when multiplying from either 100 kHz to 100 MHz or 100 kHz to 1900 MHz. In multiplying up to the same frequencies the fluctuations were one order of magnitude less when the input was at 10 MHz. By increasing the averaging time to 100 seconds, the fluctuations given above were reduced another order of magnitude. Fluctuations in the power supply contributed less than one part in 10^{-13} for a 10-second observing time.

A Russian investigator obtained similar results [60]. He reported that for vacuum tube multipliers the calculated fractional frequency fluctuations, $\Delta f/f$, were:

a) 0.3×10^{-10} for 1 second averaging time
b) 0.3×10^{-12} for 100 seconds averaging time
c) 0.3×10^{-14} for 10 000 seconds averaging time.

The experimental results reported were that, with a multiplication factor of 2.25×10^{6}, $\Delta f/f$ was less than 2×10^{-11}.

More recently, a frequency multiplier less susceptible to noise has been reported [61]. The noise level of the multiplier is less than -145 dBm/Hz bandwidth at the 100 MHz output. This would permit frequency comparisons with precision of about one part in 10^{14} in 1-second observing time, with a 10-kHz bandwidth if only the multiplier noise is considered. The spectra of the source would limit the precision to much worse than this.

B. Frequency Dividers

It appears that there is very little quantitative data on the performance of frequency dividers. Some data found in the Russian literature [62] showed that fractional frequency errors of from one part in 10^{8} to one part in 10^{10} may be introduced by frequency dividers. However, no details were given concerning the type of dividers or the division ratios used.

VII. PROMISING TECHNIQUES FOR FUTURE STUDY

There are several techniques for distributing SFTS which appear to be promising and should receive further study. They involve use of: 1) satellites, 2) meteor trial reflections of VHF radio signals (also called "meteor burst"), 3) NBS multiple-carrier technique and the Omega Navigation System at VLF for distributing time, 4) "round-trip" transmissions at HF, and 5) *E*-layer reflections at HF.

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[2] The type of transmission lines used were not stated.

Satellites, multiple-carrier VLF timing, and round-trip HF transmissions are suitable for SFTS distribution over long distances (global), but the uses of meteor trial and *E*-layer reflections are limited to shorter ranges (up to about 1200 miles).

As mentioned before, the multiple carrier VLF technique devised by NBS [32], [14], [34], possibly a similar one under study in Italy, [39], [40], and the Omega System appear to be promising for the worldwide distribution of SFTS, as shown by theoretical [14], [39], [40] and experimental studies [34], [36]–[38]. The technical and economic advantages of such a system are: 1) it requires a relatively narrow bandwidth; 2) it will provide continuous and worldwide signals for clock synchronization and time interval requirements; 3) the transmissions are from a single site (a suitable backup in cases of emergency may be provided at another site) and therefore it does not have the transmitter synchronization problems inherent in other possible worldwide systems; 4) the reliability and continuity of its signals at a receiver will be many times greater than that of a network of transmitters that must be kept accurately synchronized at all times if the timing signals are to be useful; and 5) the cost of operating and maintaining a single transmitting station would obviously be much less than that of a network.

It is only fair to say that one of the stations in the network of transmitters could be used, during periods when the network was not synchronized, as a single source of the signals. However, there might be some uncertainty as to its correctness unless special provisions were made.

Some preliminary studies [63]–[65] made of the phase velocity stability of VHF signals reflected by meteor trials indicated "nanosecond" phase stability. However, it cannot be inferred directly from this that the (pulse) group velocity stability is the same, and therefore, that the system is capable of nanosecond time (epoch) distribution. Phase measurements may be made in a relatively narrow frequency band, but pulsed signals with nanosecond resolution require a very wide band; for the same transmitted power the received *S*/*N* ratio for the two cases will be very much different. Furthermore, the dispersion characteristics of the propagation medium and multipath distortion become very important for pulsed signals. It can be shown by information theory that time (epoch) information cannot be sent by utilizing only the phase of a sinusoidal carrier signal.

In another experiment, in which pulses were used and their received stability measured, it was reported [66] that the "meteor burst" system was capable of supporting microsecond and fractional microsecond timing accuracies. The results were not verified by independent methods.

A preliminary timing system using pulses has been developed at NBS to determine the best accuracy (and related parameters) of meteor trail reflections. One recent result is that two atomic clocks separated by about 1600 km were synchronized with this system to about 10 microseconds. This was indicated by bringing the two clocks together [67].

The two reported experiments [51]–[54] in distributing time by means of satellites indicate the high potential accuracy of this system. Two types of satellites with two types of distribution equipment that may be used for this are stationary and nonstationary satellites carrying either a clock or a transponder. From theoretical studies made at NBS [68], it was concluded that three synchronous equally spaced satellites carrying atomic clocks could distribute time over all the globe except a small area around each pole.

Some problems to be solved include: 1) devising one or more easy and accurate methods of determining the propagation delays of the time signals from the satellite to the receiver, 2) development of an atomic clock that will run for long periods of time in the satellite, and 3) a quick and easy method of providing information to users on corrections to be applied to time signals received from satellites.

A system proposed by NBS [10] in 1959 to distribute more accurate time and frequency at HF is to use "round-trip" measurements. This requires the use of a transponder at the slave clock in order to be able to measure the propagation delay of the time signals from the transmitter to the slave clock and back. If the time pulses are sent at a rapid rate, say 100 pulses per second, the propagation medium will then change but little from pulse to pulse. The one-way delay time, obtained from the round-trip measurements, will be more accurately known than at present; and it will be updated continuously.

Reflection of HF time signals from the *E*-layer appears to be a promising method of distributing time over distances of about 800 to 1200 miles. The proper choice of transmitted frequencies, the proper angle of take-off of the signal at the transmitting antenna and the correct pattern of the receiving antenna would be necessary to insure that the *E*-layer rather than the F_2-layer was being utilized. Higher accuracies achieved by this method depend on the greater stability of the *E*-layer. Of course, the system would be limited to daylight periods over the path.

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