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XVII A.P.
DÜSSELDORF
21.5-1.6 1990
CCIR

XVIIth PLENARY ASSEMBLY
DÜSSELDORF, 1990

INTERNATIONAL TELECOMMUNICATION UNION

REPORTS OF THE CCIR, 1990
(ALSO DECISIONS)

ANNEX TO VOLUME VII

STANDARD FREQUENCIES AND TIME SIGNALS

CCIR INTERNATIONAL RADIO CONSULTATIVE COMMITTEE

Geneva, 1990

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Geneva, 1990

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STANDARD FREQUENCIES AND TIME SIGNALS

(Study Group 7)

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ANNEX TO VOLUME VII

[1] Now Recommendation 686.

SECTION 7A: GLOSSARY

There are no Reports in this Section.

SECTION 7B: SPECIFICATIONS FOR THE STANDARD-FREQUENCY AND TIME-SIGNAL SERVICES

There are no Reports in this Section.

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SECTION 7C: SYSTEMS FOR DISSEMINATION AND COMPARISON

REPORT 267-7

STANDARD FREQUENCIES AND TIME SIGNALS

Characteristics of standard-frequency and time-signal emissions in allocated bands and characteristics of stations emitting with regular schedules with stabilized frequencies, outside of allocated bands

(Question 1/7)

(1956-1959-1963-1966-1970-1974-1978-1982-1986-1990)

The characteristics of stations appearing in the following tables are valid as of 16 September, 1989. For information concerning changes which may have occurred since that date, reference may be made to the Annual Report of the time section of the Bureau international des poids et mesures (BIPM) or directly to the respective authority for each service as listed in Annex I.

TABLE I – *Characteristics of standard-frequency and time-signal emissions in the allocated bands, valid as of* 16 September 1989

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (MHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
ATA	New Delhi, India	28° 34′ N 77° 19′ E	Horizontal folded dipole	8 (PEP)	3	7	24 (2)	5, 10, 15	1, 1000	continuous	4/15	± 10	
BPM (3)	Pucheng, China	35° 00′ N 109° 31′ E	Omni-directional	10-20	2	7	24 (4)	2.5, 5, 10, 15	1, 1000	20/30 (UTC) 4/30 (UT1)	nil	± 10	Direct emission of UT1 time signal
HLA	Taejon Taedok Science Town, Republic of Korea	36° 23′ N 127° 22′ E	Vertical (conical monopole)	2	1	5 (5)	7 (6)	5	1	continuous	continuous	± 10	CCIR code by double pulse
IAM (7)	Roma, Italy	41° 47′ N 12° 27′ E	Vertical λ/4	1	1	6	2	5	1	continuous	nil	± 10	CCIR code by double pulse
IBF (7)	Torino, Italy	45° 02′ N 07° 46′ E	Vertical λ/4	5	1	7	2¾	5	1	continuous	nil	± 10	CCIR code by double pulse
JJY (7)	Sanwa, Sashima, Ibaraki, Japan	36° 11′ N 139° 51′ E	(8)	2	5	7	24 (9)	2.5, 5, 8, 10, 15	1 (10) 1000 (11)	continuous	30/60	± 10	CCIR code by lengthening
LOL (7)	Buenos Aires, Argentina	34° 37′ S 58° 21′ W	Horizontal 3-wire folded dipole	2	3	7	5	5, 10, 15	1, 440, 1000	continuous	3/5	± 20	CCIR code by lengthening

TABLE I *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (MHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
OMA (7)	Praha, Czechoslovak S.R.	50° 07′ N 14° 35′ E	T	1	1	7	24	2.5	1, 1000 (12)	15/30	4/15	± 1000	
RCH (7)	Tachkent, USSR	41° 19′ N 69° 15′ E	Horizontal dipole	1	2	7	21	2.5, 5, 10	1, 10	40/60	nil	± 50	CCIR code by double pulse, additional information dUT1 (13)
RID (7)	Irkutsk, USSR	52° 26′ N 104° 02′ E	Horizontal dipole	1 1 1	3	7	24	5.004 10.004 15.004	1, 10	40/60	nil	± 50	CCIR code by double pulse, additional information dUT1 (13)
RIM (7)	Tachkent, USSR	41° 19′ N 69° 15′ E	Horizontal dipole	1	1	7	20½	5, 10	1, 10	39/60	nil	± 50	CCIR code by double pulse, additional information dUT1
RTA (7)	Novosibirsk, USSR	55° 04′ N 82° 58′ E	Horizontal dipole	5	1	7	20½	10, 15	1, 10	40/60	nil	± 50	CCIR code by double pulse, additional information dUT1 (13)
RWM (7)	Moskva, USSR	55° 48′ N 38° 18′ E	Horizontal dipole	5 5 8	3	7	24	4.996 9.996 14.996	1, 10	40/60	nil	± 50	CCIR code by double pulse, additional information dUT1 (13)

TABLE I *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (MHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
WWV (7)	Fort Collins, Colorado, USA	40° 41′ N 105° 02′ W	Vertical λ/2 dipoles	2.5-10	5	7	24	2.5, 5, 10, 15, 20 (14)	1, 440, 500, 600	continuous (15)	continuous (16)	± 10	CCIR code by double pulse, additional information on UT1 corrections
WWVH (7)	Kekaha, Kauai, Hawaii, USA	21° 59′ N 159° 46′ W	Vertical λ/2 dipole arrays	2.5-10	4	7	24	2.5, 5, 10, 15 (14)	1, 440, 500, 600	continuous (15)	continuous (16)	± 10	CCIR code by double pulse, additional information on UT1 corrections
ZLFS	Lower Hutt, New Zealand	41° 14′ S 174° 55′ E		0.3	1	1	3	2.5	nil	nil	nil	± 100	

Notes to Table I:

The daily transmission schedule and hourly modulation schedule is given, where appropriate, in the form of Figs. 1 and 2 supplemented by the following notes:

(1) This value applies at the transmitter; to realize the quoted uncertainty at the point of reception it could be necessary to observe the received phase time frequency over a sufficiently long period in order to eliminate noise and random effects.

(2) 5 MHz: 1800-0900 h UTC; 10 MHz: 24 hours; 15 MHz: 0900-1800 h UTC.

(3) Call sign in Morse and language.

(4) 2.5 MHz: 0730-0100 h UTC; 15 MHz: 0100-0900 h UTC; 5 MHz and 10 MHz: continuous.

(5) Monday to Friday (except national holidays in Korea).

(6) 0100 to 0800 h UTC. Pulses of 9 cycles of 1 800 Hz modulation. 59th and 29th second pulses omitted. Hour identified by 0.8 s long 1 500 Hz tone. Beginning of each minute, identified by a 0.8 s long 1 800 Hz tone, voice announcement of hours and minutes each minute following 52nd second pulse. BCD time code given on 100 Hz sub-carrier.

(7) These stations have indicated that they follow the UTC system as specified in Recommendation 460. Since 1 January 1972 the frequency offset has been eliminated and the time signals remain within about 0.8 s of UT1 by means of occasional 1 s steps as directed by the Bureau international de l'heure.

(8) Vertical $\lambda/4$ for 2.5 MHz, horizontal $\lambda/2$ dipole for 5 and 8 MHz, and vertical $\lambda/2$ dipoles for 10 and 15 MHz.

(9) Interrupted from 35 to 39 minutes of each hour.

(10) Pulse consists of 8 cycles of 1600 Hz tone. First pulse of each minute preceded by 655 ms of 600 Hz tone.

(11) 1000 Hz tone modulation between the minutes of 0-5, 10-15, 20-25, 30-35, 40-45, 50-55 except 40 ms before and after each second's pulse.

(12) In the period from 1800-0600 h UTC, audio-frequency modulation is replaced by time signals.

(13) The additional information about the value of the difference UT1 − UTC is transmitted by code dUT1. It provides more precisely the difference UT1 − UTC down to multipes of 0.02 s. The total value of the correction is DUT1 + dUT1. Possible values of dUT1 are transmitted by marking of p second pulses between the 21st and 24th seconds of the minute, so that dUT1 = + 0.02 s × p. Negative values of dUT1 are transmitted by marking of q second pulses between the 31st and 34th second of the minute, so that dUT1 = − 0.02 s × q.

(14) As of Feb. 1, 1977 transmissions on 25 MHz from WWV and 20 MHz from WWVH were discontinued, but may be resumed at a later date.

(15) In addition to other timing signals and time announcements, a modified IRIG-H time code is produced at a 1-pps rate and radiated continuously on a 100 Hz sub-carrier on all frequencies. A complete code frame is 1 minute. The 100 Hz sub-carrier is synchronous with the code pulses, so that 10 ms resolution is obtained. The code contains DUT1 values and UTC time-of-year information in minutes, hours and days of the year.

(16) Except for voice announcement periods and the 5-minute semi-silent period each hour.

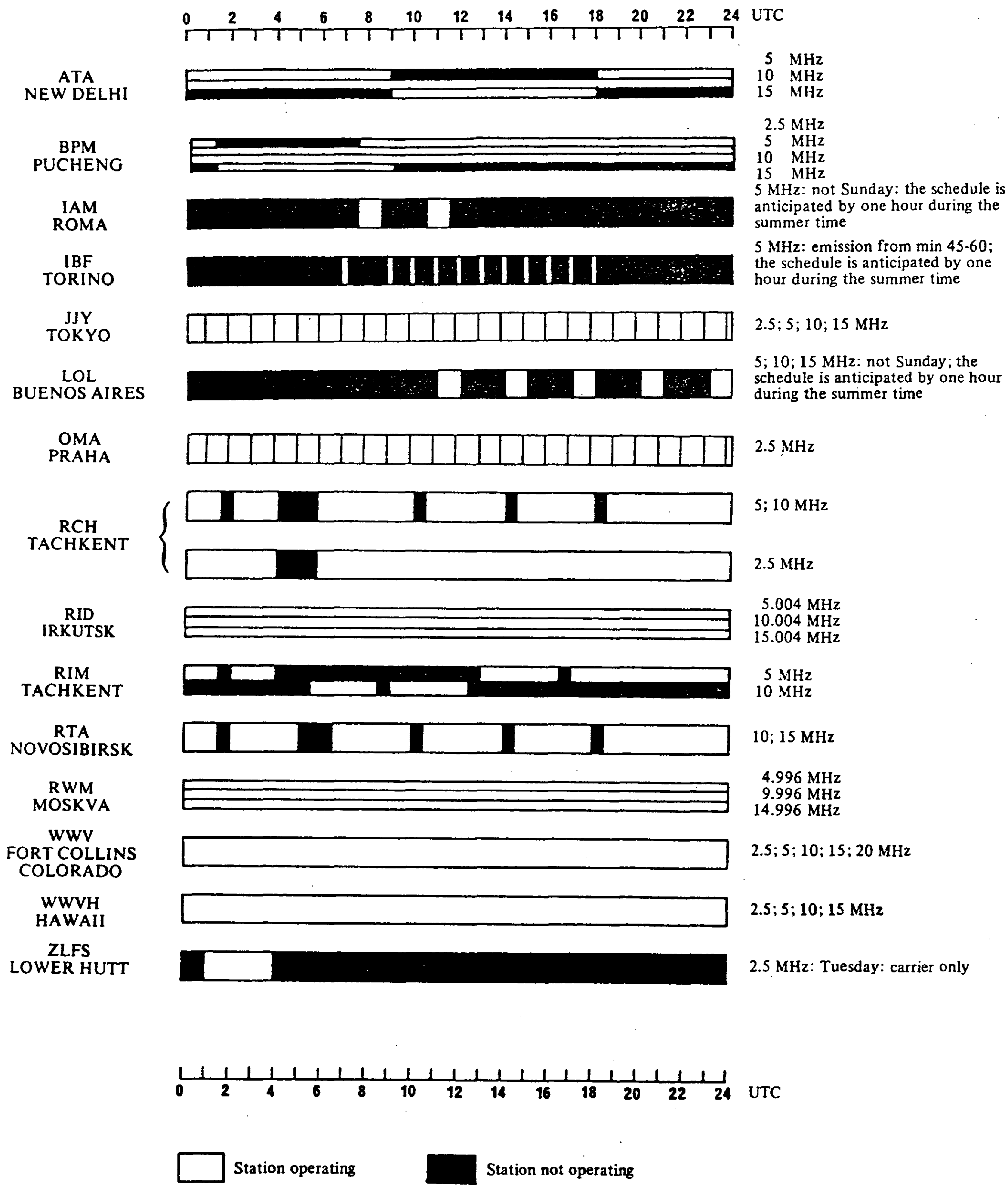
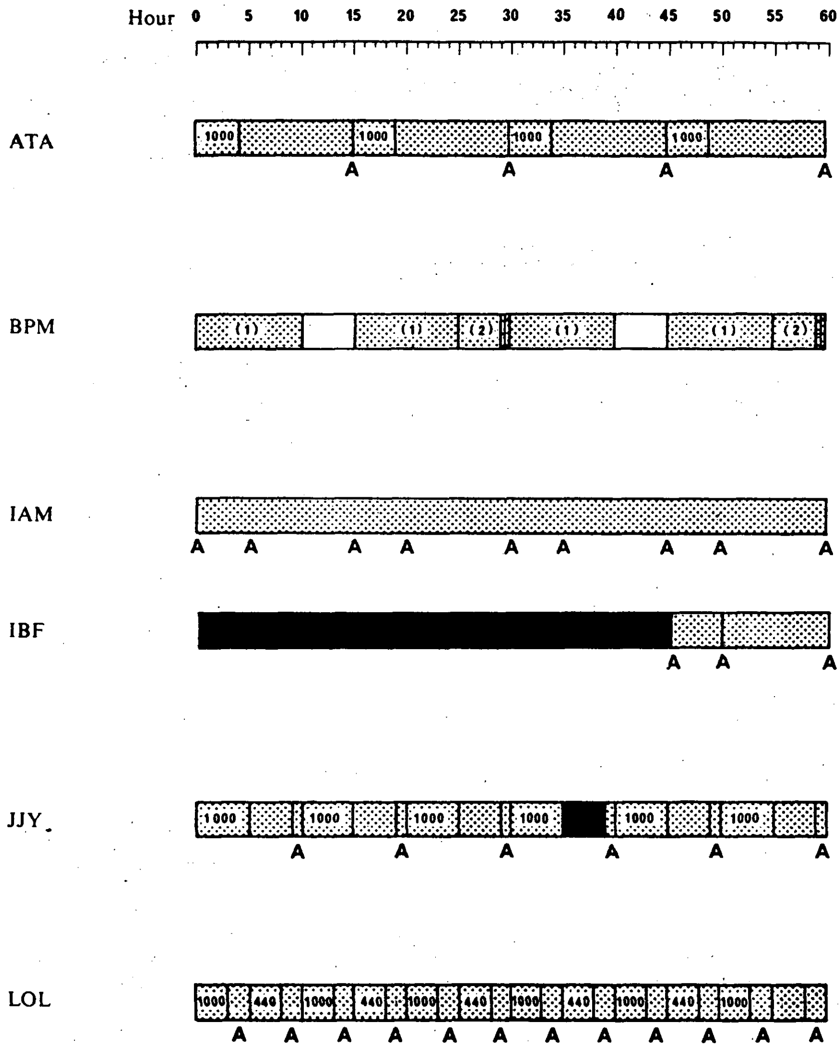


FIGURE 1 – *Daily emission schedule*



Min.

Form of second and minute signals: Morse and voice announcements (A).

Pulse of 5 cycles of 1000 Hz tone, lengthened to 100 ms at the beginning of each minute. Call sign and time (UTC) in Morse.

(1) Pulse of 10 cycles of 1000 Hz tone (UTC time signal), the first pulse of every minute is a 300 ms pulse of 1000 Hz tone. In order to avoid mutual interference the second pulses of UTC of BPM precede UTC of BIH by 20 ms.

(2) 100 ms pulse of 1000 Hz tone UT1 time signal, the first pulse of every minute is a 300 ms pulse of 1000 Hz tone.

Pulse of 5 cycles of 1000 Hz tone: minute pulse of 20 cycles of 1000 Hz tone. Call sign and time (UTC) in Morse and voice identification.

Pulse of 5 cycles of 1000 Hz tone repeated 7 times at minute. Call sign and time (UTC) in Morse, voice identification at the beginning and end of emission.

Pulse of 8 cycles of 1600 Hz tone: minute pulse is preceded by a 600 Hz tone of 655 ms duration. Call sign and time (JST) in Morse and voice. Radio propagation warnings in letter code: N (normal), U (unstable) or W (disturbed). DUT1 is indicated, by the number and position of the lengthened second's pulses of 45 ms duration, instead of the 5 ms duration of the normal second's pulse.

Pulse of 5 cycles of 1000 Hz tone, 59th pulse omitted. Call sign in Morse: identification and time (UTC − 3 h) in voice.

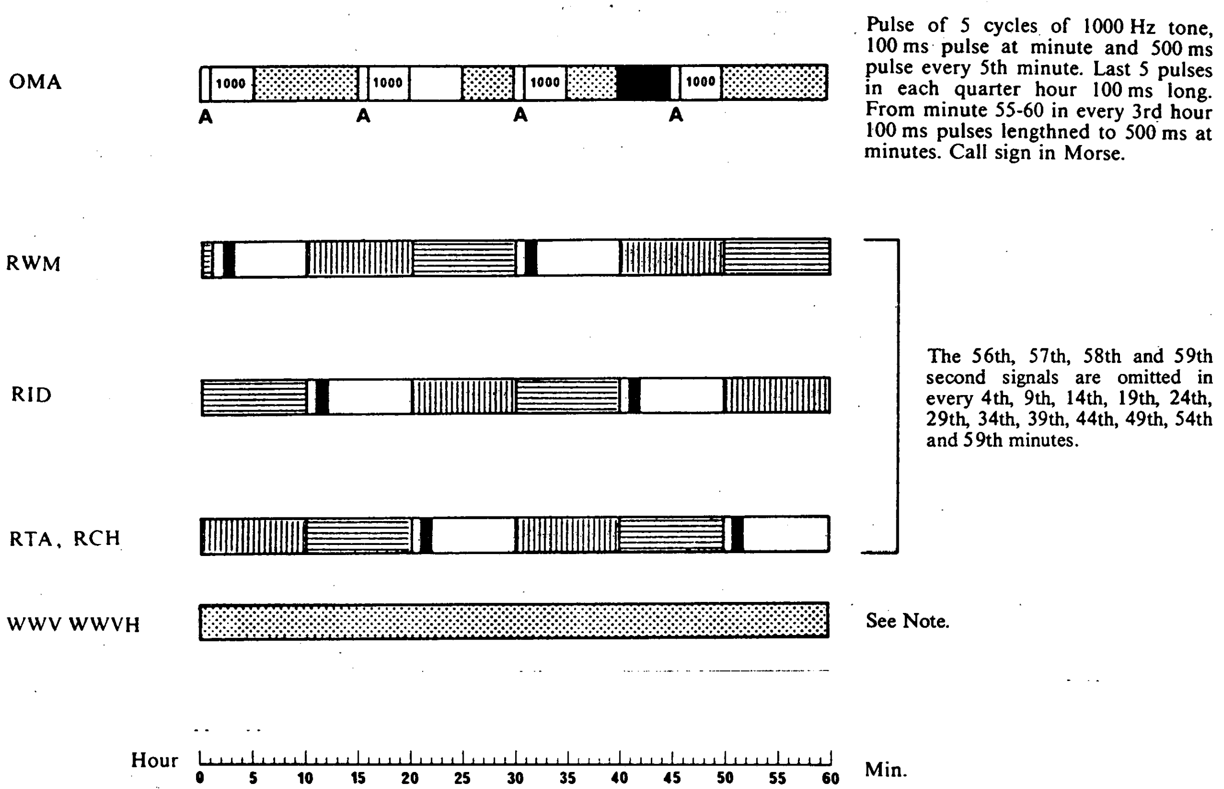


FIGURE 2 – *Hourly modulation schedule*

Note. – Pulse of 5 cycles of 1000 Hz (WWV) or 6 cycles of 1200 Hz (WWVH) tone, lengthened to 0.8 s at beginning of each minute. An 0.8 s pulse of 1500 Hz begins each hour at both stations. 29th and 59th pulses each minute are omitted. Voice time announcements preceding each minute. 45-second audio tones alternating between 500 and 600 Hz each minute, except when special announcements or station identification messages are given in voice. One 45-second segment of 440 Hz is included each hour at one minute (WWVH) or two minutes (WWV) past the hour. A modified IRIG-H time code, giving day, hour, minute and UT1 information, is broadcast continuously on a 100 Hz sub-carrier. DUT1 information is provided by the number and position of doubled second pulses each minute. All modulations interrupted for 40 ms around each second's pulse.

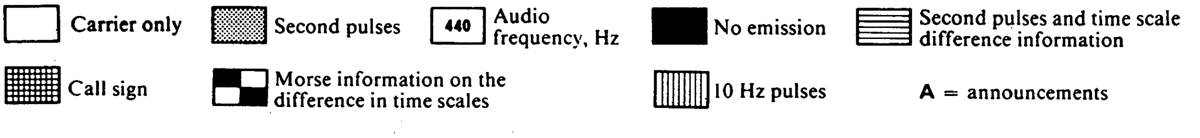


TABLE II – *Characteristics of standard-frequency and time-signal emissions in additional bands, valid as of* 16 September 1989

Station			Type of antenna(s)	Carrier power (kW)	Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
	Allouis, France	47° 10′ N 02° 12′ E	Omni-directional	1000 to 2000	1	7	24	162	1 (2)	continuous	A3E broadcast continuously	± 2	No DUT1 transmission
CHU(3)	Ottawa, Canada	45° 18′ N 75° 45′ W	Omni-directional	3, 10, 3	3	7	24	3330, 7335, 14 670	1 (4)	continuous	nil	± 5	CCIR code by split pulses
	Donebach, F.R. of Germany	49° 34′ N 09° 11′ E	Omni-directional	250	1	7	24	153	nil	nil	A3E broadcast continuously	± 2	
DCF77 (3)	Mainflingen, F.R. of Germany	50° 01′ N 09° 00′ E	Omni-directional	20 (5)	1	7	24	77.5	1	continuous (6)	continuous (7)	± 0.5	No DUT1 transmission
	Droitwich, United Kingdom	52° 16′ N 02° 09′ W	T	400	1	7	22	198 (8)	nil	nil	A3E broadcast continuously	± 20	
	Westerglen, United Kingdom	55° 58′ N 03° 50′ W	T	50	1	7	22	198 (8)	nil	nil	A3E broadcast continuously	± 20	
	Burghead, United Kingdom	57° 42′ N 03° 28′ W	T	50	1	7	22	198 (8)	nil	nil	A3E broadcast continuously	± 20	
GBR (3)(9) (10)	Rugby, United Kingdom	52° 22′ N 01° 11′ W	Omni-directional	750 60 (5)	1	7	22 (11)	16.0	nil	nil	nil	± 10	
HBG (12)	Prangins, Switzerland	46° 24′ N 06° 15′ E	Omni-directional	20	1	7	24	75	1 (13)	continuous	nil	± 1	No DUT1 transmission

TABLE II *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
JJF2 (3) JG2AS	Sanwa, Sashima, Ibaraki, Japan	36° 11′ N 139° 51′ E	Omni-directional	10	1	7	24 (14)	40	1 (15)	continuous (16)	nil	± 10	
MSF	Rugby, United Kingdom	52° 22′ N 01° 11′ W	Omni-directional	25 (5)	1	7	24 (17)	60	1 (18)	continuous	nil	± 2	CCIR code by double pulse
	Milano, Italy	45° 20′ N 09° 12′ E	Omni-directional	600	1	7	24	900	nil	nil	A3E broadcast continuously	± 2	
NAA (3) (10) (19)	Cutler, Maine, USA	44° 39′ N 67° 17′ W	Omni-directional	1000 (5)	1	7	24 (20)	24.0 (21)	nil	nil	nil	± 10	
NAU (3) (10) (19)	Aguada, Puerto Rico	18° 23′ N 67° 11′ W	Omni-directional	100 (22)	1	7	24	28.5	nil	nil	nil	± 10	
NTD (3) (10) (19)	Yosami, Japan	34° 58′ N 137° 01′ E	Omni-directional	50 (5)	1	7	24 (23)	17.4	nil	nil	nil	± 10	
NLK (3) (10) (19)	Jim Creek, Washington, USA	48° 12′ N 121° 55′ W	Omni-directional	125 (5)	1	7	24 (24)	24.8	nil	nil	nil	± 10	
NPM (3) (10) (19)	Lualualei, Hawaii, USA	21° 25′ N 158° 09′ W	Omni-directional	600 (5)	1	7	24 (25)	23.4	nil	nil	nil	± 10	
NSS (3) (10) (19)	Annapolis, Maryland, USA	38° 59′ N 76° 27′ W	Omni-directional	400 (5)	1	7	24 (26)	21.4	nil	nil	nil	± 10	

TABLE II *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul- taneous trans- missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio- modulation (min)		
NWC (3) (10)(19)	Exmouth, Australia	21° 49′ S 114° 10′ E	Omni- directional	1000 (5)	1	7	24 (27)	22.3	nil	nil	nil	± 10	
OMA	Podebrady, Czechoslovak S.R.	50° 08′ N 15° 08′ E	T	5	1	7	24	50	1 (28)	23 hours per day (29)	nil	± 1000	No DUT1 transmission
RBU (3)	Moskva, USSR	55° 48′ N 38° 18′ E	Omni- directional	10	1	7	24	$66\frac{2}{3}$	10, 100 312, 5	Continuous DXXXW (30)	Continuous (31)	± 5	CCIR code by double pulse (32)
RTZ (3)	Irkutsk, USSR	52° 26′ N 104° 02′ E	Omni- directional	10	1	7	23	50	1, 10	6/60	nil	± 5	CCIR code by double pulse (32)
RW-166	Irkutsk, USSR	52° 18′ N 104° 18′ E	Omni- directional	40	1	7	23	198		nil	A3E broadcast continu- ously	± 5	
RW-76	Novosibirsk, USSR	55° 04′ N 82° 58′ E	Omni- directional	150	1	7	22	270		nil	A3E broadcast continu- ously	± 5	
SAJ	Stockholm, Sweden	59° 15′ N 18° 06′ E	Omni- directional	0.02 (e.r.p.)	1	3 (33)	2 (34)	150 000	nil	10 (35)		± 2	
UNW3	Molodechno, USSR	54° 26′ N 26° 48′ E	Omni- directional	–	1	7	2	25.5 25.1 25.0 23.0 20.5	1, 10, 40 (36)	40 min twice per day (37)	nil	± 10	

TABLE II *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
UPD8	Arkhangelsk, USSR	64° 24′ N 41° 32′ E	Omni-directional	–	1	7	2	25.5 25.1 25.0 23.0 20.5	1, 10, 40 (36)	40 min twice per day (38)	nil	± 10	
UQC3	Khabarovsk, USSR	48° 30′ N 134° 51′ E	Omni-directional	300	1	7	2	25.0 25.1 25.5 23.0 20.5	1, 10, 40 (36)	40 min 3 times per day (39)	nil	± 10	
USB2	Frunze, USSR	43° 04′ N 73° 39′ E	Omni-directional	–	1	7	3	25.5 25.1 25.0 23.0 20.5	1, 10, 40 (36)	40 min 3 times per day (40)	nil	± 10	
UTR3	Gorky, USSR	56° 11′ N 43° 58′ E	Omni-directional	300	1	7	2	25.0 25.1 25.5 23.0 20.5	1, 10, 40 (36)	40 min 3 times per day (41)	nil	± 10	
VNG (3)	Lyndhurst, Victoria, Australia	38° 03′ S 145° 16′ E	Omni-directional	10	2	7	24 (42)	4500 7500 12 000	1, 1000 (43)	continuous	nil	± 100	CCIR code by 45 cycles of 900 Hz immediately following the normal second markers
WWVB (3)	Fort Collins, Colorado, USA	40° 40′ N 105° 03′ W	Top-loaded vertical	13 (5)	1	7	24	60	1 (44)	continuous	nil	± 10	No CCIR code

TABLE II *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
Y3S	Nauen, German Democratic Republic	52° 39′ N 12° 55′ E	Omni-directional	5	1	7	24	4525	nil	continuous (45)	continuous	(8)	CCIR code by split pulses
	Motala, Sweden	58° 26′ N 14° 59′ E	Omni-directional	300	1	7	17	189	nil	21 s once per day (46)	A3E broadcast continu-ously	± 50 (8)	CCIR code by decreased audio-modulation frequency
EBC	San Fernando, Cadiz, Spain	36° 28′ N 06° 12′ W	Omni-directional	1	1	7	1	12 008 6840	(47)	10	(48)	± 100	CCIR code by double pulse

Notes to Table II:

(1) This value applies at the transmitter: to realize the quoted uncertainty at the point of reception it could be necessary to observe the received phase time frequency over a sufficiently long period in order to eliminate noise and random effects.

(2) Phase modulation of the carrier by + and − 1 radian in 0.1 s every second except the 59th second of each minute. This modulation is doubled to indicate binary 1. The numbers of the minute, hour, day of the month, day of the week, month and year are transmitted each minute from the 21st to the 58th second, in accordance with the French legal time scale. In addition, a binary 1 at the 17th second indicates that the local time is 2 hours ahead of UTC (summertime), a binary 1 at the 18th second indicates when the local time is one hour ahead of UTC (wintertime); a binary 1 at the 14th second indicates the current day is a public holiday (Christmas, 14 July, etc.), a binary 1 at the 13th second indicates that the current day is the eve of a public holiday.

(3) These stations have indicated that they follow one of the systems referred to in Recommendation 460.

(4) Pulses of 300 cycles of 1000 Hz tone: the first pulse in each minute is prolonged.

(5) Figures give the estimated *radiated* power.

(6) At the beginning of each second (except the 59th second) the carrier amplitude is reduced to 25% for a duration of 0.1 or 0.2 s corresponding to "binary 0" or "binary 1", respectively. The number of the minute, hour, day of the month, day of the week, month and year are transmitted in BCD code from the 21st to the 58th second. The time signals are generated by the Physikalisch-Technische Bundesanstalt (PTB) and are in accordance with the legal time of the Federal Republic of Germany which is UTC (PTB) + 1 h (Central European Time CET) or UTC (PTB) + 2 h (Central European Summer Time CEST). In addition, CET and CEST are indicated by a binary 1 at the 18th or 17th second, respectively.

To achieve a more accurate time transfer and a better use of the frequency spectrum available an additional pseudo random phase shift keying of the carrier is superimposed on the AM second markers.

(7) Call sign is given by modulation of the carrier with 250 Hz tone three times every hour at the minutes 19, 39 and 59, without interruption of the time signal sequence.

(8) No coherence between carrier frequency and time signals.

(9) FSK is used, alternatively with CW; both carriers are frequency controlled.

(10) MSK (minimum shift keying) in use: a phase-stable carrier can be recovered after suitable multiplication and mixing in the receiver. It will be recalled that the use of minimum shift keying means that no discrete component exists at the respective carrier frequencies which are given in the Table. The MSK signal can be expressed as [Pasupathy, 1979].

$$S(t) = \cos\left(2\pi f_c t + a_n(\pi t/2T) + \varphi_n\right)$$

where $a_n = i(-1)$ for mark (space) and $\varphi_n = 0, \pi$ (modulo 2π)

If the transmission is to be useful as a frequency reference it is necessary to recover a phase coherent carrier free from the $\pi/2$ increments introduced by the modulation. There are two approaches.

The MSK signal is considered as a continuous-phase frequency shift keying (CPFSK) with a modulation index of 0.5. Squaring the signal followed by band-pass filtering at centre frequency $2f_c$ produces a CPFSK signal with spectral components at $2f_c + 2f_b$ and $2f_c - 2f_b$, corresponding to mark and space, respectively. The components can be extracted by means of two phase-locked loops (PLL) and the reference carrier recovered by multiplication, division and filtering [de Buda, 1972].

The other approach treats the MSK signal as a form of phase-shift keying (PSK), MSK being obtained by transformations from binary PSK (BPSK) or quadrature PSK (QPSK). The carrier recovery techniques available for PSK such as Costas-loop can thus be applied to MSK; such a demodulator has been realised in a single-chip form [Suzuki et al., 1986].

(11) Maintenance period from 1000 to 1400 h UTC each Tuesday.

(12) Coordinated time signals.

(13) Interruption of the carrier during 100 ms at the beginning of each second; double pulse each minute; triple pulse each hour; quadruple pulse every 12 hours.

(14) JJF-2: telegraph, JG2AS: in the absence of telegraph signals.

Notes to Table II (continued)

(15) —— There are two types of formats: One is the transmission of the carrier frequency for 500 ms duration at the beginning of each second, except for the 59th second which is for 200 ms duration. The second format is generated in a slow time code (1 bit/s) which consists of a transmitted carrier frequency for 500 ms and 800 ms duration, corresponding to "binary 1" and "binary 0" respectively. The duration of the "position mark" at each 9th second and that of the frame reference marker is 200 ms. The number of the minute, hour, day of the year and the time offset to DUT1 are transmitted in BCD code from the 1st through the 43rd second.

(16) In absence of telegraphic traffic.

(17) The transmission is interrupted during the maintenance period from 1000 to 1400 h UTC (on the first Tuesday of each month).

(18) Carrier interrupted for 100 ms at each second and 500 ms at each minute; fast time code, 100 bit/s, BCD NRZ emitted during min-interruption giving month, day-of-month, hour and minute. Slow time code, 1 bit/s, BCD PWM emitted from seconds 17 to 51 giving year, month, day-of-month, day-of-week, hour and minute together with 8-bit Identifier from seconds 52 to 59. CCIR DUT1 code by double pulse.

(19) This station is primarily for communication purposes; while these data are subject to change, the changes are announced in advance to interested users by the US Naval Observatory, Washington, DC, USA.

(20) From 1200 to 2000 h UTC each Sunday while NSS is off the air (until 15 July).

(21) As of 23 January 1984, until further notice.

(22) Became operational on 14 August 1984, 74 kW.

(23) 2300 to 0900 h UTC just first Thursday-Friday, 2300 to 0700 h UTC all other Thursday-Fridays. Half power 2200 to 0200 h UTC each Monday and Friday.

(24) Except from 1600 to 2400 h UTC each Thursday. During Daylight Saving Time 1500 to 2300 h UTC each Thursday.

(25) 2.5 MHz: 0000-1000 h UTC; 5 MHz: 0900-0100 h UTC; 10 MHz: continuous; 15 MHz: 0100-0900 h UTC.

(26) Off the air until 2100 h UT on 15 July, except for fourteen hours each Sunday to cover the period when NAA is off the air.

(27) From 0000 to 0800 h, usually each Monday.

(28) A1A telegraphy signals.

(29) From 1000 to 1100 h UTC, transmission without keying except for call-sign OMA at the beginning of each quarter-hour.

(30) The standard frequencies and time signals are DXXXW type emissions and are made up of carrier sine-wave oscillations with the frequency of 66 2/3 kHz, which are interrupted for 5 ms every 100 ms; 10 ms after an interruption the carrier oscillations are narrow-band phase-modulated for 80 ms by sine-wave signals with sub-carriers of 100 or 312.5 Hz and a modulation index of 0.698. Amplitude-modulated signals with a repetition frequency of 10 Hz are used to transmit time markers. Signals with a sub-carrier of 312.5 Hz are used to indicate second and minute markers, and also "1's" in the binary code for the transmission of time-scale information; signals with a frequency of 100 Hz are used to indicate "0's" in the binary code.

(31) NON signals may be transmitted in individual cases.

(32) The additional information about the value of the difference UT1 − UTC is transmitted by code dUT1. It provides more precisely the difference UT1 − UTC down to multiples of 0.02 s. The total value of the correction is DUT1 + dUT1. Possible values of dUT1 are transmitted by marking of p second pulses between the 21st and 24th seconds of the minute, so that dUT1 = + 0.02 s × p. Negative values of dUT1 are transmitted by marking of q second pulses between the 31st and 34th second of the minute, so that dUT1 = −0.02 s × q.

Notes to Table II (continued)

(33) Each Monday, Wednesday and Friday.

(34) From 0930 to 1130 h UTC. When Summer Time, add one hour to the times given.

(35) Second pulses of 8 cycles of 1 kHz modulation during 5 minutes beginning at 1100 h UTC and 1125 h UTC. When Summer Time, add one hour to the instants given.

(36) Two types of signal are transmitted during a duty period:

a) A1A signals with carrier frequency 25 kHz, duration 0.0125; 0.025; 0.1; 1 and 10 s with repetition periods of 0.025; 0.1; 1; 10 and 60 s respectively,

b) N0N signals with carrier frequencies 25.0; 25.1; 25.5; 23.0; 20.5 kHz. The phases of these signals are matched with the time markers of the transmitted scale.

(37) From 0736 to 1817 h and 1936 to 2017 h UTC from 1 October to 31 March.
From 0736 to 1817 h and 2036 to 2117 h UTC from 1 April to 30 September.

(38) From 0836 to 0917 h and 1136 to 1217 h UTC.

(39) From 0036 to 0117 h, 0636 to 0717 h and 1736 to 1817 h UTC from 1 October to 31 March.
From 0136 to 0217 h, 0536 to 0617 h and 1736 to 1813 h UTC from 1 April to 30 September.

(40) From 0436 to 0517 h, 0936 to 1017 h and 2136 to 2217 h UTC from 1 October to 31 March.
From 0436 to 0517 h, 1036 to 1117 h and 2236 to 2317 h UTC from 1 April to 30 September.

(41) From 0536 to 0617 h, 1336 to 1417 h and 1836 to 1917 h UTC from 1 October to 31 March.
From 0636 to 0717 h, 1336 to 1417 h and 1837 to 1917 h UTC from 1 April to 30 September.

(42) 4500 kHz, from 0945 to 2130 h UTC, 12 000 kHz, from 2145 to 0930 h UTC, 7500 kHz, continuous service, with a technical interruption from 2230 to 2245 h UTC.

(43) Pulses of 50 cycles of 1000 Hz tone, shortened to 5 cycles from the 55th to the 58th second; the 59th pulse is omitted. At the 5th, 10th, 15th, etc. minutes, pulses from the 50th to the 58th second are shortened to 5 cycles; voice identification between the 20th and 50th pulses in the 15th, 30th, 45th and 60th minutes.

(44) Time code used which reduces carrier by 10 dB at the beginning of each second.

(45) A1A time signals of 0.1 s duration (minute marker of 0.5 s duration) followed by code pulses from 0.25 to 0.3 s for information about DUT1, dUT1 and time of the day (minute, hour) in UTC.

(46) A3E time signals of 0.1 s duration between 11 h 58 min 55 s and 11 h 59 min 16 s UTC. The minute marker is of 0.5 s duration. When Summer Time, add one hour to the instants given.

(47) Seconds pulses of a duration of 0.1 s, modulated at 1000 Hz,
Minutes pulses of a duration of 0.5 s, modulated at 1250 Hz.

(48) Minutes 00 to 10, 12 008 kHz, A2A.
15 to 25, 12 008 kHz, J3E.
30 to 40, 6 840 kHz, A2A.
45 to 55, 6 840 kHz, J3E.

During the minute immediately preceding each of the periods indicated, transmission of call sign in slow Morse twice.

TABLE III – *Characteristics of some navigational aids, valid as of* 16 September 1989

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (µs)	Time signal	Audio-modulation	
BPL	Pucheng, China	34°56.9°N 109°33.1°E	Omni-directional	800	1	7	8	100	60000	continuous	nil	± 1
Loran-C (2) (7980-Z, 9960-Y)	Carolina Beach, NC, USA	34° 03.8′ N 77° 54.8′ W	Omni-directional	550 (3)	1	7	24	100	99 600 79 800 (4)	continuous (5)	nil	± 1
Loran-C (7980-Y)	Jupiter, Florida, USA	27° 02.0′ N 80° 06.9′ W	Omni-directional	325	1	7	24	100	79 800 (4)	continuous (5)	nil	± 1
Loran-C (2) (5930-Y, 7930-W)	Cape Race, Newfoundland	46° 46.5′ N 53° 10.5′ W	Omni-directional	1500 (3)	1	7	24	100	79 300 59 300 (4)	continuous (5)	nil	± 1
Loran-C (2) (5930-X, 9960-X)	Nantucket Island, USA	41° 15.2′ N 69° 58.6′ W	Omni-directional	325(3)	1	7	24	100	59 300 (4) 99 600	continuous (5)	nil	± 1
Loran-C (2) (8970-M, 9960-Z)	Dana, Indiana, USA	39° 51.1′ N 87° 29.2′ W	Omni-directional	400 (3)	1	7	24	100	89 700 (4) 99 600	continuous (5)	nil	± 1
Loran-C (2) (7930-X, 9980-W)	Angissoq, Greenland	59° 59.3′ N 45° 10.4′ W	Omni-directional	760 (3)	1	7	24	100	79 300 (4)	continuous (5)	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (μs)	Time signal	Audio-modulation	
Loran-C (2) (7970-M, 9980-X)	Ejde, Faeroe Is.	62° 18.0′ N 7° 04.4′ W	Omni-directional	325 (3)	1	7	24	100	79 300 79 700 (4)	continuous (5)	nil	± 1
Loran-C (7970-W)	Sylt, F.R. of Germany	54° 48.5′ N 8° 17.6′ E	Omni-directional	325 (3)	1	7	24	100	79 700 (4)	continuous (5)	nil	± 1
Loran-C (7970-X)	Bo , Norway	68° 38.1′ N 14° 27.8′ E	Omni-directional	165 (3)	1	7	24	100	79 700 (4)	continuous (5)	nil	± 1
Loran-C (2) (7970-Y, 9980-M)	Sandur, Iceland	64° 54.4′ N 23° 55.4′ W	Omni-directional	1500 (3)	1	7	24	100	79 300 (4)	continuous (5)	nil	± 1
Loran-C (7970-Z)	Jan Mayen, Norway	70° 54.9′ N 8° 44.0′ W	Omni-directional	165 (3)	1	7	24	100	79 700 (4)	continuous (5)	nil	± 1
Loran-C (5930-Z, 7930-M)	Fox Harbour, Canada	52° 22.6′ N 55° 42.5′ W	Omni-directional	800 (3)	1	7	24	100	59 300 79 300	continuous (5)	nil	± 1
Loran-C (7990-M)	Sellia Marina, Italy	38° 52.3′ N 16° 43.1′ E	Omni-directional	165 (3)	1	7	24	100	79 900 (4)	continuous (5)	nil	± 1
Loran-C (7990-X)	Lampedusa, Italy	35° 31.3′ N 12° 31.5′ E	Omni-directional	325 (3)	1	7	24	100	79 900 (4)	continuous (5)	nil	± 1
Loran-C (7990-Y)	Kargabarun, Turkey	40° 58.3′ N 27° 52.0′ E	Omni-directional	165 (3)	1	7	24	100	79 900 (4)	continuous (5)	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) [1]
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (µs)	Time signal	Audio-modulation	
Loran-C (7990-Z)	Estartit, Spain	42° 03.6′ N 3° 12.3′ E	Omni-directional	165 [3]	1	7	24	100	79 900 [4]	continuous [5]	nil	± 1
Loran-C (4990-M)	Johnston Is.	16° 44.7′ N 169° 30.5′ W	Omni-directional	325 [3]	1	7	24	100	49 900 [4]	continuous [5]	nil	± 1
Loran-C (4990-X)	Upolu Point, Hawaii, USA	20° 14.8′ N 155° 53.2′ W	Omni-directional	325 [3]	1	7	24	100	49 900 [4]	continuous [5]	nil	± 1
Loran-C (4990-Y)	Kuré, Hawaii, USA	28° 23.7′ N 178° 17.5′ W	Omni-directional	325 [3]	1	7	24	100	49 900 [4]	continuous [5]	nil	± 1
Loran-C (9970-M)	Iwo Jima, Japan	24° 48.1′ N 141° 19.5′ E	Omni-directional	1815 [3]	1	7	24	100	99 700 [4]	continuous [5]	nil	± 1
Loran-C (9970-W, 7930-M)	Minami, Tori Shima (Marcus Is.,) Japan	24° 17.1′ N 153° 58.9′ E	Omni-directional	2160 [3]	1	7	24	100	99 700 [4]	continuous [5]	nil	± 1
Loran-C (9970-X, 7930-X, 5970-W)	Hokkaido, Japan	42° 44.6′ N 143° 43.2′ E	Omni-directional	1000 [3]	1	7	24	100	99 700 [4] 79 300 59 700	continuous [5]	nil	± 1
Loran-C (9970-Y, 7930-Y, 5970-Z)	Gesashi, Okinawa, Japan	26° 36.4′ N 128° 08.9′ E	Omni-directional	1000 [3]	1	7	24	100	99 700 [4] 79 300 59 700	continuous [5]	nil	± 1
Loran-C (7930-Z)	Yap, Caroline Is.	9° 32.8′ N 138° 09.9′ E	Omni-directional	1000 [3]	1	7	24	100	79 300 [4]	continuous [5]	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) ([1])
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (µs)	Time signal	Audio-modulation	
Loran-C (9990-M)	St. Paul, Pribiloff Is., Alaska	59° 09.2′ N 170° 15.1′ W	Omni-directional	325 ([3])	1	7	24	100	99 900 ([4])	continuous ([5])	nil	± 1
Loran-C (9990-X)	Attu, Alaska	52° 49.7′ N 173° 10.8′ E	Omni-directional	325 ([3])	1	7	24	100	99 900 ([4])	continuous ([5])	nil	± 1
Loran-C ([2]) (9960-M, 8970-X)	Seneca, NY, USA	42° 42.8′ N 76° 49.6′ W	Omni-directional	800 ([3])	1	7	24	100	99 600 ([4]) 89 700 ([4])	continuous ([5])	nil	± 1
Loran-C ([2]) (9960-W, 5930-M)	Caribou, ME, USA	46° 48.5′ N 67° 55.6′ W	Omni-directional	350 ([3])	1	7	24	100	59 300 ([4]) 99 600 ([4])	continuous ([5])	nil	± 1
Loran-C ([2]) (8970-W, 7980-M)	Malone, FL, USA	30° 59.6′ N 85° 10.1′ W	Omni-directional	800 ([3])	1	7	24	100	89 700 ([4]) 79 800 ([4])	continuous ([5])	nil	± 1
Loran-C (8970-Y)	Baudette, MN, USA	48° 36.8′ N 94° 33.3′ W	Omni-directional	800 ([3])	1	7	24	100	89 700 ([4])	continuous ([5])	nil	± 1
Loran-C (7980-W)	Grangeville, LA, USA	30° 43.6′ N 90° 49.7′ W	Omni-directional	800 ([3])	1	7	24	100	79 800 ([4])	continuous ([5])	nil	± 1
Loran-C (7980-X)	Raymondville, TX, USA	26° 31.9′ N 97° 50.0′ W	Omni-directional	400 ([3])	1	7	24	100	79 800 ([4])	continuous ([5])	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) [1]
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (μs)	Time signal	Audio-modulation	
Loran-C (9990-Y)	Pt. Clarence, Alaska	65° 14.7′ N 166° 53.2′ W	Omni-directional	1000 [3]	1	7	24	100	99 900 [4]	continuous [5]	nil	± 1
Loran-C [2] (9990-Z, 7960-X)	Narrow Cape, Alaska	57° 26.3′ N 152° 22.2′ W	Omni-directional	400 [3]	1	7	24	100	99 900 79 600 [4]	continuous [5]	nil	± 1
Loran-C (7960-M)	Tok, Alaska	63° 19.7′ N 142° 48.5′ W	Omni-directional	540 [3]	1	7	24	100	79 600 [4]	continuous [5]	nil	± 1
Loran-C [2] (7960-Y, 5990-X)	Shoal Cove, Alaska	55° 26.3′ N 131° 15.3′ W	Omni-directional	540 [3]	1	7	24	100	79 600 59 900 [4]	continuous [5]	nil	± 1
Loran-C (5990-M)	Williams Lake, BC, Canada	51° 58.0′ N 122° 22.0′ W	Omni-directional	400 [3]	1	7	24	100	59 900 [4]	continuous [5]	nil	± 1
Loran-C [2] (5990-Y, 9940-W)	George, Washington, USA	47° 03.8′ N 119° 44.6′ W	Omni-directional	1600 [3]	1	7	24	100	59 900 99 400 [4]	continuous [5]	nil	± 1
Loran-C (9940-M)	Fallon, Nevada, USA	39° 33.1′ N 118° 49.9′ W	Omni-directional	400 [3]	1	7	24	100	99 400 [4]	continuous [5]	nil	± 1
Loran-C (9940-X)	Middletown, California, USA	38° 46.9′ N 122° 29.7′ W	Omni-directional	400 [3]	1	7	24	100	99 400 [4]	continuous [5]	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (µs)	Time signal	Audio-modulation	
Loran-C (9940-Y)	Searchlight, Nevada, USA	35° 19.3′ N 114° 48.3′ W	Omni-directional	540 (3)	1	7	24	100	99 400 (4)	continuous (5)	nil	± 1
Loran-C (5990-Z)	Port Hardy, BC, Canada	50° 36.5′ N 127° 21.5′ W	Omni-directional	400 (3)	1	7	24	100	59 900 (4)	continuous	nil	± 1
RNS-E(A)	Briansk, USSR	53° 13′ N 34° 24′ E	Omni-directional	800 (3)	1	7 (6)	10 (7)	100	80 000 (8)	continuous	nil	± 5
RNS-E(D)	Syzran, USSR	53° 11′ N 49° 46′ E	Omni-directional	800 (3)	1	6 (6)	10 (7)	100	80 000 (8)	(9)	nil	± 5
RNS-W(A)	Aleksandrovsk, Sakhalinsky	50° 56′ N 142° 38′ E	Omni-directional	400 (3)	1	7 (1)	12 (10)	100	50 000 (8)	continuous	nil	± 5
Omega Ω/A	Aldra, Norway	66° 25′ N 13° 08′ E	Omni-directional	10 (11)	1	7	24	11.05-F 10.2-A (12) 11⅓-C 13.6-B	nil	(12)	nil	± 5
Omega Ω/ B	Monrovia, Liberia	06° 18′ N 10° 40′ W	Omni-directional	10 (11)	1	7	24	11.05-G 10.2-B (12) 11⅓-D 13.6-C	nil	(12)	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (µs)	Time signal	Audio-modulation	
Omega Ω/ C	Haiku, Hawaii, USA	21° 24′ N 157° 50′ W	Omni-directional	10 (11)	1	7	24	11.05-H 10.2-C (12) 11⅓-E 13.6-D	nil	(12)	nil	± 1
Omega Ω/ D	Lamoure, North Dakota, USA	46° 22′ N 98° 20′ W	Omni-directional	10 (11)	1	7	24	11.05-A 10.2-D (12) 11⅓-F 13.6-E	nil	(12)	nil	± 1
Omega Ω/E	La Reunion	20° 58′ S 55° 17′ E	Omni-directional	10 (11)	1	7	24	11.05-B 10.2-E (12) 11⅓-G 13.6-F	nil	(12)	nil	± 1
Omega Ω/ F	Golfo Nuevo, Argentina	43° 03′ S 65° 11′ W	Omni-directional	10 (11)	1	7	24	11.05-C 10.2-F (12) 11⅓-H 13.6-G	nil	(12)	nil	± 1
Omega Ω/G	Woodside, Victoria, Australia	38°29'S 146°56'E	Omni-directional	10 (11)	1	7	24	11.05-D 10.2-G 11⅓-A 13.6-H	nil	(12)	nil	±1
Omega Ω/ H	Tsushima Is., Japan	34° 37′ N 129° 27′ E	Omni-directional	10 (11)	1	7	24	11.05-E 10.2-H (12) 11⅓-B 13.6-A	nil	(12)	nil	± 1

Notes to Table III:

(1) No transmission on the 20th or 21st of each month.

(2) Dual-rated stations.

(3) Peak radiated power.

(4) Time pulses appear in groups of 9 for the master station (M) and groups of 8 for the secondary stations (W, X, Y, Z).

(5) Maintained within $\pm$ 5 µs of UTC. Time of Coincidence (TOC) with the UTC second changes with the recurrence of leap-seconds and is designated in TOC Tables issued to interested users by the US Naval Observatory, Washington DC, USA.

(6) No transmission on the 10th and 11th of each month.

(7) From 0400 to 1000 h and 1400 to 1800 h UTC.

(8) The signals of primary stations (A) are marked by the transmission of an additional ninth pulse in each group. Each pulse group coinciding with a UTC second marker is marked by the transmission of an additional (tenth) pulse. In the event of coincidence with the minute marker, the subsequent ten groups are additionally marked, and in the event of coincidence with the five-minute marker after 12 seconds, the subsequent 11 groups are also marked. The UTC second markers are accompanied by characteristic points situated at the leading edges of the eighth pulses at a level of 0.6 of the maximum signal value.

(9) Generally operates without a second marker. In individual cases operates with a second marker shifted in relation to UTC.

(10) From 2300 to 2400 h and 0000 to 1100 h UTC.

(11) Figures give the estimated radiated power.

(12) See Table IV.

TABLE IV – *OMEGA signal format*

0 1 2 3 4 5 6 7 8 9 10

Segment	A	B	C	D	E	F	G	H
Duration	0.9	1.0	1.1	1.2	1.1	0.9	1.2	1.0
kHz:								
10.2	Norway	Liberia	Hawaii	North Dakota	La Reunion	Argentina	Australia	Japan
$11^1/_3$	Australia	Japan	Norway	Liberia	Hawaii	North Dakota	La Reunion	Argentina
13.6	Japan	Norway	Liberia	Hawaii	North Dakota	La Reunion	Argentina	Australia
11.05	North Dakota	La Reunion	Argentina	Australia	Japan	Norway	Liberia	Hawaii

Note 1. – Segment A does not begin at 0.0 s UTC. Time of segments changes with leap-seconds. Segment A begins at second 45.0 in January 1990.

Note 2. – The OMEGA stations are for general navigation purposes: while these data are subject to change, the changes are announced in advance to interested users by the United States Coast Guard Commandant*.

Note 3. – In addition to the navigational frequencies of 10.2 kHz, 13.6 kHz and 11⅓ kHz transmitted by all the stations, the stations transmit "unique frequencies". These stations and their frequencies/segments are given in Table V.

* United States Coast Guard Commandant (G-WAN-3/73), 400 Seventh Street, S.W., Washington, DC 20590.

TABLE V – *Omega radionavigation system signal transmission format*

Station \ Segment	1	2	3	4	5	6	7	8
Norway (A)	10.2	13.6	11 1/3	12.1(¹)	12.1(¹)	11.05	12.1(¹)	12.1(¹)
Liberia (B)	12.0(¹)	10.2	13.6	11 1/3	12.0(¹)	12.0(¹)	11.05	12.0(¹)
Hawaii (C)	11.8(¹)	11.8(¹)	10.2	13.6	11 1/3	11.8(¹)	11.8(¹)	11.05
North Dakota (D)	11.05	13.1(¹)	13.1(¹)	10.2	13.6	11 1/3	13.1(¹)	13.1(¹)
La Reunion (E)	12.3(¹)	11.05	12.3(¹)	12.3(¹)	10.2	13.6	11 1/3	12.3(¹)
Argentina (F)	12.9(¹)	12.9(¹)	11.05	12.9(¹)	12.9(¹)	10.2	13.6	11 1/3
Australia (G)	11 1/3	13.0(¹)	13.0(¹)	11.05	13.0(¹)	13.0(¹)	10.2	13.6
Japan (H)	13.6	11 1/3	12.8(¹)	12.8(¹)	11.05	12.8(¹)	12.8(¹)	10.2
Transmission Interval	0.9 0.2	1.0 0.2	1.1 0.2	1.2 0.2	1.1 0.2	0.9 0.2	1.2 0.2	1.0 0.2

10 seconds

Frequencies in kHz.

(¹) is the unique frequency for the respective station.

ANNEX I

AUTHORITIES RESPONSIBLE FOR STATIONS APPEARING IN TABLES I AND II

Station	*Authority*
Allouis	Centre National d'Études des Télécommunications Département FRE 196, rue de Paris 92220 Bagneux, France
ATA	Time and Frequency Section National Physical Laboratory S.R. Krishnan Road New Delhi-110012, India
BPM	Time and Frequency Division Shaanxi Astronomical Observatory Chinese Academy of Sciences Lintong, Xian, China
CHU	National Research Council Time and Frequency Section Physics Division (m-36) Ottawa K1A OS1, Ontario, Canada.
DCF77	Physikalisch-Technische Bundesanstalt Lab. Zeiteinheit Bundesallee 100 3300 Braunschweig, Federal Republic of Germany
EBC	Instituto y Observatorio de Marina (Spanish Naval Observatory) San Fernando (Cadiz), Spain
GBR	National Physical Laboratory Electrical Science Division Teddington, Middlesex TW11 OLW United Kingdom
HBG	Service horaire HBG Observatoire cantonal CH-2000 – Neuchâtel, Switzerland
HLA	Time and Frequency Laboratory Korea Standards Research Institute P.O. Box 3, Taedok Science Town Taejon, Ch'ungnam 300-31 Republic of Korea
IAM	Istituto Superiore Poste e Telecomunicazioni Viale Europa 00100 – Roma, Italy
IBF	Istituto Elettrotecnico Nazionale Galileo Ferraris Corso Massimo d'Azeglio, 42 10125 – Torino, Italy

JJY JG2AS	Standards and Measurements Division The Communications Research Laboratory Ministry of Posts and Telecommunications Nukui-Kitamachi, Koganei, Tokyo 184, Japan
LOL	Director Observatorio Naval Av. Costanera Sur, 2099 Buenos Aires, Argentine Republic
MSF	National Physical Laboratory Electrical Science Division Teddington, Middlesex, TW11 OLW, United Kingdom
NAA, NDT, NLK, NPM, NSS, NWC, NMO, NPN	Superintendent US Naval Observatory Washington, DC 20390 USA
OMA	1. Time information Astronomický ústav ČSAV, Budečská 6 12023 Praha 2 Vinohrady, Czechoslovak S. R. 2. Standard frequency information: Ústav radiotechniky a elektroniky ČSAV Lumumbova 1 18088 Praha 8, Kobylisy, Czechoslovak S. R.
RAT, RCH, RID, RIM, RWM	Comité d'Etat des Normes Conseil des Ministres de l'URSS Moscou, USSR Leninski prosp., 9
SAJ Motala	Swedish Telecommunications Administration Radio Services S-123 86 Farsta, Sweden
VNG	Section Head (Time and Frequency Standards) A.P.O. Research Laboratories 59 Little Collins Street Melbourne, Victoria 3000, Australia
WWV, WWVH WWVB	Time and Frequency Services Group Time and Frequency Division National Institute of Standards and Technology 325 Broadway Boulder, Colorado 80303, USA
Y3S	Amt für Standardisierung, Messwesen und Warenprüfung Fachgebiet Zeit und Frequenz DDR-1162 Berlin Fürstenwalder Damm 388 German Democratic Republic
ZUO	Time Standards Section Precise Physical Measurements Division National Physical Research Laboratory P.O. Box 395 0001 – Pretoria, South Africa

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REPORT 270-3

OPTIMUM USE OF THE FREQUENCY SPECTRUM FOR HIGH-PRECISION TIME SIGNALS

(Study Programme 3A/7)

(1963-1966-1970-1978)

There is an increasing number of applications requiring the use of a very precise reference for time-signal synchronization. In an effort to achieve greater precision, it is desirable to make use of a suitable bandwidth up to the limits imposed by:

- the band allocated;
- the instabilities of the propagation;
- considerations of noise and interference.

Opportunities also exist for time dissemination and comparison by the use of signals which are transmitted for other purposes, such as VLF communication, broadcasting and television, or as aids to navigation. Use of these signals, when possible, conserves resources both of frequency-spectrum and of equipment and is therefore to be encouraged, but it is not considered further in this Report unless special features of the emissions make possible timing uncertainties significantly smaller than would normally be available within the same bandwidth.

The Loran-C navigation system, operating within the band 100 kHz ± 10 kHz, is in widespread use and yields timing uncertainties less than 1 µs over distances of up to 2000 km. The phase-encoded pulse modulation provides discrimination against signals received via the ionosphere and so makes possible measurements in which the ground-wave-propagated signal is dominant. The use of different modulation rates allows the operation of several separate transmitter chains within the same frequency band [Potts and Wieder, 1972].

At high frequencies, where long-distance propagation is wholly dependent upon the ionosphere, the precision with which the time signals can be received is limited by the characteristics of the propagation medium. The bandwidths in use have been largely determined by administrative rather than technical or scientific considerations. It may be noticed that many stations listed in Report 267 use an audio-frequency modulation as the time signal. This takes the form previously recommended by the CCIR and consists of n cycles of 200 n Hz audio modulation, leading to a pulse of constant length equal to 5 ms. The value of n can be varied conveniently to distinguish the various emissions.

Thus, WWV and several other stations have adopted a pulse wave form with $n = 5$, i.e., 5 cycles at 1000 Hz. For WWVH, $n = 6$ has been chosen, while JJY has adopted a pulse with $n = 8$. The use of this form of pulse does not make it possible to resolve one of the several components of a signal received via more than one path (multipath propagation). It is, however, reasonably economical in bandwidth. Disturbed propagation conditions produce easily recognizable distortions of the pulse wave form.

A method of signal dissemination which does not require the use of excessive bandwidth has been investigated for use in navigation [Casselmann and Tibbals, 1958] and timing [Morgan and Baltzer, 1964]. This method makes use of the interference between two closely-spaced phase coherent carrier frequencies to generate a coarse reference. When this coarse reference can be realized at the receiver with sufficient phase stability it serves to identify one particular cycle of the carrier frequencies and a precise time reference can then be obtained from observations of the carrier phase.

Early experiments using 19.9 and 20.0 kHz over a 1400 km path showed promise for cycle identification. Later experimental studies, including a technique for extracting time using conventional VLF receivers and giving results covering a period of months over a 2400 km path have been reported [Fey and Looney, 1966]. Further studies using several frequency separations and paths have been described [Raules and Burgess, 1967]. An experimental dual-frequency timing receiver has been constructed for use with the 20.0 and 19.9 kHz transmissions of WWVL [Chi and Witt, 1966]. The result of these various investigations suggested that a 100 Hz frequency difference between the carrier frequencies is too small to permit reliable daily cycle identification over arbitrary paths and in a further series of experiments a third carrier frequency was added to the WWVL emission to give frequency differences of 500 and 600 Hz. The results obtained under these conditions indicate that, with suitable averaging, cycle identification can be achieved at distances up to 8000 km. An analytical study using information theory techniques indicates that a multiple CW system may be optimum from the bandwidth conservation viewpoint [Jespersen, 1967]. Morgan [1967] has a useful bibliography on the general subject.

Theoretical studies have been made on a similar, very narrow bandwidth system at VLF [Egidi, 1969]. Two procedures have been investigated. The first uses a particular wave form, which can be interpreted as the product of two sinusoidal signals of the same amplitude, having frequencies in an integral ratio with a convenient phase relation. This procedure takes advantage of the timing index given by phase modulation of the radio frequency signal [Egidi and Oberto, 1964a and b] (not of the envelope). The second procedure uses periodic phase inversions of the carrier wave; the cases where inversions occur at zero phase and $\pi/2$ phase have been treated in detail [Egidi, 1968]. This reference also presents the results of calculations giving the relation between time discrimination and the bandwidth of the system.

A system using multiple carriers at VLF has also been proposed [CCIR, 1966-69] which enables the transmission of both 1 s and 10 ms time signals without interruption to the communication service. A theoretical description of the transmissions with three frequencies and of the receiving devices is given in the reference.

There is a limit to the timing accuracy which can be achieved by using two or more closely spaced signals. The limitation arises because the group delay T of the composite signal is given by

$$T = (\varphi_2 - \varphi_1)/2\pi(f_2 - f_1)$$

where φ_1 and φ_2 are the phase delays experienced by the two frequencies f_1 and f_2. The variation in the phase delays due to propagation can be expected to approach zero as $(f_2 - f_1)$ approaches zero. However the effect of additive noise is essentially independent of the frequency spacing. Under these conditions the standard deviation of the group delay σ_T is given by [Morgan and Baltzer, 1964]:

$$\sigma_T = (\sqrt{2}\sigma_\varphi)/2\pi(f_2 - f_1)$$

where $\sigma_\varphi = \sigma_{\varphi 1} = \sigma_{\varphi 2}$ is the standard deviation of the phase delays due to additive noise. As an example, if $\sigma_\varphi = 1$ μs and $f_1 = 20$ kHz while $f_2 = 20\,001$ Hz, $\sigma_T = 20\,000$ μs; whereas, if $f_2 = 20\,100$ Hz, $\sigma_T = 200$ μs. Thus, as the spacing of the frequencies decreases, the error due to uncorrelated phase fluctuations increases.

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REPORT 271-8

STABILITY AND ACCURACY OF STANDARD FREQUENCY AND TIME SIGNALS IN VLF AND LF BANDS AS RECEIVED

(Question 3/7)

(1963-1966-1970-1971-1974-1978-1982-1986-1990)

The propagation time (phase delays) of VLF signals from a transmitter to locations thousands of kilometres distant varies little from day to day but has predominant diurnal and annual cycles created by ionospheric changes related to the solar zenith angle [Azuma, 1966; Iijima *et al.*, 1968; Decaux and Gabry, 1964]. Empirical and theoretical considerations have permitted accurate predictions of the propagation time which account not only for the diurnal and annual cycle, but also the sunspot number and the conductivity of the lower boundary of the wave guide supporting the VLF transmissions. The propagation time is sporadically altered by generally unpredictable sudden ionospheric disturbances (SID) which typically alter the ionosphere for 20 to 30 minutes and by polar cap absorption (PCA) events which alter the polar ionospheres for up to a week [Pierce, 1955; Reder *et al.*, 1964; Becker *et al.*, 1973a].

It has been observed that the phase shift accumulated during a 24-hour interval does not necessarily cancel, but can be ± 2π or a multiple thereof. The "cycle loss" can occur in several circumstances. For example, for great distances it will occur when the ratio of the amplitudes of the first to second order wave guide modes is less than unity at night and greater than unity during the day [Walker, 1967]. A second case may occur because of excessively large mode conversion at sunrise termination [Ries, 1967]. In addition, when the receiver is at a great distance (> 10 000 km) from the transmitter, it is possible that signals may be received along the long great circle path instead of the short great circle path for part of the day [Thompson *et al.*, 1963]. If the stability of the local frequency standard is sufficient, this situation is easily recognized and taken into account. Such effects have been observed for the signals of GBR, NBA and NPM in Australia, the signals of NBA and NPM in France and WWVL in the British Isles.

Other sources of variation include the cyclic variations at periods of 27, 29.53 and 14.765 days. The 27-day period is related to the average solar rotation rate and has been observed in ionospheric data [Ratcliff, 1960]. The 29.53 and 14.765-day periods are respectively related to the lunar synodic and semi-synodic tides and have been observed to exist in the lower atmosphere [Appleton and Beynon, 1949; Brady and Crombie, 1963; Rastogi, 1969; Chakravarty and Rastogi, 1970].

The effect of dispersion, which causes the phase and group velocities of VLF and LF waves to be different, must be considered in timing systems. At LF, appreciable dispersion occurs in the ground wave for propagation over ground of finite conductivity. At VLF, two sources of dispersion are important. The first occurs as a result of cut-off effects in the Earth-ionosphere wave guide [Crombie, 1966]. The second [Burgess, 1967] and less predictable source of dispersion is caused by interference between several wave-guide modes at night and thus causes spatially periodic variations in group velocity.

The time service provided by the transmitter HBG on 75 kHz located near Geneva (see Report 267, Table II) reaches a large part of Central Europe. Experiments have shown that the time signal of HBG can be received using simple receivers with an accuracy greater than ± 50 µs at medium distances (100-1000 km). The phase of the carrier is typically stable to better than ± 2 µs at the distance of 500 km during daylight hours.

The standard-frequency and time-signal transmitter DCF77 on 77.5 kHz, transmitting the official time signal and standard frequency of the Physikalisch-Technische Bundesanstalt (PTB) in the Federal Republic of Germany, is modulated in the following manner: at the beginning of each second, the carrier amplitude is reduced to about 25% of its normal amplitude, then, at the end of the second-markers, whose duration is 0.1 s or 0.2 s, the carrier amplitude is restored to its normal value.

Studies carried out at PTB and by some manufacturers working on this problem showed that simple oscillators can be more reliably synchronized with the residual carrier present as compared with zero carrier conditions during the period of the time markers.

In the modulation technique used by PTB the steepness of the falling edge is retained. The technique is as follows: at the beginning of each second, the transmitter drive is set to zero until the antenna amplitude has fallen to 25% of its maximum amplitude. The transmitter drive is then increased to retain 25% of carrier amplitude during the time marker.

In addition to the amplitude modulation with second markers, the carrier frequency of DCF77 is phase-modulated according to a pseudo-random binary sequence [Hetzel, 1988]. The sequence of maximum length used in this context is phase synchronous with respect to the carrier and to the AM second markers. On the receiving side, it can be reproduced as searching signal and cross-correlated with the pseudo-random signal received. The purpose of this cross-correlation method is to make better use of the bandwidth available and thus to increase the accuracy of the time transmission. Measurements performed at a distance of 300 km from the location of the transmitter [Hetzel, 1987] have confirmed that by applying the cross-correlation method, the arrival times of the pseudo-random signal received can be determined more reliably and with lower uncertainty as it is possibly with AM time signals under normal receiving conditions. In the daytime, except for the winter months, the resultant fluctuations of the pseudo-random signal received were less than half the period of the carrier (< 6.5 µs). The pseudo-random signal does not affect the reception of the AM time signals and the long-term average of the carrier phase.

An investigation [Becker *et al.*, 1973b] has shown that the standard-frequency and time-signal transmitter DCF77 on 77.5 kHz can be well received in Central Europe and Scandinavia. During the day-time the carrier phase as received at 300 km distance from the location of the transmitter (Mainflingen near Darmstadt, Federal Republic of Germany) deviates only a few tenths of a microsecond from the average due to propagation changes. This results in a daily average relative frequency deviation of the carrier of 2.1×10^{-12} and in a weekly average deviation of 0.4×10^{-12} at a distance of 300 km. The time signals of DCF77 at noon were received with a spread of 37.5 μs as an average over three years [Becker, 1972; Becker and Hetzel, 1973].

Similar studies in the United Kingdom in respect of MSF 60 kHz [Richards, 1987] have demonstrated the limitations of the service, especially during the winter day, due to the presence of an appreciable ionospheric component which is in essentially random phase, from day-to-day, to the predominant ground wave. This gives rise to phase (time) variations in the total signal amounting to about 0.3 μs at a distance of 300 km from the transmitter (in solar minimum-conditions) corresponding to a daily frequency stability of 3.2×10^{-12}. In contrast, the frequency of 198 kHz (Droitwich) suffers to a much lesser extent from ionospheric dilution and provides a stability, under equivalent conditions, at least one order better than is possible at 60 kHz.

France Inter's AM station at Allouis, which broadcasts programmes on 162 kHz, also transmits France's standard frequency and time signals.

The carrier transmitted is phase-stabilized by a signal from a caesium oscillator [Dubouis, 1986a], thus permitting the broadcast of a signal free from interference due to transmitter power stage operation.

The carrier is phase-modulated to transmit a time code (see Reports 577 and 267).

Reception and decoding of this modulation enables standard receivers to obtain a UTC-related date and time reference at all times throughout metropolitan France to an accuracy of 1 ms. This accuracy is limited mainly by the amplitude modulation of the sound programme broadcast which current receiver filtering circuits cannot totally eliminate, although an averaging process using more sophisticated receivers enables the accuracy to be improved by a few tens of microseconds.

Reception of the carrier enables the oscillator frequency to be controlled to an accuracy of close to 10^{-7} s/τ (10^{-12} is obtainable over one day).

Rubidium and quartz oscillators have been carrier frequency-stabilized to accuracies of between 5.10^{-13} and 5.10^{-12} and between 5.10^{-11} and 5.10^{-12}, respectively.

Phase-stabilization has also been achieved with an accuracy of close to 50 ns, even with standard quartz oscillators [Dubouis, 1986b].

A digital technique has been employed at the Free University, Brussels, to study the stability of the MSF 60 kHz time signals received at a distance of 420 km from the transmitter. The received pulse profile is sampled at 250 points, tests for quality are applied, and average values based on about 200 successive pulses are produced by a mini-computer.

The time of arrival may be taken as the time at which the signal envelope reaches a clearly defined percentage of the mean amplitude of the carrier (Am). Theoretical and experimental studies have shown that error is at a minimum at a characteristic point selected between 0.75 Am and 0.9 Am [Andrews *et al.*, 1970]. For the present study, the value chosen was 0.85 Am. In the case of the measurements carried out in the middle of the day – between 0900 and 1300 hours UTC – the standard deviation was usually between 5 and 10 µs. On the other hand, the fluctuations observed over long periods (several months) may attain 25 µs, taking account of the shape correction factor applied [Liévin *et al.*, 1975].

Studies on a new form of time-signal modulation have been carried out in the USSR to improve the synchronization reliability of generators using the carrier frequency of station RBU (66 2/3 kHz) as a reference.

Compared with previous signals, the duration of the pause has been reduced to 5 ms and the frequency of the pause repetition increased to 10 Hz. Marker and coding pulses with a duration of 80 ms are used for the identification of the second and minute markers. The pulses are obtained by narrow-band phase modulation with an index of 698 of two sub-carriers off-set by 100 Hz and 312.5 Hz. This has increased the protection band [Cherenkov, 1984a] to 50 Hz, which now makes it possible to synchronize signal generators with an equivalent passband of the automatic phase control circuit of up to 20 Hz. The phase jitter of the output signal of the synchronized generator (or the signal at a receiver output with the same passband), due to the phase modulation of the carrier wave, does not exceed 20 ns.

The use of phase modulation made it possible to use the full transmitter power and yielded higher power levels for both marker and information bits, equal to 0.735 and 0.215 respectively, relative to the maximum power of the unmodulated emission [Cherenkov, 1984b].

The generation of the information and marker bits on the sub-carrier frequencies, increases the capacity of the information that can be transmitted by frequency or phase modulation of the sub-carrier during the other 80 ms intervals, which are not currently used. The increased repetition frequency (10 Hz) of the time markers makes for more accurate determination of their time position by averaging over a larger number of results for the same measurement interval.

Experiments on the propagation of LF (40 kHz) signals at a distance of 400 km have been reported by Japan. The standard deviation of the daily phase fluctuations was found to be 1 µs in summer and 2 µs in winter; the seasonal variation in the phase of the signal as received at midday amounted to 3.3 µs.

The effect of sudden ionospheric disturbances (SID) in the D layer on the Loran-C timing and calibrating frequency was investigated in China by the Shaanxi Astronomical Observatory (CSAO). During the period of the disturbance, because the sky-wave signals are enhanced and advanced and some of them mix with the sampled ground-wave signals, phase deviations of about 0.1-2 µs of the ground-wave signals occur [Miao and Yang, 1981].

Measurements of a Loran-C 100 kHz pulsed signal have been carried out continuously for several years by CSAO (the distance between the transmitting and receiving sites is 2,006 km). From analyses of these measurements, it was possible to ascertain how the delay (phase) and the field strength of a one-hop sky-wave vary with the solar cycle, the seasons, the time of day, etc. and to determine the range of the variations. Furthermore, in connection with the refraction effect of the ionosphere, the corresponding values of the effective reflection height and of the exponent parameter of the electron density model for the D layer of the ionosphere, and the way in which these values vary, have been derived from the measurements and analyses. On the basis of these results, the accuracy of the time information sent via a one-hop sky-wave can be improved to ± 1.2 μs (r.m.s.) and ± 2.8 μs (r.m.s.) during the daytime and at night (except at sunrise and sunset), respectively. This is true because the difference between the predicted values and the measured values are within ± 1.5 μs and ± 2.5 dB for the delay and the field strength, respectively, in the area where a one-hop BPL (see Note below) sky-wave signal can be used for time information [Pan and Li, 1986; Pan, 1988].

Note - BPL is the call sign of the 100 kHz time signal transmitter at Shaanxi, China.

Analysis has been done on variations in Loran-C signals from the Northwest Pacific Chain Y Station to the Shaanxi Astronomical Observatory of China over a distance of about 2,000 km, 1,200 km of which are subject to typically complex ground propagation conditions, and checked the results by GPS common view comparison for the period from June 1987 to June 1988. The results show that the short-term phase fluctuation in the long-wave signal is the main component of the time-delay variation, and $\sigma = \pm(0.20 \sim 0.26)$ μs. The value of the delay variation may be kept within 0.5 μs by means of digital filtering. With an integration time of ten days, the delay variation in one year will be within about 0.2 μs. [Potts and Wieder, 1972; and Wu, Liang and Qu, 1988].

Propagation time of the Loran-C ground wave over land in northern Japan was measured at 21 sites. The observed phase retardation was 8.9 ps/m with respect to a wave travelling in the atmosphere of refraction index of 1.000338. Fluctuations of the received phase were mostly in the range of ± 0.5 μs with the exceptions of ± 1.5 μs at two sites. Phase delay of 5.7 ps/m was observed on the boat at sea and at a site on land where the terrain effect is considered small. The average value of the calculated phase delay is 5.4 ps/m when the effective conductivity map for the frequency of 1 MHz is used. [Hara et al., 1988; and Ono, 1985].

Experimental evidence [Noonkester, 1972] indicates that VLF propagation time is subject to semi-synodic variations that would affect the dissemination of time and frequency information by VLF transmissions. The average amplitude of the lunar semi-synodic period was found to be 0.18 µs at midday and 0.52 µs at midnight for one north-south VLF path at 10.2 kHz. The maximum amplitude was found to be 1.3 µs during mid-winter months at midnight. Users of VLF transmissions for time and frequency information should be made aware of the known periodic components so that they may anticipate a certain error range.

As regards the long-term integration of the received phase, the accuracy which can be achieved will depend to a large extent on the complexity of the receiving equipment and measuring procedures. It has been reported [Leschiutta, 1968] that when using quartz oscillators at the receiving station the accumulated overall error for path lengths of 1000 to 5000 km is between 25 and 50 µs per year when receiving transmissions in bands 4 and 5. However, when the received phase is referred to an atomic standard and use is made of a receiver which can be calibrated and which does not lose the phase reference [Becker *et al.*, 1969] much improved results can be obtained. Thus, NSS received at a distance of 5000 km and recorded over a period in excess of 450 days shows variations relative to the mean phase of at most ± 10 µs and generally less than ± 3 µs. This latter figure is equivalent to a frequency uncertainty of about 1×10^{-13} over a year. Further improvements in the stability of the received phase can be obtained by forming a linear combination of the phase of two emissions at different frequencies to significantly reduce the major solar effects; the improvement is most noticeable when comparisons are made simultaneously for both directions of transmission over the same path at carrier frequencies not too far separated in band 4. Still greater accuracy in the phase reference can be obtained by the application of smoothing techniques based on the statistical character of the phase fluctuations [Becker *et al.*, 1969; Guetrot *et al.*, 1969] but these are effective only over limited periods where the statistical behaviour can be assumed representative of the process.

When Loran-C became available for precise time comparisons, the variations of propagation delays, and thus time comparison using VLF carrier phase, became easier to measure (for Loran-C phase values see United States Naval Observatory (USNO) Time Service Announcements, Series 4). Such measurements were made for several years over a path length of about 5000 km between North America and Europe. Three VLF transmissions (NAA, 17.8 kHz; GBR, 16 kHz; Omega-Trinidad, 12.0 kHz) were used. Typical results are given in Table I. In Table I, $\sigma_{\Delta t}(\tau)$ is the average change (divided by $\sqrt{2}$) of the measured time difference Δt, occurring during the time of measurement τ. This statistical processing technique is due to Kolmogorov [1941], Malakhov [1966a and b] and Allan [1966]. $\sigma_y(\tau)$ is the relative uncertainty of a frequency comparison in the measuring time τ.

TABLE I – *Typical fluctuations of propagation delays of VLF signals between North America and Europe*

τ (days)	$\sigma_{\Delta t}(\tau)$ (µs)	$\sigma_y(\tau)$ (10^{-12})
1	1.9	31
10	2.6	4.2
100	3.7	0.61
1000	5.3	0.09

Similarly, seasonal influences on $\sigma_{\Delta t}(\tau)$, as well as yearly and half-yearly correlations of the propagation fluctuations, were found. Due to the correlation between adjacent values, the possibility of improving the accuracy of measurement by means of averaging values is limited: in the most favourable case the measuring error is halved (from 2.2 µs to 1.1 µs) by averaging one hundred daily values instead of taking one daily value only.

In more recent experiments performed at NPL (India), long term integration results of the GBR carrier were confirmed indirectly with Loran-C measurements and directly via a geosynchronous satellite link. Over a period of one year an accuracy of a few parts in 10^{14} in frequency and 1-2 µs in time was achieved [Sen Gupta *et al.*, 1980; Mathur *et al.*, 1980].

For restoration of a VLF phase relationship, specific measuring techniques have been developed as well as a calibration technique to measure the time delay of the antenna and receiver [Becker *et al.*, 1973a; Becker, 1973]. This technique uses a test signal which is monitored by a parallel divider chain from which the time scale is generated. If this method is used to re-establish the lost phase relationship, an average error of 1.1 μs results if the break is short, and the values before and after the break are correlated. If the break is long (e.g. longer than 60 days), the measured values before and after the break are uncorrelated and an average error of 4.7 μs results.

Other techniques for cycle identification are available. The use of two coherent VLF signals for time transmission was first proposed in 1962 [Morgan, 1962], and demonstrated in 1966 [Chi and Witt, 1966; Fey and Looney, 1966]. It is a two-step time recovery technique. The phases of the VLF signals are used to determine the time difference between the clocks at the transmitting and receiving sites of less than one cycle (fine time) and the phase difference between the received signal and the locally generated signal data of the two coherently transmitted signals are used to determine the carrier cycle of one of the received signals (coarse time). Experimental radio station WWVL of the United States National Bureau of Standards at Fort Collins, Colorado was used from 1964 to 1968 to conduct the feasibility test. The signal frequencies were 19.9 and 20 kHz. Larger frequency separations up to 700 Hz were tested. For frequency separation higher than 500 Hz, cycle identification was degraded due to the larger frequency dispersion effect of the propagation medium.

The Omega VLF navigation system uses multiple frequency VLF transmissions for the dissemination of time and frequency information. The advantages of this technique are well established [Swanson and Kugel, 1972]. These transmissions are a useful source of frequency and precise time and should also enhance the status of VLF techniques for obtaining these items. A total of eight stations provides continuous and redundant world-wide coverage. Each station derives its radiated phase from an ensemble of four caesium frequency standards, and transmits navigational frequencies on a time-shared basis every 10 s. The four navigational frequencies are 10.2, 11.05, 11⅓ and 13.6 kHz. Each station also radiates one additional frequency in the range 11.8 to 13.1 kHz from which time or frequency information can be extracted. Report 267 lists these additional transmissions in Table III.

Development work on precise two-frequency timing has already taken place [Chi *et al.*, 1972]. Tests conducted in 1973 and 1974 using the 13.10 and 12.85 kHz signals transmitted for time transmission from the Omega station in North Dakota, showed reliable cycle identification for path lengths up to 7000 km [Chi and Wardrip, 1973 and 1974]. Further tests for path links up to 15 000 km using experimental transmissions from Omega stations, in North Dakota and Hawaii have been made.

The long range and phase stable VLF transmissions offer potential time reference signals for international time comparison to an accuracy of ± 1 μs.

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REPORT 363-7

METHODS FOR THE TRANSFER AND DISSEMINATION OF TIME AND STANDARD FREQUENCIES

(Study Programme 3C/7)

(1966-1970-1974-1978-1982-1986-1990)

1. Introduction

In time-transfer and standard-frequency dissemination, new methods have come into use which are particularly suited for the comparison of atomic clocks within an international coordinated timing system. These applications, however, go far beyond the more traditional use of a standard-frequency and time-signal service (SF and TSS) which existed when atomic clocks were first introduced into widespread use. Compared to a capability for millisecond timing which is typically required by the vast majority of the SF and TSS users, the utilization of atomic standards requires measurement uncertainties which should be as small as possible. The best performance obtained so far in long distance comparison has been a measurement uncertainty approaching 1 ns.

This Report reviews the general principles involved and gives an overview of the various characteristics and experience gained with the experimental and operational use of these methods.

2. Background

2.1 *Requirements for operational coordinated timing*

In contrast to the need for immediate access to a reliable source of time, which is typically required by the large majority of users of an SF and TSS, the measurements needed for international coordinated timing require a very precise means of time transfer which is only occasionally used. Instrumental cost is of lesser concern as precision or repeatability of measurements is the primary goal. For such reasons, many methods have been employed even though they could not be used in operational systems in the conventional sense. As examples, one may cite the global positioning system (GPS) which was used for time transfer long before it became accepted, as an operational navigation system. Another example would be the use of very long baseline interferometry (VLBI) for time comparisons or the "common view" technique which can be used with any source of timed or untimed signals.

2.2 *Correction for relativity effects for highest precision time transfer*

Report 439 discusses the principles and gives formulae for relativistic corrections which have to be applied in all cases where the accuracy required is of the order of 100 ns or better.

2.3 *Bandwidth and signal-to-noise ratio in high-precision time transfer*

Low uncertainty mesurements of time of arrival require a commensurately large bandwidth. This is due to two reasons: the rise time must be minimized to reduce trigger uncertainty and secondly, the variations of group delay through the circuits must be minimized. These changes could represent a small percentage of the group delay itself. Therefore, pre-detection bandwidth should be as large as is practicable. The signal-to-noise ratio available only dictates the integration time (post-detection bandwidth) necessary to make a measurement with a given uncertainty. In practice, this has led to the increased importance of spread-spectrum techniques for timed systems. A distinction must also be made between the bandwidth required for a given information flow and the effective bandwidth of the signal used. In the case of the GPS, the effective bandwidth of the C/A code is 1 MHz, while the actual information transfer (the navigation message) takes place at the modest rate of 50 Bd. However, the timing itself is done by using the fast transitions of the spread-spectrum modulation and therefore benefits from the full available bandwidth of the code. For Loran-C, which is an LF navigation system widely used for timing, the effective bandwidth of the signal is 20 kHz (the signal is pulsed) and there is no transmission of information. In this case, the uncertainty of timing is a few tenths of a microsecond (1% of 50 μs is 0.5 μs, again demonstrating the rule of thumb that uncertainty is limited to about 1% of the reciprocal of the effective bandwidth). For a general discussion on spread-spectrum techniques see [Dixon, 1976]. Added advantages of the use of spread-spectrum techniques are a substantial reduction in the susceptibility to interference for reception in urban areas (television harmonics can be a serious problem) and a reduced variability of circuit path delay due to changes in the bandwidth occupancy of the signal. This latter effect is a major source of error in normal HF standard frequency and time signal service reception. On the other hand, the large bandwidth can also create problems if dispersion or multipath is present in the channel.

2.4 *One-way versus two-way time transfer*

The one-way method, i.e. reception only, can be used with high precision if the path delay can be either assumed to be fixed (in which case it needs to be measured only once), or if the delay can be determined in some other way. This explains the intrinsic feasibility of using electronic navigation systems for timing because such systems have been designed to provide position information i.e. path delay, as an essential feature. In these systems, the user does not have to transmit which is an additional burden for two-way systems. On the other hand, by a near-simultaneous two-way exchange of signals, the path delay can easily be determined, assuming reciprocity. This assumption, however, has to be tested before a two-way method of time transfer can be used with confidence. In principle, the two-way method offers the lowest uncertainty.

2.5 *Effects of the choice of frequency (VLF – optical frequency)*

While the lower frequencies up to, and including, HF have been the backbone of time transfers in the past, all very high-precision methods require that the influence of the ionosphere be kept as small as possible which is the reason why the bands from VHF and upwards are increasingly used. However, with increasing frequency and the consequent decreasing influence of the ionosphere, tropospheric effects soon become an important factor. Water vapour, in particular, turns out to be more of a problem than expected because of rapid and irregular variations in the line-of-sight water vapour content as measured by various means. This constitutes a powerful argument in favour of optical frequencies (lasers) for extremely high-precision time transfer. (For details, see also Report 271.)

2.6 *Satellite links versus terrestrial microwave links*

The great advantage of satellite links is the large available bandwidth and line-of-sight connections at frequencies where the ionospheric influences can be minimized. The disadvantage is that the path delay is very large in comparison to terrestrial microwave links and must be continuously determined. Optical fibre link technology can be expected to replace microwave links and to find extensive use during the present decade. It remains to be seen to what extent highest-precision timing can be obtained via long distance fibre link cables. The state-of-the-art in highest-precision time transfer at this time is entirely dependent on satellite technology using communications and navigation satellite systems.

2.7 *Remote computer controlled time measurements using common view and multiple timing sources*

The low price of mini- and microcomputers has introduced yet another dimension into long distance time intercomparison and measurement techniques. Remote and completely automated time stations have been introduced which perform regular measurements of common view signals, or of all timed signals available at the site. A central computer collects the data, filters the measurements and correlates them with measurements obtained elsewhere. The result is then sent back to the station for local print-out and use. Several such systems have been reported by the USNO [Wheeler, 1983] and by NBS [Allan and Weiss, 1980; Stein *et al.*, 1983]. One NBS system utilized an NBS-design GPS receiver while another is based on the reception of either Loran-C or WWVB broadcasts. The USNO system used only high-grade commercial equipment such as automatic Loran-C receivers or commercial GPS time transfer units. Such systems can be tailored to the particular needs of the remote site [Wheeler, 1983]. In cases where a GPS receiver is installed at the remote site, uncertainties of the order of 10 ns and precision of a few nanoseconds have been reported [Allan *et al.*, 1985].

3. Overview of utilized time and frequency transfer methods

3.1 *Comparison using signals in bands 4 to 7 and via portable clocks*

Methods using bands 4 to 7 signals and portable clocks, have been in routine use for over twenty years but must now be considered as declining in importance with the following exceptions:

- VLF: in remote areas, frequency-stabilized transmissions from the Omega navigation network and also from certain high-power communications stations can serve as inexpensive phase references. They are actually used for air navigation in small aircraft. The timing capability has been documented by Guinot [1968 and 1969] (see also Report 271);
- frequency-stabilized LF transmissions, such as WWVB, DCF 77, HBG, MSF, and others, are still used by a large number of time-code receivers which are automatically kept synchronized with millisecond accuracies. Phase tracking has largely ceased due to problems with cycle ambiguity and interference between some of these stations;
- Loran-C has permitted the introduction of completely automatic receivers which eliminate the cycle identification problem. Loran-C is still widely available and remains the best routine comparison method for purposes where uncertainties of a few tenths of a microsecond due to, among other effects, seasonal variations [De Jong, 1984] are acceptable and where ground-wave coverage exists (most of the Northern Hemisphere); see [Potts and Wieder, 1972] and Report 271. The French transmission from Allouis on 162 kHz is received clearly throughout continental France and enables oscillator frequencies to be controlled with an accuracy of 10^{-7} s/τ with a limit of about 5×10^{-13}, where τ is the observation time in seconds [Dubouis, 1986];
- the HF, SF and TS service remains the main source of time for ships, radio amateurs and other users who appreciate the very low cost and who are satisfied with uncertainties of a few milliseconds [Ogawa, 1958]; see also [Iijima *et al.*, 1978]. CSAO has put forward a new HF time signal reception method which enables users to obtain a timing accuracy of ± 1.5 ms [Fan Rong Mei, 1986].
- portable clocks which have demonstrated a capability of tens of nanoseconds in round-the-world experiments [Hafele and Keating, 1972] are likely to be used less in the future due to the advent of high-precision satellite methods such as GPS or commercial wide-band channel satellite links.

3.2 *Television*

Television is a timed electronic system and as such can be used for time comparisons. Due to the existence of different systems such as the NTSC, PAL, SECAM, etc. and to the difficulties of establishing the exact path delay for each intercomparison, particularly over large distances, the method has found its greatest application in the simultaneous reception of a transmitter within its local coverage area. A novel and more promising method is the reception of satellite television programmes if the satellite position can be obtained elsewhere, with sufficient precision e.g. from the operating authorities. Extended tests have been conducted between stations in Austria, the Netherlands, the United Kingdom and the Federal Republic of Germany [De Jong, 1984]. In the United States of America, the widespread use of frame synchronizers has effectively terminated the long distance use of television for timing because these devices store a complete frame and release it for transmission with time reference to the local clock. For more detailed information within its local coverage area, see Reports 1016 and 897.

3.3 *Intercontinental clock synchronization by VLBI*

The fundamentals of VLBI have been described by Klemperer [1972], who gives an extensive list of references, as well as of the basic accuracies and limitations. Clark [1972] also considered the fundamentals and listed a number of current experimental VLBI programmes. Accuracies in frequency comparisons of 10^{-13} to 10^{-14} and in clock synchronization of the order of 1 ns are apparently possible.

The 10-100 MHz bandwidths required for clock synchronization to a resolution of 1-10 ns are achievable by the bandwidth synthesis techniques described by Hinteregger *et al.* [1972] and Rogers [1970].

In principle, hydrogen maser stability is not required for clock synchronization; in fact, prototype system demonstrations used rubidium oscillators. A series of three experiments have been conducted between the NASA stations at Madrid (Spain) and Goldstone (California) [Hurd, 1972]. Although measurements demonstrated a resolution of 50-500 ns (1 σ), depending on the amount of data used, the accuracy of the clock differences obtained could only be verified to within about 10 μs.

If a sufficient amount of data is available and if a sufficiently large bandwidth can be obtained (50 MHz) then the VLBI synchronization method seems to be mainly limited in accuracy by difficulties in determination of the overall system delay and, in particular, in the atmospheric delay and the receiver delay.

In order to make an accurate determination of the delay difference of VLBI receivers, Communications Research Laboratory (CRL), Japan, conducted Zero Baseline Interferometry (ZBI) experiments at both Kashima VLBI station and Richmond station of the United States Naval Observatory (USNO) in collaboration with USNO in 1986 and 1987 [Hama et al., 1987 and Kiuchi et al., 1987]. The accuracy of the ZBI technique was estimated to be about 0.3 ns which includes the worst case systematic errors of 0.1 ns to 0.2 ns for the positions of the radio sources and for the baseline vector used.

3.4 *Satellites*

Experimental time comparisons over large distances via artificial satellites have been conducted successfully since 1962. Both one-way and two-way techniques are used with each offering certain advantages. In the one-way mode a user simply receives the timing signal which either originates from an on-board clock or is relayed to the user from another terrestrial location via a satellite transponder. Because the user is not required to transmit signals, simple equipment can be used and many users can be served simultaneously in a broadcast mode of operation. However, since the propagation path delay must be determined by calculation or calibration using some other technique, the one-way time transfers are generally characterized by larger uncertainties than for the two-way methods. Depending on the method and expense, accuracies from a few μs to a few ns can be obtained.

Two-way techniques involve the exchange of timing signals between two terrestrial sites, using a satellite transponder to relay the signals back and forth nearly simultaneously. More complex equipment is required since the user must also transmit, but lower uncertainties in the time transfers are generally possible as a result of being able to measure, and thus compensate for, the path delay directly. Two-way techniques offer the possibility of state-of-the-art time transfers to small numbers of sophisticated users requiring this level of performance. An example can be found in the numerous Symphonie satellite experiments.

More complete descriptions, comparisons and references pertaining to these and other satellite techniques or systems may be found in Report 518.

3.5 *Other methods*

Different time comparison methods can be combined. In the Federal Republic of Germany, television pulses have been used in conjunction with the LF standard-frequency and time-signal transmitter DCF77. The LF second marker allows identification of a television pulse. This pulse, in turn, is helpful in identifying a carrier cycle of DCF77 [Becker *et al.*, 1973]. Similarly, LF and VLF signals can be used if they are synchronously transmitted.

The use of power lines has been suggested as a means of synchronization. Tests at the Physikalisch-Technische Bundesanstalt (PTB) and in Italy have shown that the precision is usually from 0.25 to 0.5 ms for a distance of 200 km with the possibility of phase changes due to switching of lines [Becker and Enslin, 1973; Angelotti and Cordare, 1974]. Similar results were obtained in the US over even longer paths of greater than 2000 km [Allan *et al.*, 1972].

Time comparison using telephone lines is one simple and inexpensive method. Experiments were carried out by the Radio Research Laboratories (RRL), (presently Communications Research Laboratories (CRL)), Japan, using an acoustic coupler on local and 800 km long-distance telephone circuits. Measurements of reception time and round-trip time were made for different carrier frequencies used for the call and answer-modes of the couplers, and the results were averaged. An accuracy of within ± 0.1 ms was obtained for both the local and long-distance circuits [CCIR, 1982-86]. This method can only be applied if the two paths are equal.

Since 1988 in Austria a time code has been disseminated via telephone modems. It consists of a string of ASCII-characters containing date and time (UTC and local time) information and additional advance information on switching between standard and daylight-saving-time and leap seconds. It furthermore provides the possibility to insert additional user-relevant information.

It can be used to set clocks, computers or automated measurement systems. The signal delay and jitter of the delay mainly depends on the operating mode of the modems. In CCITT Recommendation V.23 the delay of the modems is about 5 ms with a jitter below 100 μs and for CCITT Recommendation V.22 the corresponding figures are 60 ms and 3 ms, respectively. At present no propagation delay measurement capability is foreseen [Kirchner, 1989].

At NRC in Canada and at USNO in the United States a similar system has been operating since 1986 in which the user equipment can estimate the time code delay to an accuracy of about a millisecond [Jackson, et al., 1986].

Since 1988, NIST in the United States has operated a system, which estimates the delay for each user, so that the time code arrives on time at the user site with an accuracy of about a millisecond [Levine et al., 1989].

Since 1979 the Istituto Elettrotecnico Nazionale (IEN) in Italy has been supplying to the Italian broadcasting company (RAI) a coded frequency-shift keyed, audio time-signal [Leschiutta and Pettiti, 1979] that is extensively used for automatic synchronization of remote clocks. This technique allows a synchronization precision better than 1 ms. The use of these coded time signals to control remote oscillators with low daily frequency drift, can provide a traceability to UTC(IEN) within $\pm 1 \times 10^{-10}$, if the synchronization data used to compute the frequency parameters of the oscillators are taken over a suitable period of time (> 2 days) [F. Cordara et al., 1987].

Experiments have been made [Norton *et al.*, 1962] on the instability introduced by propagation over a 50 km line-of-sight microwave link. The deterioration of the transmitted wave phase stability due to propagation is usually less important than the inherent fluctuations in the signal due to the generator noise. For a measurement time interval of 1 s, the contribution of instability due to the propagation can be represented by a normalized standard error of about 3×10^{-12} which decreases to 1×10^{-14} as the averaging time is increased to 10^6 s.

In the USSR two-way synchronization experiments were conducted over a 750 km Moscow-Kharkov path by observing 72 MHz signals reflected from meteor trails [Dudnik *et al.*, 1971; 1973]. With transmitted powers of 40 kW, 5620 successful synchronization measurements per hour were usable. After compensating for the measured path delays, synchronization accuracies in the 0.1-0.2 µs range were achieved. Possible non-uniformities of the equipment delays in the forward and return channels are considered to be the principal error sources.

Considerable improvement has been made. Starting in 1987 in the USSR six links of radiometeor synchronization have been regularly exploited, and they provide comparisons of time-scales at distances of 600 to 2,200 km. The two-way method of synchronization in more recent times utilizes 57 MHz for the comparisons. Accuracies of comparisons of time-scales obtained on the paths of 750 to 1,200 km (Moscow-Kharkov, Moscow-Uzhgorod) were 20 to 30 ns as determined with portable clocks [Dudnik et al., 1986].

Experiments were conducted in France during 1974 to determine how well two clocks separated by 6 km could be synchronized using a two-way exchange of laser pulses to compensate for the propagation delay. In one series of experiments the clock difference was determined within an uncertainty of 4 ns. By using better laser detectors over a 300 m path, the uncertainties were reduced to less than 1 ns [Sannier, 1974; Besson, 1974; Besson and Parcelier, 1974]. Further improvements have been made in the timing pulse control equipment, leading to a potential resolution of the overall transmission and reception system of 100 ps [Moreau, 1977].

A cooperative experiment between France and Spain was carried out in 1977, involving the comparison of the time-scales of Paris (OP) and San Fernando (OMSF) observatories by means of the over-flight of both observatories by an aircraft equipped with a retroreflector, a laser emitter and the necessary time-keeping equipment. The difference between UTC(OP) and UTC(OMSF) was determined to within 20 ns [Benavente *et al.*, 1979].

TABLE I – *Comparison of time transfer methods*
(Status as of 1985)

System/Method	Coverage	Equipment cost (in thousands of US $)	Performance	Notes
Omega (VLF)	World-wide	5-25	2 μs	Frequency reference
Loran-C (LF)	Regional, Northern Hemisphere	3 1 10	1 μs 100 ns-2 μs (¹) 100 ns (¹)	Automatic, time code Manual Automatic
HF Time signal	World-wide	0.2	1 ms	Operator training
GOES	America	4	50 μs	Automatic, code
TRANSIT	World-wide	14	10-25 μs	Automatic, code
GPS	World-wide	25	10 ns	Automatic, code
Communication satellite	Point to point	100	1 ns	Two-way, transmit/receive

(¹) Excluding sky wave and overland paths.

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REPORT 518-5

TIME/FREQUENCY DISSEMINATION AND COORDINATION VIA SATELLITE

(Question 2/7)

(1971-1974-1978-1982-1986-1990)

1. Introduction

Present users of time and frequency (T/F) information have access to a variety of services and techniques for disseminating this information. These include: the well-known HF, LF and VLF broadcast services operated by many different administrations throughout the world; portable clock methods; the use of television transmission and radionavigation signals as T/F transfer standards; telephone-accessible services; and satellite techniques. Available accuracies may range all the way from the millisecond region down to the sub-microsecond region, depending on such factors as the particular technique used, the geographical locations involved, propagation conditions experienced, etc. (Reports 267, 271 and 363).

Although available services can satisfy many of the present user needs for T/F information, increasing numbers of measurement applications are developing that require, or can benefit from, T/F reference signals with improved accuracy, coverage, and reliability. For example, the rapid growth of technology as applied to such areas as precise navigation/position location, digital communications, scientific data monitoring, and space applications, has resulted in needs for time synchronization and intercomparisons over large geographical areas at the nanosecond or better level. Furthermore, an analysis of the long-term historical trends in timekeeping capabilities and the related application areas suggests strongly that the next 20 years will produce many more requirements for such time distribution levels.

While existing T/F services are undoubtedly capable of some further improvement, experience to date indicates that satellite techniques may offer the best chance for substantially improved dissemination and coordination services in the future. A number of different satellite techniques and systems are available for consideration, each with its own set of advantages and disadvantages for particular needs and applications.

Section 2 of this Report discusses some of the present and emerging needs for improved dissemination and coordination capabilities. Section 3 outlines some of the general advantages of using satellite-based techniques. In § 4 the most promising satellite alternatives are discussed and compared with respect to methods of use, present status, coverage, accuracy capabilities, user cost considerations, feasibility for on-site use, operational-versus-experimental status, and the most important advantages and disadvantages. In addition, a summary of experience to date and some indications of future plans for each technique or system are also included.

2. Some applications that can benefit from improved T/F time-transfer capabilities

Various laboratories throughout the world have already developed atomic frequency standards with well-documented uncertainty levels of about 1×10^{-13} and long-term stabilities of better than 1×10^{-14} (Report 364). Atomic time scales based on such reference standards show departures of less than 10 ns per day. If such time scale capabilities maintained within various national laboratories are to be of maximum usefulness in widespread T/F applications, techniques must be implemented for intercomparing the time scales at the subnanosecond level and disseminating corresponding reference signals to the user community.

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Another potential beneficiary of improved T/F capabilities is the digital communications area. There is a strong trend towards synchronized, all-digital networks which, in some cases, are likely to be implemented using many atomic frequency standards to provide the necessary timing stabilities for maintaining bit-synchronism throughout the communiction networks. For example, a network operating at 1.5 Mbit/s and maintaining bit-synchronism at the 1 bit/day level requires frequency reference stable to 1×10^{-11}. As typical communication rates increase in the future, the T/F reference requirements also become more stringent. Other systems use satellite links in a time-division, multiple-access (TDMA) mode and require system time synchronization as good as 10 ns.

The general field of transportation, and, in particular, navigation/position location applications, are already generating requirements for improved timing at the 10 ns level, and in some cases, at the better-than-1 ns level. For example, extensive satellite navigation systems to provide positioning to a few metres by employing atomic frequency standards with 1×10^{-13} stabilities and timing capabilities of 10 ns are in the advanced planning stage. Navigation requirements for future planetary space probes imply a need for better-than-1 ns timing. Various specialized marine applications for precise position-location, such as dredging, pipe laying, cable laying, salvage operations, oil exploration, geophysics, and hydrography all require the use of precise timing, in some cases, of the order of 1 ns. Other needs for better T/F distribution are evolving with the continuing development of time-ordered air-traffic control systems and techniques. Further systems are likely to employ air-to-ground digital data links for integrated aircraft navigation, communications, separation, and traffic flow control.

Space applications [Cooper and Chi, 1979] are generating needs for expanded T/F dissemination capabilities while improved techniques for tracking satellites and for making geodetic measurements via satellites are developed and implemented. Satellites can already be tracked with a total uncertainty of only a few metres on a world-wide basis. Laser ranging systems are operating with uncertainties of only a few centimetres, implying that subnanosecond timing resolution could be achieved.

Some of the more demanding applications that are expected to develop during the 1980's in applied satellite geodesy will require timing at the 0.1 to 1 ns level.

A variety of scientific applications can benefit from better T/F capabilities. Significantly better relativity experiments may require the availability of frequency references stable to 1×10^{-16} over hours, while very long baseline interferometry (VLBI) work would be aided by the general availability of better than 1×10^{-14} frequency stabilities for periods up to one day. Similarly, measurements of earth strains and continental drift require 1 ps time stabilities over 1000 s. As a final example, the availability of better T/F reference signals should make possible the improved modelling of the troposphere and the ionosphere, which in turn could have favorable impact in many other applications where propagation uncertainties limit the results.

Many other applications which do not necessarily require state-of-the-art accuracy or precision can nevertheless benefit from improvements in other aspects of T/F dissemination service capabilities, such as wider coverage, more reliable reception, reduced interference, greater convenience of use by non-specialists, and lower cost requirements. Two examples are scientific data monitoring systems where data needs to be correlated from various dispersed sites and electric power networks that need T/F references for coordinating and controlling power flow within the network, for event timing, and for fault location and analysis.

Many of the specific requirements quoted here are operational requirements for time and frequency, where the numbers are chosen so that this error source will not be the limiting factor in the overall system error budget. It is perhaps worth noting also that it is generally desirable to keep the T/F technology capabilities a factor of 10 or so ahead of the operational requirements.

3. General advantages of satellite techniques

Present methods for distributing T/F information that are generally available to most users do not appear to have potential for satisfying the types of needs discussed above. HF, LF and VLF services are limited by propagation effects and, based on many years of accumulated experience, cannot reasonably be expected to offer much better time-transfer accuracy capabilities than are now achievable. Time transfers via television signals have been performed at the 10 ns level, but only within local areas where both timing sites are within line-of-sight in a common reception area of the same television station. Longer distance television comparisons using interconnected television networks show significant deterioration (to a few microseconds) due to the additional propagation path uncertainities. Portable-clock techniques can achieve much better results (50 ns) if special precautions are taken, but again do not appear to be practical solutions for more general problems.

Satellite-based methods for transferring T/F, on the other hand, appear to offer the potential to satisfy the future needs for higher accuracy and the other improvements noted previously. Uncertainties introduced by the signal propagation path are reduced considerably in most satellite techniques, since the Earth-to-satellite and/or satellite-to-Earth paths used are largely in free space with minimal perturbations from the ionosphere and troposphere. The use of higher frequencies, for example, greater than 1 GHz, such as is common inmany satellite systems, also reduces ionospheric uncertainties in the total path delay. In the case of two-way satellite timing techniques, in which two sites exchange timing signals simultaneously (or nearly so) through the satellite, the propagation path delays, in principle, do not need to be determined and do not contribute directly to the uncertainty of the time transfer.

Satellites also offer significant advantages in coverage by virtue of their height above the Earth. A single satellite in the geostationary orbit, for example, can continuously broadcast or relay a timing signal to about one-third of the Earth's surface. Similarly, a single, polar-orbiting satellite in a lower-altitude orbit can provide total global coverage, though not continuously at a given point on the Earth. In general, reception reliability is very high for satellite signals anywhere in the coverage area, since propagation-medium disturbances are much reduced in importance compared to the case of terrestrial T/F signals.

Based on great variety of satellite experiments and evaluations performed using many different satellite systems, receiving equipment can be developed that is relatively inexpensive, highly automatic, and easy to use by non-specialists. To achieve the highest possible accuracies however, it may be necessary to use more expensive and more sophisticated equipment, requiring greater operating skills.

Satellite time transfer experiments have been performed successfully by a number of organizations throughout the world since 1962. Though no satellites dedicated exclusively for T/F applications are currently available, or are likely to be in the future, experimenters have been able to make effective use of satellite systems primarily designed for other functions. These include navigation, communication, television broadcast, meteorological, scientific, and experimental satellite systems. A tabular presentation of a number of these satellite experiments since 1962 is given in Annex I.

In recognition of these needs for improved services and the potential of satellite techniques for satisfying them, the World Administrative Radio Conference, Geneva, 1979, allocated the following frequency bands for T/F dissemination via satellites:

400.1 ± 0.025 MHz;
4202 ± 2 MHz (space-to-Earth);
6427 ± 2 MHz (Earth-to-space);
13.4 to 14 GHz (Earth-to-space);
20.2 to 21.2 GHz (space-to-Earth);
25.25 to 27 GHz (Earth-to-space);
30 to 31.3 GHz (space-to-Earth).

4. Satellite alternatives for improved T/F dissemination and coordination

In discussing the various satellite alternatives which appear potentially useful for improved T/F transfer in the future on an operational basis, frequent references will be made to one-way and two-way techniques. In this Report one-way operation implies that the user only employs receiving equipment for the reception of a transmission either originated or relayed by a satellite. One-way transmissions generally operate in a broadcast mode with the intent of serving a large number of users. They offer widespread service areas, good timing accuracies, simple methods and equipment for time recovery, and moderate user costs. Two-way operation implies that the users employ both transmitting and receiving equipment, normally in a point-to-point communications mode. Two-way techniques in general offer higher accuracy potential by virtue of being relatively independent of the propagation path connecting the user sites.

The various satellite alternatives are divided for convenience into three separate groups:

- those which have primary application for high-accuracy time transfer;
- those which appear most useful for general T/F dissemination to large numbers of users; and
- those systems/techniques which offer potential for both improved dissemination *and* improved high-accuracy T/F transfer.

For each alternative considered some more general information is first given, which describes the system or technique and its present status. Accompanying this is a summary, in Table I, giving some comparative information about each system or technique, including coverage, accuracy capability, some user cost considerations, a judgement about the feasibility of on-site use, and an indication of the experimental-versus-operational nature of the alternative. Table II summarizes some of the principal advantages and disadvantages of each of the alternatives considered. For each alternative a summary is also given of any experimental and/or operational experience to date along with some indication of future plans.

TABLE I – *Selected comparative information for satellite alternatives*

Satellite alternative	Coverage	Accuracy capability	User cost estimates (US dollars 1987)	Feasible for on-site use	Satellite system – operational or experimental
1. Communication satellites	Regional or global (networks)	< 10 ns	$ 15 000 (VSAT) + $ 15 000 (MITREX modem)	Depends on specific satellite system and location	Operational
2. GPS: Normal mode	Global; continuous	Possibly ≈ 100 ns if not degraded	Present timing receiver > $ 15 000. Should decrease with development	Yes	6 satellites now in orbit. Full implementation sometime after 1990
Common-view mode	Intercontinental	Depends on specific geometry of link. Possibly ≈ 10 ns in time and 10^{-14} in frequency if not degraded	> $ 15 000	Yes	See above
3. LASSO	Europe, Africa. Depends on satellite location	< 1 ns projected	Very expensive: full laser stations ≈ $ 1 million. Usually requires auxiliary timing links to laser sites	Not in general. Requires laser station	MID 1988 (METEOSAT-P2). Could develop operational add-on package later with synchronization accuracy of 100 ps
4. Space shuttle experiment	Depends on specific flight. Possibly covering ± 57° in latitude	< 1 ns (time) and 1×10^{-14} (frequency) projected	Requires two-way links to shuttle possibly with 3-frequency method. Expensive	Possibly, with further equipment development for later operational use	Experiment NAVEX on the Spacelab mission D1, Nov. 1985: no plans for operational system
5. Use of new 13-31 GHz allocations	Depends on satellite system used	Precision: < 1 ns Accuracy: limited by delay uncertainties, 6 ns achieved	Expensive until further development	Probably	No present plans for operational or experimental use
6. Simultaneous reception of ranging signals	Regional	10 ns	< $ 30 000	Yes	Operational using GMS

TABLE 1 *(continued)*

Satellite alternative	Coverage	Accuracy capability	User cost estimates (US dollars 1987)	Feasible for on-site use	Satellite system – operational or experimental
7. Meteorological satellites	Depends on system. Hemispheric for US GOES time code. Possible expansion to Europe and Japan	± 16 ms (uncorrected) ± 1 ms (corrected for mean path delay) ± 100 μs (fully corrected)	$ 3500 (1 ms accuracy) $ 4500 (100 μs accuracy) Antennas included	Yes	GOES satellite system is operational. Time code on US satellites since 1974
8. Use of 400.1 MHz allocation	Depends on satellite system used	Basic level: ≈ 1 ms Probably could achieve < 1 μs via PRN code	Basic level: < $ 500 PRN code: < $ 3000	Yes	Allocation exists but no known plans for use
9. VHF transponder or dedicated 10 kHz channel on communication satellite	Regional	≈ 1 μs possible. Could also disseminate less accurate codes or voice	Should be fairly low	Yes	India planned use of 10 kHz channel on INSAT in about 1984
10. TRANSIT Operational system	Global, including high latitudes, on an intermittent basis	≈ 30 μs (single satellite) ≈ 10 μs (satellite ensemble)	≈ $ 12 000 for fully automatic receiver and omni-directional antenna	Yes	Operational
Improved TRANSIT (Nova)	Same as above, except only two satellites are now in orbit	< 100 ns	$ 15 000 to $ 50 000 after initial receiver development	Yes	Experimental
11. Television broadcasting satellite: High-accuracy mode	Regional (OTS-2) or global	Depends on quality of ephemeris data. 300 ns and possibly < 50 ns	At present: ≈ $ 3300. Should be reduced significantly in production quantities	Yes. 1 m antennas may be usable	Experimental at present but many operational satellites are planned
General dissemination mode	Same as above	Depends on path correction capability. Possible time code for general use	Same as above. Less demand on users for handling path delays	Yes	Same as above

TABLE II – *Principal advantages and disadvantages of satellite alternatives*

Satellite alternative	Principal advantages	Principal disadvantages
1. Communication satellites	Technology and operational systems available now. Much accumulated experience. Long-term continuity assured. Two-way technique provides high accuracy. Costs and required antenna size decreasing. High reliability regional and international coverage. On-site operation feasible in some cases. Large bandwidth may be available. Many governments already directly involved in operation systems	Present costs, though decreasing, are reletively high. Large antennas necessary in some cases – especially for INTELSAT links. User must have transmit capability. In some cases need auxiliary links to satellite facilities from T/F laboratories. Highest accuracy requires a difficult calibration of ground-station delays.
2. GPS: Normal mode	High-accuracy capability. World-wide, continuous coverage. Ample redundancy and system support. One-way technique. Long-term continuity of system. Strong receiver development effort likely if access and accuracy not unduly restricted. Small antennas feasible. On-site operation	Timing accuracy for civilian users may be degraded to 250 ns (two-sigma). Present receiver costs > $ 15 000. Complex signal format. One-way method requires path delay determination by users
Common-view mode	Potentially lower receiver costs. High synchronization accuracy for distances of several thousand kilometers. Convenient on-site operation. Any ephemeris errors partly compensated for. Requires only knowledge of *differential* path delay	Usable for regional and intercontinental distances. May be restrictions on access and available accuracy for civilian users. Requires some coordination and scheduling among labaratories, being coordinated by the BIPM
3. LASSO	Potentially one of the most accurate alternatives. May allow < 1 ns time transfer. Synchronization requires only a few minutes. Standard LASSO packages could be added to other satellites in future	High user costs for equipment. Most laser sites not co-located with T/F laboratories. Laser operations subject to weather conditions. No operational plans. Lack of laser experience
4. Space shuttle experiment	Potentially one of the most accurate alternatives for global time transfer. Use of the two-way method eliminates position and velocity uncertainties. Use of multiple frequencies reduces frequency uncertainties. Not weather sensitive. Allows direct frequency comparisons	No plans for operational mode. Expensive, complex equipment required. Shuttle use for experiment limits observation time during each pass
5. Use of new 13-31 GHz allocations	Frequencies are internationally allocated for T/F use. Large bandwidths would permit measurement precisions of < 100 ps. Not restricted to a particular satellite system	Technology in this frequency range needs further development and cost reduction. Allocations are on a shared *secondary* basis. Probably not feasible for 5 to 10 years

TABLE II *(continued)*

Satellite alternative	Principal advantages	Principal disadvantages
6. Simultaneous reception of ranging signals	Some suitable satellites are operational. High-accuracy potential. Potential for global coordination use. Relatively inexpensive equipment can be used on-site. Accurate ephemeris information simultaneous with time transfer. Convenient one-way technique	Must have access to satellite ephemeris information. Requires several special monitoring sites to link regional systems for global time transfer.
7. Meteorological satellites	Low user cost. Some commercial receivers already available. Continuous service available from geostationary satellites. Time code already operational on GOES satellites. GOES time code contains complete date and time information referenced to UTC. Relatively secure long-term continuity for prime satellite mission. On-site use	Coverage of present GOES time code limited to western hemisphere. Occasional time deviations of > 100 μs possible with GOES. 468 MHz frequency used is not a specific T/F allocation. Secondary status of allocation may result in interference from land mobile service in some areas. Must have cooperation of non-T/F organizations
8. Use of 400.1 MHz allocation	Frequency is already internationally allocated for T/F use on a *primary* basis (with minor exceptions in some areas). Compatible with very inexpensive user equipment. Usable bandwidth could permit a dual-level service. Compatible with off-the-shelf satellite transponders. Could use 400.1 MHz transponder as add-on package to any satellite-of-opportunity. Service operating costs would be much lower than for current HF services. Could relieve HF interference problems. Flexibility of signal design. Could easily provide global, or at least international, coverage with multilanguage capability. On-site use	No present known plans for operational implementation. Need to identify appropriate satellites and develop cooperative arrangements. May be difficult to convince large numbers of users to convert to satellite service, even if technically superior. As replacement for HF services, would need long overlap period with both services to allow equipment amortization and user education
9. VHF transponder or dedicated 10 kHz channel on communication satellite	VHF transponders used mainly during orbit insertion and may be available later for T/F use. Convenient frequencies. Long-term continuity of primary satellite mission. Could be low cost. 10 kHz channel allows complete time information to be disseminated. India may implement operationally via INSAT. On-site use	Availability of transponders uncertain. Requires agreements and active cooperation with non-T/F organizations. Dedicated channels probably not generally available to T/F organizations, except in special situations. Limited accuracy capability with 10 kHz channel

TABLE II *(continued)*

Satellite alternative	Principal advantages	Principal disadvantages
10. TRANSIT Operational system	Fully operational, strongly supported with five satellites. Global coverage. Commercial receivers available. Time signals referenced to UTC. On-site use. Automatic receivers can average passes and select specific satellites for improved accuracy. Long-term TRANSIT operation likely	Polar orbits result in timing signals being available only periodically at a given location. Time information has 30 min ambiguity. Receivers must handle Doppler shifts
Improved TRANSIT (Nova)	High accuracy possible with one-way technique. Global coverage, including high-latitude regions. Simple antennas; on-site operation. Should provide improved performance with present receivers. Two Nova satellites in orbit	NOVA improvements for time transfer still have only experimental status. Time signals available intermittently. Availability of most precise ephemeris information to general users may be restricted
11. Television broadcasting satellite: High-accuracy mode	Some forms of user equipment for television timing measurements already developed. Many television satellites planned throughout the world. User equipment can be fairly simple with small antennas feasible. Accuracy can be excellent if satellite position is determined via auxiliary measurements at certain selected sites. Large signal-to-noise ratios and bandwidths available. On-site operation. Long-term continuity assured by primary satellite mission	Requires auxiliary facilities and techniques to determine satellite position and distribute this data to users for path corrections. Coverage generally confined to regions or, in some cases, individual countries
General dissemination mode	Equipment already developed for using television synchronization pulses. Time code could be added to vertical interval. Small antennas, simple receivers and simple measurement techniques are feasible. Likely to be numerous, long-term television satellite systems in operation. On-site reception. Large S/N and bandwidth	Some knowledge of propagation path delays is needed. Coverage is mainly regional or to individual countries. Requires cooperation of non-T/F organizations for addition of vertical-interval time code

4.1 *Alternatives primarily for high-accuracy T/F transfer*

4.1.1 *Communication satellites*

The availability and use of communication channels provided by operational communication-satellite systems operated by many companies, nations and regional groups of nations are growing dramatically. For high-accuracy, point-to-point time comparisons two sites might for example, arrange to simultaneously exchange suitable timing signals through the satellite link. At each site the measurements consist of time differences between the transmitted and received time markers. Assuming that signal delays through the propagation medium, the satellite transponder, and the receiving/transmitting equipment are symmetrical, the time difference between the two sites can be computed simply from the measured time differences at each site without any knowledge of the satellite or user locations. Typically, measurements are conducted for periods of only 10 to 60 minutes at a time and once or twice per week. Other variations of the technique are also possible, not requiring the simultaneous exchange of signals. Currently available communication satellites operate either in the 4/6 GHz or the 11/12/14 GHz allocated bands. The user has considerable flexibility in selecting signal design and, in some cases, the channel bandwidth. With some systems entire 36 MHz wide transponder channels must be leased; in others, each channel can be subdivided. In digitally-oriented systems data bit rates of 56 kbit/s are often available as a "standard" channel, but bit rates of 1.5 Mbit/s and higher are often available.

In some situations (in the United States, for example) international comparison links via communication satellites may require a two-hop process with one link from the time laboratory to an international gateway satellite terminal via a domestic satellite and a second link from the international gateway terminal to the other country via an international satellite carrier.

Experience in using communication satellites for precise time transfer extends back to 1962 when clocks at the US Naval Observatory (USNO), the National Physical Laboratory (NPL), United Kingdom, and the Royal Greenwich Observatory (RGO), United Kingdom, were compared to an accuracy of 1 µs using a two-way exchange of 5 µs pulses repeated at a 10 Hz rate. The experimental communication satellite Telstar was used [Steele *et al.*, 1964]. Nearly three years later the Relay satellite was used for similar time transfers between the USNO and the Radio Research Laboratories (RRL) Japan, achieving a stated accuracy of 0.1 µs [Markowitz *et al.*, 1966]. In these early experiments up-link and down-link frequencies were in the range of 1.7 to 6.4 GHz.

The US experimental communication satellite ATS-1 was used by several different organizations during 1974-1975 for two-way time transfer experiments using more complex signals in the form of pseudo-random noise (PRN) codes. Correlation detection of these PRN-coded transmissions resulted in very high accuracies and precisions during the time transfers. In the first series of experiments which were designed to have a master station in the western United States synchronize a slave station in the eastern United States, the US NASA organization was able to demonstrate an accuracy of 50 ns and a measurement resolution of better than 1 ns [Chi and Byron, 1975]. Also in 1975 similar time transfers using a sophisticated spread-spectrum, random-access communication system were made over intercontinental distances between RRL in Japan and the USNO and NASA in the USA with an accuracy of about 10 ns after applying relativistic corrections [Saburi *et al.*, 1976]. All the ATS-1 experiments made use of 4/6 GHz band. Similar time transfers at the 100 ns accuracy level have been performed on an operational basis among more than twenty stations since 1970 using the US Defense Communications System satellites. Time transfers use low-level PRN-coded signals which do not interfere with the normal communications function [Easton *et al.*, 1976].

Another group of two-way transfers has been accomplished during the 1976-1982 period using the 4/6 GHz band on the experimental European Symphonie series of satellites. Successful two-way time transfers with accuracies of about 50 ns or better and measurement precisions of a few nanoseconds have been reported between Raisting (Federal Republic of Germany) and Pleumeur-Boudou (France) [Brunet, 1979]; NRC (Canada), Pleumeur-Boudou (France), and LPTF (France) [Costain *et al.*, 1979]; NRC (Canada) and PTB (Federal Republic of Germany) via Raisting; Shanghai, Beijing, and Nanjing in the People's Republic of China; National Institute of Metrology (People's Republic of China) (NIM) [Cuiying, 1981] and PTB (Federal Republic of Germany); Shanghai and Shaanxi Observatories (People's Republic of China) and LPTF (France); and NPL (India) and PTB (Federal Republic of Germany) [Mathur <u>et al</u>., 1980].

In the case of the NRC-LPTF comparisons, regular time transfers continued for four years from June, 1978 to July, 1982. In February, 1980 the PTB began participating in these regular comparisons via Symphonie. These transatlantic time links have been used by the BIH instead of the Loran-C links. In most of these time transfers, relatively simple signal formats featuring 1 pulse/s signals were used. The main contributions to the overall time transfer uncertainties were usually related to difficulties in determining the exact delays through the satellite ground terminal equipment and uncertainties associated with the necessary timing links connecting the satellite receiving facilities and the timing laboratories. The introduction of a new 1 MHz modulation technique (modems devised by NRC) reduced the random uncertainty associated with the space link to a few tenths of a nanosecond. The addition of PTB to the comparisons permitted three separate pairs of measurements to be made each time and the resulting closure error Δ to be evaluated as an indication of the uncertainty. Using only 1 Hz modulation produced $\Delta = -42 \pm 8$ ns while the 1 MHz system resulted in $\Delta = -8 \pm 6$ ns.

The joint US/Canadian CTS/Hermes satellite provided an opportunity during 1978-79 for the USNO and NBS laboratories in the USA, and NRC (Canada) to experiment with some variations on the two-way transfers used previously [Costain *et al.*, 1979]. First, higher up-link and down-link frequencies, in the 12/14 GHz band, were used to advantage. Second, as in the technique mentioned above, 1 MHz signals were exchanged in part of the experiment in addition to the usual 1 pulse/s signals. This resulted in an improved measurement precision of about 0.2 ns (1σ) and allowed accurate time comparisons to be made with only a few minutes, or even seconds, of actual measurement time. Third, small on-site receiving terminals with dishes as small as 2.4 m in diameter were able to be used part of the time at two of the three sites. The UTC time scales were compared with an uncertainty of about 1×10^{-14}. Fourth, it was possible occasionally to link NBS with Pleumeur-Boudou (France) via a two-hop process by linking NBS and NRC via CTS/Hermes and then NRC and France via Symphonie. Measurements precisions for the two-hop mode were less than 10 ns (1σ).

The Istituto Elettrotecnico Nazionale (IEN) laboratory in Italy used the Sirio-1 experimental communication satellite in the 12/17 GHz band to evaluate still another variation of the two-way time transfer technique [Detoma and Leschiutta, 1980]. In this case the satellite motion was continuously accounted for so that only a single communication link needed to be used in a time-sharing mode between the two stations. The satellite motion effect on the time transfer accuracy was only a few nanoseconds for measurement times of up to 20 seconds. Measurement precisions were 1 to 5 ns.

At the NRC in Ottawa, experiments on two-way time transfer via commercial 6/4 GHz geostationary satellites have been carried out using pairs of low power CW signals. Two experimental satellite ground stations with 3 m antennas and 1 W power have been installed at ground level 100 m from the Time Laboratory, with triax cables connecting directly with the laboratory [Costain *et al.*, 1982].

In 1983, signals of $f_0 \pm 0.5$ MHz were transmitted through the Anik-A3 satellites, and the 1 MHz frequency was recovered directly [Costain *et al.*, 1983]. The r.m.s. deviation of the measurements was 0.4 ns. The experiments showed that time transfer using CW signals or PRN code is practical with low-cost terminals.

One of the NRC 6/4 GHz 3 m terminals has been converted for operation in the 14/12 GHz band, and a PRN code modem recommended by Interim Working Party 7/4 has been acquired. An experimental network using a 14/12 GHz geostationary satellite for two-way time transfer between NRC, USNO and NBS is being implemented. This should provide a valuable check on the GPS time transfer method now in operation.

The Radio Research Laboratories in Japan (RRL, presently CRL (Communications Research Laboratory)) are developing a domestic accurate time-comparison system which uses the Japanese geostationary communication satellite CS (medium capacity communication satellite for experimental purpose), spread spectrum random access (SSRA) equipment and 30/20 GHz earth stations such as the Kashima main station and two small mobile stations. Two-way time transfer experiments were carried out in 1981 and 1982 between the main station and a small station placed at the headquarters and between two small stations, both of which were located at the same site. In each case, time fluctuation of about 1 ns and a frequency stability of less than 1×10^{-13} for averaging times of 100-200 min were obtained. The accuracies of the experiments were estimated at about 13 ns for the time comparison between the main station and the headquarters using as a reference a two-way time transfer through a terrestrial microwave link, and about 0.74 ns for that between a two-way time transfer experiment using two small earth stations at the same site with a common clock. The time delay of each station was measured by inserting a pulse-modulated signal into each of the up-link and down-link paths of the station and detecting it at the other end of the path for comparison with the input pulse. For the main station, the delay was estimated with about 7.7 ns of accuracy (capability) while for the small stations it was estimated with about 3.6 ns of accuracy [Imae *et al.*, 1983] (see Table III).

TABLE III – *Measurement results of the delays at the two small stations*

		Time delay (ns)
1 m antenna diameter station up-link delay	(U_1)	329.6
1 m antenna diameter station down-link delay	(D_1)	372.0
2 m antenna diameter station up-link delay	(U_2)	361.3
2 m antenna diameter station down-link delay	(D_2)	401.0
$K = (U_1 - D_1) - (U_2 - D_2)$	(K_1)	−2.7
K by the common clock method	(K_2)	−6.3
$K_1 - K_2$		3.6

Standard time comparison experiments via communication satellite using SSRA (Spread Spectrum Random Access) equipment were also carried out by the Chinese National Institute of Metrology (NIM). Results of experiments carried out between the Beijing earth station and the Wulumuqi earth station via STW-1 show that the SSRA technique can give a precision of about 1 ns and an uncertainty of about 10 ns for two-way operation (Cuiying Xiao, 1987).

Intercontinental time transfer experiments were performed in the summer, 1983 in cooperation between the USNO, COMSAT, Technical University of Berlin and DFVLR (Federal Republic of Germany) using Intelsat-V communication channels between stations in Washington, DC, and Oberpfaffenhofen (Federal Republic of Germany). At the earth station, the time signal was inserted via a MITREX modem as a pseudo-random noise (PRN) sequence with a 2 MHz chip-rate at the intermediate frequency (IF) interface into the communication link and retransmitted at the receiving end. Time transfer accuracy is measured by correlation detection of the original PRN sequence with its received replica. With earth stations of G/T values of 20 dB(K^{-1}) and 26 dB(K^{-1}) (corresponding to antenna diameters of 2.2 m and 4.5 m) and transmitter powers as low as 170 mW and 80 mW, respectively, reliable time transfer experiments were performed resulting in an r.m.s. time jitter of less than 1 ns. With the chosen link characteristics, the time transfer signal which is spread over a 2 MHz bandwidth is received at a signal-to-noise ratio of −9 dB, well below the thermal noise level [Hartl <u>et al.</u>, 1983].

In Europe a time transfer experiment between FTZ, Germany, and TUG, Austria was carried out using MITREX modems with the ECS-1 satellite. Similar results were obtained while sharing the satellite transponder with a TV signal [Kirchner et al., 1986; Kirchner, et al. ...].

Furthermore, at TUG extensive measurements were performed on the MITREX modem itself. For a carrier-to-noise power density ratio above 58 dB Hz the typical measurement precision is below 0.5 ns with a lower limit of about 0.1 ns. The time required for signal acquisition is less than 20 seconds. The signal delay variations were less than 0.5 ns for a wide range of the parameters of operation (different codes, settings of built-in attenuator, input signal power). The most critical parameter is the input frequency which must be kept within ±3 kHz of the nominal value in order to keep the delay variations less than 0.5 ns [Kirchner, 1986].

In North America efforts are proceeding to establish an operational time comparison network connecting the United States National Institute of Standards and Technology (NIST), (formerly the National Bureau of Standards), the United States Naval Observatory, and the Canadian National Research Council. The emphasis is on using relatively small, affordable, carefully calibrated ground stations equipped with MITREX spread-spectrum modems to provide regular two-way exchanges of timing signals through available commercial communication satellite channels operating in the 11 to 12 GHz band. Recent experience at the NIST has shown that it may be practical in such comparisons to make use of very-small-aperture terminals, commonly known as VSATs, with antenna dish diameters of 1.8 m. The measured stability performance $\sigma_y(\tau)$ of the NIST VSAT equipment is $4 \times 10^{-10}\ \tau^{-1}$ for a carrier-to-noise power density ratio of 65 dBHz, which can be improved to about 3×10^{-15} for averaging times of a few days [Howe, 1987]. The ground station differential delays, which are critical to the overall accuracy of the time comparisons, can be effectively calibrated at the 1 ns level by using the technique developed in Japan [Imae et al., 1983] involving the exchange of signals between two co-located ground stations driven from a common timing reference. To aid in these equipment calibrations a small mobile earth station has been acquired which can be transported between the various participating laboratories in the operational network.

Since August 1987 the United States National Institute of Standards and Technology (formerly, the National Bureau of Standards) and the United States Naval Observatory have conducted regular (three times per week) time comparisons using the two-way technique with commercial communication satellite channels. During one three-month period these data showed typical daily measurement precisions of less than 500 ps using only 100 one-second measurements for each day. The residuals from a linear regression for the three-month period were within 10 ns [Klepczynski, 1988].

4.1.2 *GPS (global positioning system)*

The GPS (also known as NAVSTAR) is being implemented by the US Department of Defense as a high-accuracy, continuously available navigation/position-location system [Milliken and Zoller, 1978]. The system is planned to include as many as 24 (21 primary plus 3 in-orbit spares) operating satellites, arranged in 6 orbital planes. The

24 satellites in 12-hour orbits would result in several being in view of any specific location at any time. Each satellite contains atomic clocks (caesium, rubidium, and hydrogen devices were investigated) to generate extremely well characterized timing signals as part of the navigation message format. The system is supported by an extensive network of monitoring stations and control stations which provides updated timing corrections to the on-board atomic clocks. Although GPS system time will not necessarily track UTC precisely, its relationship to UTC will be accurately known at all times. The complex GPS signal format is transmitted to users on frequencies of 1575 and 1228 MHz and can be received with small omnidirectional antennas. Coded information is including giving clock corrections, ionospheric correc-

tions, and satellite ephemeris data for calculating the one-way propagation delay. The GPS signal is designed in such a way that its navigation and time transfer potential can be made available at two different accuracy levels.

In 1985, the United States Department of Defense announced that the GPS C/A code, including the time and satellite position data, would continue to be made available to civilian users and that no user fees would be charged. Furthermore, it was stated that the two-sigma time and position uncertainties available to the civilian users will be no greater than 250 ns (relative to GPS time), 100 m (horizontal position) and 156 m (vertical position).

A civil GPS service is being planned to coordinate the release of information needed by the civilian user community such as data, ephemerides, advisories, and clock information. The service is to serve as an interface between the United States Air Force and the civilian community.

Six useful GPS satellites are currently in orbit (September 1989) and are usable for high accuracy time transfer. Three carry rubidium standards and three carry caesium standards. Full system implementation (24 satellites) is projected by 1991. A variety of GPS navigation and timing receiver developments, intended for various applications, are in progress.

It may be possible to use the GPS timing signals in several different ways to perform high accuracy time transfers and comparisons. In the "normal" mode the transmitted signals are received at a user's site; decoded; corrected for GPS clock errors, ionospheric effects, and satellite ephemeris using encoded data in the transmission; and then compared with local clock outputs. The realizable accuracy will be strongly influenced by the specific correction information made available to the users.

In the "common-view" mode of use, the same GPS signal is received simultaneously at two (or more) sites [Allan and Weiss, 1980]. Since all of the clock errors and some of the ephemeris and the path correction uncertainties are common to each site's observations, a degree of compensation for such uncertainties is realized and relatively good synchronization accuracy is possible. It has now been shown by extensive GPS time and frequency comparisons conducted by many different laboratories on a global basis that time comparisons with precisions of less than 10 ns and frequency comparisons with uncertainties of less than 1×10^{-14} can be achieved on essentially an operational basis [Allan *et al.*, 1985]. An averaging time of the order of a week is sufficient to achieve this level of frequency comparison precision. At distances of the order of 500 km, the uncertainty can be reduced by one or two nanoseconds provided that the precise differential geodetic coordinates are known to the nearest few decimetres; however, it has been shown that these coordinates could be deduced from the time comparisons themselves [Guinot and Lewandowski, 1987]. A variation of this technique, involving the sequential observation of the same satellite with a time lag between, may also prove useful for intercontinental time transfers due to the extremely stable behaviour of the GPS satellite clocks over periods of many hours.

For clock comparisons, the receiver delay difference must be known. This may be measured in each laboratory by transport of a receiver taken as a transfer standard. Several calibration campaigns have been conducted [Buisson et al., 1985; Lewandowski et al., 1986]. The BIPM has carried out such calibrations.

Since the GPS comparisons have proved to be from 10-100 times better than the corresponding Loran-C data, certain inconsistencies and errors as large as 1 μs have been detected and eliminated in the process of formulating TAI and UTC. The GPS results have been compared with portable clock data in some cases and the agreement has normally been within the combined uncertainties (a few tens of nanoseconds) of the techniques used. In the case of the primary laboratory caesium standards, such as those operated by NIST, NRC and PTB, the GPS common-view comparisons now permit these devices to be compared with uncertainty contributions of less than one part in 10^{14} from the comparison process itself. A number of specific comparisons of time scales and primary frequency standards using GPS are given in references [Allan *et al.*, 1985; USNO, 1985].

The international time and frequency community continues to use GPS in the common-view mode more and more extensively. As of 1 January 1987, the International Atomic Time (TAI) scale and UTC were composed of 160 clocks and 10 primary frequency standards. As of that date 62% of the clocks and 80% of the primary frequency standards contributed to TAI and UTC via GPS in common-view. The BIPM distributes an international tracking schedule to the contributors in order to take advantage of the common-view approach.

A number of laboratories have reported their specific experiences using the GPS technique. Some of these results are summarized in the remainder of this section.

The United States Naval Observatory (USNO), using a commercially available GPS receiver, has monitored GPS transmissions since November, 1979. GPS data obtained by this unit extends from 10 October, 1980 (MJD – 44 522) in machine readable form. Ths most current data is available in real-time through the USNO Automated Data Service and is published in USNO Time Service Announcement, Series 4. Since 1 December, 1982, GPS System Time has been maintained within 1 μs of UTC(USNO), and transmitted corrections allow synchronization to within 100 ns of UTC(USNO).

The United States National Bureau of Standards has developed its own version of a GPS timing receiver, primarily intended for use in the common-view mode of reception. The internal receiver delay stabilities are at the 1 ns level and satellite signal stabilities are routinely observed at the 5 ns level for 15 s averages [Davis et al., 1981a].

Routine time comparisons, conducted at the USNO and NBS over many months using these receivers of different design, showed that the GPS is capable of time transfers with a precision of better than 100 ns [Putkovich, 1980; Davis *et al.*, 1981b]. One series of comparisons at these two laboratories during a 14-day period provided a comparison of their two UTC time scales with a precision of about 2×10^{-15}.

An intercontinental frequency comparison between the space agency of the Federal Republic of Germany (DFVLR) and the USNO in Washington, DC, using an experimental receiver, showed an accuracy of 2×10^{-14} during a measurement period of 12 days [Starker *et al.*, 1982].

Using an experimental Naval Research Laboratory GPS timing receiver, it was possible to compare hydrogen masers located in the United States of America and France [Wardrip *et al.*, 1983]. The Jet Propulsion Laboratory in the United States of America uses the GPS to coordinate time and frequency between three hydrogen maser clocks located approximately equidistantly around the Earth. By using GPS timing receivers, the hydrogen maser clocks can be characterized in near real-time to within 50 ns in time offset and 1×10^{-15} in frequency offset [Clements *et al.*, 1984].

The GPS time transfer system was introduced at the Tokyo Astronomical Observatory (TAO) in 1982 [Fujimoto *et al.*, 1983] and regular measurements with world-wide cooperation are being conducted. The transpacific common-view link between TAO and USNO [Allan and Weiss, 1980; Klepczynski, 1982; Allan *et al.*, 1985] was checked by three portable clock experiments and the two techniques agreed to within the experimental errors [Aoki *et al.*, 1984]. The precision of the GPS time transfer of this link was evaluated to be 4×10^{-13} over an averaging time of 1 day and 3×10^{-14} over an averaging time of 10 days.

The Communications Research Laboratory (CRL, formedy RRL (Radio Research Laboratory))(Japan) have made international time comparison since August, 1984, using two GPS time transfer receivers, one of which was developed by CRL and the other independently by a Japanese electrical firm. The receivers have a precision of 6-20 ns for time comparison and the receiver delays were measured with an accuracy of 15 ns by using a GPS signal simulator [Yoshimura et al., 1986; Imae et al., 1985].

A time-synchronization experiment using the GPS common-view mode was carried out in China between two regions - Beijing and Xian - during the period 12-18 July 1987. BIRMM (China), CSAO (China), CXIN (China) and WAO (China) took part in this experiment. During this same period, a portable caesium experiment was also conducted between these two regions. A time synchronization uncertainty of 10-17 ns was obtained for two places 1,000 km apart. [YIN-BAI ZHANG and ZONG-YANG LI, 1988].

The United States National Bureau of Standards initiated in 1983 a new calibration service based on the GPS common-view technique. NBS provides at each user's site a completely automated, turn-key GPS receiving system, including receiver, system controller, data storage and analysis capabilities, telephone access, and personnel training and system support. The receiver which is located at the user's facility communicates its data automatically to an NBS computer which stores the raw data, determines which data elements are suitable for time transfer calculations and provides an optimally filtered value for the time and frequency of the user's clock with respect to the NBS automic time scales. The user is given an account on one of the NBS computers through which he may access both the raw data and the results of the NBS analysis.

Experience with the service has shown that precisions of a few nanoseconds and frequency stabilities of 1×10^{-14} or below are realizable. In addition, all of the primary frequency standards contributing to TAI via the GPS common-view technique are accessible at the calibration site, which can be anywhere in the world. This has been extremely useful, for example, in measuring the frequency stability about a secular rate deceleration of the millisecond pulsar, PSR 1937+21, at the few parts in 10^{14} level [Rawley, 1987].

The increasing use of the GPS common-view technique has been aided by several developments. Many laboratories routinely make their GPS comparison data generally available by recording the results in the GE Mark 3 Information System. This exchange of data is amplified by an agreement to use a "standardized" data format. Also, to assist laboratories in determining when to make GPS measurements that are simultaneous with those of other selected laboratories, NBS regularly generates and distributes such scheduling information based on certain geographical ragions. The number of sources of suitable GPS timing receivers seems to be increasing significantly. While some laboratories continue to develop their own versions, several different commercial products are also available.

4.1.3 GLONASS (Global Navigation Satellite System)

The global navigation satellite system (GLONASS) being implemented by the USSR has many similarities to the GPS system described above. At present it is operational; by the end of 1990 it is expected that 10-12 satellites will be deployed while the full system envisaged for 1991-1995 will embrace a total of 24 operational satellites, including three spares.

Information on the technical characteristics and performance of the GLONASS system is given in a USSR document presented to the Fourth Meeting of the Special Committee on Future Air Navigation Systems, International Civil Aviation Organisation [ICAO, 1988]. Various aspects of GLONASS, including orbital configuration and signal structure and content, have also been studied in the United Kingdom by Daly [1988] and Dale et al. [1989].

Although the general concepts of GPS and GLONASS are similar a number of differences are to be noted. The GLONASS constellation is at a lower height than GPS of 19,100 km, in near circular orbit with a period of 11h 15m and an inclination of 64.8 degrees. The ground-tracks repeat after an interval of 17 orbits as compared with 2 orbits for GPS. Unlike GPS each satellite has a unique frequency in the band above 1 600 MHz determined by the relation, for the j-th satellite.

$$f_j = f_1 + (j - 1)\,\Delta f, \text{ where } j = 1, 2, \ldots, 24$$

$$f_1 = 1\,602.5625 \text{ MHz}, \ \Delta f = 0.5625 \text{ MHz}$$

The message data transmitted by each satellite provides an ephemeris, generally every half-hour, in the form of position and velocity vectors. Computation of intermediate orbital positions via the osculating Kepler ellipse yields accuracies of 10-20 m. No ionospheric information is provided on the data stream and the user requiring corrections for ionospheric signal delay must generate these from other sources or, possibly, from a determination of the P-code delay as between the L1 and L2 frequencies, the latter falling in the range 1 240-1 260 MHz with a channel spacing of 0.4375 MHz.

4.1.4 *LASSO (laser synchronization from geostationary orbit)*

The concept, as proposed to the European Space Agency (ESA) by the Bureau international de l'heure (BIH), employs a laser retroreflector mounted on a suitable geostationary satellite and the ground stations which are to be synchronized are equipped with laser telescopes [Serene and Albertinoli, 1979 ; Serene, 1980] Each ground station arranges to transmit laser pulses to the spacecraft, detect the returned pulses, and measure the round-trip delay time. On the spacecraft the pulses received from the ground stations are also detected, and their times of arrival are measured in terms of a spacecraft clock in order to determine the difference in arrival times. These measured differences in the arrival time at the spacecraft are then combined with the measured round-trip delays from each ground station and the known time relationship of the emitted laser pulses to the local clock at each station to provide the time differences among the ground station clocks. Thereafter, the spacecraft timing data can be sent to the ground stations by normal telemetry channels and the ground stations can exchange their data via teletype or other terrestrial links. A LASSO instrument package was successfully launched on the Meteosat P2 satellite in June 1988. Initial data are being obtained from one site (CERGA, Grasse, France) and are currently being analysed. Additional sites are expected to participate in the future.

4.1.5 US space shuttle T/F transfer experiments

The intent of these experiments is to demonstrate the feasibility of 1 ns time transfers and 1×10^{-14} frequency comparisons on a global basis. The technique involves the use of high-accuracy, two-way microwave time and data transfer links between the U.S. Space Shuttle vehicle and appropriately equipped ground stations.

During the first German Spacelab Mission (D1) on the U.S. Space Shuttle in November 1985, two atomic clocks (one cesium and one rubidium) were placed in an orbit with a height of 326 km and an inclinition of 57°. These clocks were part of a navigation experiment, NAVEX, which involved a cooperative arrangement among DFVLR (Deutsche Forschungs und Versuchsanstalt für Luft-und-Raumfahrt), PTB, and other organizations [Starker et al., 1987].

Six Shuttle passes per day could be observed from the ground control station at DFVLR Oberpfaffenhofen. During these passes time comparisons were performed between the Cs-clock on board and two other Cs-clocks on the ground.

The time transfer was implemented by a two-way microwave link at 1.53/1.43 GHz using pseudo-noise code signals, correlation receiver techniques and a spread spectrum data transfer.

After testing the technical and operational main functions of the equipment a comparison of on-board and ground based time-scales was performed in a measurement series lasting 74 hours. During this time the rate between the on-board clock and the ground reference clock was determined with an uncertainty of $\sigma_y \approx 0.16 \cdot 10^{-13}$. The clock readings at different passes showed random fluctuations of $\sigma_x \approx 5.8$ ns. The relativistic frequency shift was determined by comparing the flight measurements with ground measurements before and after the D1-mission [Starker et al., 1988]. The result $\Delta y = -(294.69 \pm 0.15) \cdot 10^{-12}$ agrees with the theoretical value better than 0.5%.

4.1.6 Use of 13-31 GHz allocations made by the WARC-79

The World Administrative Radio Conference, 1979, made the following additional allocations for T/F transfer using satellites:

13.4-14.0 GHz (Earth-to-space);
20.2-21.2 GHz (space-to-Earth);
25.25-27.0 GHz (Earth-to-space);
30.0-31.3 GHz (space-to-Earth).

In each case the T/F allocations are secondary allocations, so that considerable coordination and sharing arrangements would need to be worked out with the primary services and other secondary services to assure that harmful interference is not caused to the other services. However, the wide bandwidth available may make such an effort worthwhile, particularly in the future when extreme time transfer accuracies (< 1 ns) may be needed and are technically feasible.

At present there has been no use of these frequencies for T/F transfer nor are any experiments in the definite planning stage. Cost-effective use will require further development of the technology needed in this frequency range.

4.1.7 *Simultaneous reception of ranging signals*

The proposed technique consists of the sumultaneous reception of ranging signals from appropriate satellite systems at two or more sites and comparing the received phase with local clock outputs. If such measurements are performed at the same time that the ranging signals are used to accurately determine the position of the satellite, the differential propagation path uncertainties can be very low, resulting in very accurate time comparisons of the two clocks.

The world-wide meteorological satellite system that includes the GOES satellites, the European METEOSAT satellites, and the Japanese GMS satellites, offers some opportunities for use of this technique for regional time comparisons. Although the GOES satellite system does not currently include suitable ranging signals., the GMS and METEOSAT systems do use a trilateration ranging technique that includes the transmission of suitable microwave ranging signals several times each day. Other satellite systems may also be available now or in the future which are well suited for this time transfer technique.

One experiment to evaluate such a technique was performed in 1970 by the United States NBS which used ranging signals with the US LES-6 and Tacsat satellites to synchronize clocks in North and South America [Hanson and Hamilton, 1971]. Although the low-resolution of the ranging measurements limited the synchronization accuracies achieved to a few tens of microseconds, the basic feasibility of the technique was established. Studies of this technique made in the Federal Republic of Germany indicate that the use of 2 m dishes with the Meteosat ranging signals that are available every three hours should permit time synchronization accuracies of 30 ns [Nottarp *et al.*, 1979].

The time comparison system using the trilateration ranging signal of GMS-III which covers the Asian and Oceanian regions has been developed by Communications Research Laboratory (CRL) of Japan. The first international time comparison experiment via the satellite was made between CRL and National Measurement Laboratory of Australia which also developed their own system, and attained the direct link of time comparison between Japan and Australia. The precision of time comparison is 20 ns and the frequency stability is 2×10^{-13} for averaging time of 1 day [MORIKAWA et al., 1986]. The Republic of Korea Standards Research Institute and Shanghai Observatory of the People's Republic of China also take part in the GMS time comparison project.

4.2 Alternatives primarily for general T/F dissemination

4.2.1 Time signals from meteorological satellites

Four geostationary satellites are currently operating to observe weather and environmental conditions on a world-wide basis: the two American GOES satellites located over the USA at 75° at 135° W longitude, the European Meteosat satellite located at 0° longitude; and the Japanese GMS satellite at 140° E longitude. The two GOES satellites are the only ones to include the time code capability described below, but, owing to their similarity with the other two, it might also be possible to include this capability in the European and Japanese spacecrafts at some point in the future. During normal operation of the GOES system a 100 bit/s data interrogation message is transmitted continuously from the GOES master control station at Wallops Island, Virginia, through the two operating US satellites to numerous data collection platforms. This data interrogation message is down-linked to the platforms on two frequencies near 468 MHz and contains an interleaved time code provided by and referenced to the National Institute of Standards and Technology [Hanson et al., 1979]. The time code contains year, day-of-year, hour, minute, and second information as well as satellite position data that are updated each one minute. The code also contains indicators for leap years, leap seconds, daylight saving time, and current system accuracy performance. Commercial receiving equipment is available which either simply decodes and displays the time-of-day information with an accuracy of ± 10 ms (± 1 ms if the user applies correction for his location on the earth to the received data) or which decodes the satellite position data automatically, computes the signal path delay, and adjusts the output 1 pulse/s signal accordingly to be "on-time" to within approximately 100 μs. The timing signals from the satellites are derived from atomic frequency standards maintained by NIST at the Wallops Island facility [Beehler et al., 1979].

The time code as described has been transmitted via the two US GOES satellites since 1974. As replacement satellites are added to the system, it is anticipated that all future US GOES satellites will continue to transmit this code. Experience during this period indicates that:

- the time code as transmitted can be maintained indefinitely within 10 μs of UTC (NIST); and
- the time code as received (when corrected for path delay) generally shows variations of a few tens of microseconds over a day and < 100 μs over all longer periods, except for occasional larger variations due to poor-quality satellite orbital elements used to generate position predictions [Beehler, 1982].

Extensive use of the GOES time code is being made in the western hemisphere for control and monitoring of events in electric power networks, correlation of recorded observations in seismic and other scientific data monitoring networks, synchronization of communication systems, phase measurements within electric power networks, and general clock calibrations.

4.2.2 *Use of 400.1 MHz transponders on satellites-of-opportunity*

The World Administrative Radio Conference for Space Telecommunications, Geneva, (1971) allocated the frequency of 400.1 ± 0.05 MHz for exclusive use for T/F dissemination by satellite. Many general timing needs for only modest accuracy levels could be efficiently satisfied by one-way time signal transmissions via a 400.1 MHz transponder added on to one or more satellites-of-opportunity. With the ± 25 kHz usable bandwidth allocated, there would be considerable flexibility in designing the timing signal. One could, of course, include voice announcements, ticks, tones, and time codes just as is done now on the HF services. On the other hand, it would also be possible to include some type of low-level, PRN code that could be optionally decoded at higher user cost to provide much higher accuracy, perhaps at the submicrosecond level. Since the satellite timing signal is inherently international in scope, one might also consider transmitting only a simple time code via the satellite transponder which could then be easily interfaced in the user's receiver to solid-state "talking chips" with digital voice storage to create locally the voice time announcement in any desired language. The development and implementation of such services might allow the gradual phasing out of many of the present terrestrial HF timing services and a potential solution to the current HF interference problems.

Although no experimentation in time dissemination using this specific frequency has taken place, the feasibility of providing such a satellite service for general T/F users has been shown previously. In August 1973, the National Bureau of Standards completed a two-year experimental one-way broadcast of a WWV type format via the ATS-3 satellite [Hanson and Hamilton, 1974]. Even with the relatively low 135 MHz space-to-Earth frequency used, time transfer accuracies of 25 μs were achieved for the one-way mode. Propagation delays could be computed to this level of accuracy by using a simple special-purpose slide rule developed for this purpose. The experiment successfully demonstrated that such results can be obtained consistently by relatively unskilled personnel after training of a few hours. As compared to using HF broadcasts, reception of the satellite signals proved far more reliable and required only simple receiving techniques and equipment of comparable cost and complexity. In spite of the fact that the ATS-3 time signals were experimental in nature and limited to two 15-minute periods per day, interest in the technique was evidenced by the thousands of requests for information which were received by the NBS.

At present there are no known plans for using the 400.1 MHz allocation.

4.2.3 *Special opportunities with communication satellites*

The direct approach of using leased channels on communication satellites to transmit timing signals has previously been discussed in connection with the high-accuracy, point-to-point alternatives, where the large available bandwidth is a necessity for highest performance. However, in special circumstances there may be other ways in which these versatile satellites can be used viably for general T/F dissemination. One suggestion that has been made is to use the VHF transponders on such satellites for time dissemination. These transponders are used mainly during initial orbit insertion manœuvres and thus may be available for other ancillary applications once the satellite is well established in its operational orbit.

The Istituto Elettrotecnico Nazionale (IEN) used such a transponder on the experimental telecommunication satellite Sirio-1, with its VHF-transponder operating at 136 MHz [Detoma *et al.*, 1981]. The experiment included also the use of the SHF transponder operating at an up-link frequency of 17 GHz and a down-link frequency of 14 GHz. The tests were performed using a coded time signal [Detoma *et al.*, 1983]. The bandwidth available in both cases (VHF and SHF) was of a few kilohertz. The standard deviation in the VHF-experiment was 1.5 ms and in the SHF experiment 30 μs.

During 1977-79 India was able to take advantage of the availability of the Symphonie-I satellite to conduct time dissemination experiments. The types of information disseminated and the associated measured standard deviations included:

- a standard HF broadcast format similar to that of ATA, 50 ns;
- time code; and
- time signals on direct television broadcasts, 70 ns. In the television case an accuracy of 0.25 μs was confirmed.

In one specific case (India) an arrangement has been worked out for possible access by NPL to a portion of the communications spectrum on the Insat Indian national communications satellite for the specific purpose of time dissemination on an operational basis. A 10 kHz channel may be made available on the S-band (approx. 2 GHz) frequency channel and planning is under way to provide a complete timing signal, including position information on the satellite for one-way path delay correction by users.

4.3 *Alternatives useful for both high-accuracy and general dissemination*

4.3.1 *TRANSIT navigation system*

The US TRANSIT navigation system currently employs seven operational, polar-orbiting satellites which continuously transmit navigation/timing signals on the dual frequencies of 150 and 400 MHz. Timing referenced to the US Naval Observatory can be extracted from fiducial timing markers transmitted each two minutes and by determining the propagation path delay from the satellite ephemeris information included in the TRANSIT signal format. Time is derived on the satellite from quartz crystal oscillators which are corrected as necessary from the ground monitoring stations to keep received time within ± 100 μs of UTC (USNO). Commercial receivers are available which can automatically average over selected Transit satellites and over a selected number of satellite passes. With a judicious use of satellite selection and averaging of satellite passes at a given location, general users can have access to a timing reference that normally remains with ± 10 μs of UTC (USNO).

The TRANSIT system is fully operational with seven satellites and should continue to provide service at least until 1997 .. Support is provided by the US Navy which also publishes corrections relating the time of each Transit satellite to UTC (USNO).

Since the TRANSIT system has been operating since 1965, a large amount of experience has been accumulated. One-way reception of the TRANSIT signals has been shown to provide a timing reference that generally remains within ± 20 μs of UTC (USNO), thus providing a highiy useful T/F resource for general dissemination needs [Laidet, 1972; Beehler *et al.*, 1979].

4.3.2 *Television broadcast satellites*

Terrestrial time comparisons, both within local areas and over much longer distances, are conducted routinely in many countries by having two sites simultaneously observe a designated synchronization pulse within the normal television transmission format. When both sites are within common view of a single television transmitter, clock time differences can be measured to accuracies of approximately 100 ns or better, assuming the differential propagation path delay can also be determined. The method is also useful at larger distances where two different television transmitters can be observed that are interconnected in a television network. With the present trend towards developing television broadcast capabilities from dedicated satellites, it may become feasible to apply the same television time synchronization methods for the satellite television case [Kovačević *et al.*, 1979 and 1981]. The satellite television pulses can certainly be received over larger areas and measured against local clocks with high resolution (a few nanoseconds). The accuracy with which two clocks can be compared, however, depends on knowing the differential propagation delay. One interesting idea is to accurately range the television satellite via a few laser ranging stations and then use this information to compute the path delays. Another variation, suggested by the BIH, would use the LASSO technique to calibrate the emission time of the satellite television pulse, which would then be used to transfer time to individual users via one-way reception of the pulse. A third possibility would be to determine the satellite position very accurately via a two-way method applied by a minimum of three ground transmitting stations [Kovačević *et al.*, 1981; Hartl *et al.*, 1983]. Still another approach for using television broadcasting satellites, in this case with emphasis more on general time dissemination, involves encoding time-of-day information into the television signal vertical blanking interval. It can then be received and decoded over wide reception areas with modest accuracy sufficient for many time keeping needs.

A number of experimental television broadcasting satellites are undergoing evaluation and, in a few cases, have also been used for T/F dissemination studies. In Japan preliminary frequency dissemination experiments have been made using the medium-scale broadcasting satellite for experimental purpose (BSE) which uses a down link of 12 GHz and an up link of 14 GHz. The measured short-term stability of the received television sub-carrier frequency was as good as in the terrestrial television broadcasting, for example, $\sigma_y(10\ s) = 3 \times 10^{-11}$. In order to establish a technique for cancelling Doppler shift, tests were made using a phase control servo included in the satellite link or a pre-compensating frequency control using measured values of the orbital data of the satellite. The amount of the residual Doppler shift at the control station can be reduced to the order of 1 part in 10^{12} or less by use of the first and the second methods. The method using the orbit data is expected to give a control capability of a few parts in 10^{11}. Thus, the maximum value of the Doppler shift at the farthermost place of the country, which is about 1500 km distant from the BSE transmitting station, is estimated to be $\pm 2 \times 10^{-10}$ without any correction [Ishida *et al.*, 1979; Saburi *et al.*, 1979].

As a result of further experiments using the BSE, an accuracy of frequency dissemination of 5×10^{-12} (1σ) was obtained at a point about 1000 km distant from the transmitting station when a calculated correction based on the orbital data was applied to the measured value. As another result of those experiments, an accuracy of 0.2 µs (1σ) and a precision of 0.12 µs (1σ) were obtained in the time comparison, carried out for five months, between two caesium clocks, situated about 400 km apart from each other, via the television synchronizing pulse. In an experiment of standard time dissemination which used a time code inserted in the vertical blanking interval, an accuracy of 10 µs was obtained all over the country, when the Doppler correction control was made at the transmitting station [Saburi *et al.*, 1980].

The National Institute of Metrology (NIM) of China used Intelsat-V and the Chinese experimental communication satellite STW-1 during the 1982-1986 period for one-way experiments on standard frequency and time signal dissemination in which the time code and a 1 MHz standard frequency were inserted in line 16 of the vertical blanking intervals of TV signals. A phase lock loop was used with the receiver to increase the signal-to-noise ratio of the receiving signal. A precision of 3 ns was obtained in these experiments. The timing uncertainty was better than 200 ns when a delay time correction was applied. When Doppler correction auto-control was applied at the transmitting station, the frequency dissemination accuracy was better than 3×10^{-12} [Cuiying Xiao, 1987].

From 1980-1983 a time comparison experiment involving VSL, NPL, IEN, DFVLR, TUG and PTB, was carried out in Europe using the television signals relayed on 11.682 GHz by the European experimental communication satellite OTS-2. During a period of one week in October 1983, it was possible to compare time and frequency transfer measurements via OTS-2 and NAVSTAR/GPS between IEN and TUG. The difference of the relative frequency differences obtained by the measurements using OTS-2 and GPS was below 3×10^{-14} and the standard deviation of both types of measurements was below 20 ns [Kirchner et al., 1985].

The OTS-2 measurements have demonstrated that it will be possible to establish high-quality links for time and frequency comparisons using direct-television-broadcasting satellites. For high-accuracy time comparisons it will of course be necessary to calibrate the delays of the receiving equipment [De Jong *et al.*, 1981; De Jong and Kaarls, 1983].

A time synchronization experiment between the time-scales of the Istituto Elettrotecnico Nazionale (IEN) in Turin and other European laboratories (TP, TUG, AOS, ASMW, VSL), based on the television signals received from ECS5 geostationary satellite, has been carried out since July 1988 and is still going on (1989).

The results obtained have shown that an uncertainty ranging from some hundreds of nanoseconds up to one microsecond is achievable over a very large area, provided that the measurements are corrected for the satellite position parameters as determined by an ESA tracking station [Buzěk et al., 1989].

For short distances between the partipating laboratories, standard orbit determination procedures as used for communication satellites, will be sufficient for the computation of the propagation delays. For long baselines, the position of the satellite has to be determined as accurately as possible and this may be done by precise range measurements carried out by the time-keeping laboratories themselves, as demonstrated by measurements such as conducted in Graz which achieved a quality comparable to that of SHF-tracking stations [Kirchner *et al.*, 1984].

4.4 *Comparison of the alternatives*

Table I gives some additional comparative information on the alternatives, including coverage, accuracy capability, some user cost considerations, and indication of whether the alternative is feasible for on-site use as contrasted with the need for auxiliary timing links to off-site receiving facilities, and the status of the system or technique in terms of being available only experimentally or on a longer-term operational basis. Table II summarizes in concise form some of the principal advantages and disadvantages of the various satellite alternatives.

ANNEX I

SATELLITE TIME/FREQUENCY COMPARISONS

Year	Organization and references	Satellite	Technique and description	Stated accuracy (A) or precision (P)
1962	USNO/USA, NPL/UK, RGO/UK [Steele *et al.*, 1964]	Telstar 6390 MHz	Two-way	1 μs (A); satellite link only 20 μs (A); total link
1965	USNO/USA, RRL[1]/Japan [Markowitz *et al.*, 1966]	Relay-II 1723 MHz (up link) 4175 MHz (down link)	Two-way	0.1 μs (A) 0.01 μs (P)
1967	NBS/USA [Gatterer *et al.*, 1968]	ATS-1 136 MHz	One-way	10-60 μs (A)
1967	NBS/USA [Jespersen *et al.*, 1968]	ATS-1 149 MHz (up link) 136 MHz (down link)	Two-way	< 5 μs (A)
1968	NASA/USA [Laios, 1972]	GEOS-2 136 MHz	One-way; spacecraft crystal clock	20 μs (A)
1969	CNES/France [Laidet, 1972]	Transit 400 MHz	One-way; spacecraft crystal clocks	20 μs (A)
1970	NRL/USA [Murray *et al.*, 1971]	US Defense, Communications Satellite X band	Two-way	0.1-0.2 μs (A)
1970	NBS/USA [Hanson and Hamilton, 1971]	Tacsat/LES-6 side-tone ranging signals on 250 MHz carrier	One-way of low-resolution ranging signals	40 μs (A)
1971	NASA/USA [Mazur, 1972]	ATS-3 6212 MHz (up link) 4119 MHz (down link)	Two-way	50-70 ns (A)
1971	NBS/USA [Hanson and Hamilton, 1974]	ATS-3 136 MHz	One-way transmission of WWV signals via satellite transponder	25 μs (A) 10 μs (P)
1974	APL/JHU/USA [Taylor, 1974]	Improved Transit 150 MHz 400 MHz	One-way; spacecraft clock; PRN-coded signal	< 75 ns (A) 10 ns (P)
1974	NASA/USA, FAA/USA [Chi and Byron, 1975]	ATS-1 6301 MHz (up link) 4178 MHz (down link)	Two-way; PRN-coded signal	50 ns (A) 20 ns (P)
1975	NRL/USA, USNO/USA, RGO/UK, DNM/Australia	NTS-1 335 MHz	One-way; spacecraft clock	< 500 ns (A) 50 ns (P)
1975	RRL[1]/Japan, NASA/USA, USNO/USA [Saburi *et al.*, 1976]	ATS-1 6 GHz (up link) 4 GHz (down link)	Two-way with spread-spectrum, random-access communications system	10 ns (A) 1 ns (P)

ANNEX I *(continued)*

Year	Organization and references	Satellite	Technique and description	Stated accuracy (A) or precision (P)
1975	NBS/USA [Beehler *et al.*, 1979]	GOES 468 MHz	One-way	< 100 μs (A)
1976	CNES/France, LPTF/France, PTB/Federal Republic of Germany [Brunet, 1979]	Symphonie 6 GHz (up link) 4 GHz (down link)	Two-way	50 ns (A) < 10 ns (P)
1978	DNM/Australia, NRC/Canada, RGO/UK, BIH, IFAG/Federal Republic of Germany, NASA/USA, NBS/USA, NRL/USA, USNO/USA [Buisson *et al.*, 1978]	NTS-1 NTS-2 335 MHz 1580 MHz	One-way; spacecraft clocks	< 1 μs (A)
1979	NRC/Canada, NBS/USA, USNO/USA, LPTF/France [Costain *et al.*, 1979]	CTS/Hermes Symphonie 4/6 GHz 12/14 GHz	Two-way	50 ns (A) 0.2 ns (P)
1979	NPL/India, PTB/Federal Republic of Germany [Mathur *et al.*, 1980]	Symphonie 4/6 GHz	Two-way	< 100 ns (A) < 10 ns (P)
1979	IEN/Italy [Detoma and Leschiutta, 1980]	Sirio-1 12/17 GHz	Two-way; single, time-shared channel	50-100 ns (A) 1-5 ns (P)
1979	NIM/People's Republic of China, PTB/Federal Republic of Germany	Symphonie	Two-way	< 80 ns (A) < 10 ns (P)
	SO and CSAO/People's Republic of China, LPTF/France	Symphonie	Two-way	< 100 ns (A) < 10 ns (P)
Since 1980	NBS/USA, USNO/USA, BIH/France, LPTF/France, PTB/Federal Republic of Germany, NRL/USA, VSL/Netherlands, TUG/Austria, TAO/Japan, JPL/USA, RRL/Japan(1)	GPS	Common-view	< 100 ns (A) 10-30 ns (P) (20 ns (A) and 1-10 ns (P) has been achieved for 1987)
1980	(1) RRL/Japan [Saburi *et al.*, 1980]	BSE	One-way	5×10^{-12} (1000 km) (A) 0.2 μs (A) 0.12 μs (P)
1978-1982	NRC/Canada, LPTF/France, CNES/France	Symphonie	Two-way	0.5 ns (P)
1980-1982	PTB/Federal Republic of Germany	Symphonie	Two-way	0.5 ns (P)

ANNEX I *(continued)*

Year	Organization and references	Satellite	Technique and description	Stated accuracy (A) or precision (P)
Since 1981	RRL/Japan (1) [Imae *et al.*, 1983]	CS 30/20 GHz	Two-way, 1.3 m-2 m antenna with SSRA Two-way, 1 m-2 m antenna with SSRA	1 ns (P) 13 ns (A) 1 ns (P) 13 ns (A)
1982	VSL/Netherlands, NPL/UK, IEN/Italy, DFVLR, PTB/Federal Republic of Germany, TUG/Austria [De Jong *et al.*, 1981; De Jong and Kaarls, 1983]	OTS-2	One-way	300 ns (A) 20 ns (P)
1982	NIM/ People's Republic of China	Intelsat-V	One-way	2 ns (P) 5×10^{-11} (A)
1983	USNO/USA, COMSAT/USA, DFVLR/Federal Republic of Germany [Hartl, 1983]	Intelsat-V	Two-way	300-500 ps (P)
1984-1986	NIM/ People's Republic of China	STW-1	One-way Two-way with spread-spectrum, random-access communications system	3 ns (P) 200 ns (A) 3×10^{-12} (A) 1 ns (P) 10 ns (A)

Note to Table

(1) RRL: now —— CRL (the Communications Research Laboratory)

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REPORT 576-3

STANDARD-FREQUENCY DISSEMINATION VIA STABILIZED BROADCAST STATION CARRIERS

(Study Programme 4A/7)

(1974–1978–1982–1986)

Many users of the standard-frequency and time-signal service emissions, particularly in the radio and electronic industries, require a frequency reference with only moderate precision. These users are often located in environments with severe electromagnetic interference which can seriously reduce the usefulness of standard frequencies and time signals in allocated and other bands. Moreover, there is a need for simple and inexpensive equipment to perform such frequency comparisons.

The requirements are met in Europe with a number of standard-frequency and time-signal services operating in band 5 and by the stabilization of broadcast station carriers: Allouis, 162 kHz; Donebach, 153 kHz; Droitwich, Westerglen, Burghead, 198 kHz; ——— Motala, 189 kHz and Milan I, 900 kHz. The carriers of these latter stations are derived from atomic frequency standards. For further details of some of these stations, see Report 267.

Due to the propagation characteristics in the LF band and depending on transmitter power, the primary service area can be very large (with a radius of the order of some hundreds of km). In this prime coverage area, frequency comparisons are possible with an uncertainty between 1×10^{-11} and 1×10^{-9}, provided that the measurement is performed during daylight hours and with a sufficiently long measurement period.

Experiments have been carried out in the United States of America in band 6 with the stabilization of a broadcast station carrier at 650 kHz operating with 50 kW carrier power. A frequency comparison uncertainty of 1×10^{-10} was obtained at a distance of 800 km during daylight hours.

In the Federal Republic of Germany about 160 television transmitters are operating in band 9 with the carriers remotely controlled by the use of a standard frequency of 10 MHz supplied via the television programme distribution circuits set up on radio-relay links. An average normalized carrier frequency departure of 3×10^{-12} was observed with a standard deviation of 3×10^{-11} (Report 363). By means of the stabilized carrier, frequency comparisons with an uncertainty of a few parts in 10^{10} are achievable in less than one minute.

In the USSR, standard frequencies are transmitted via stabilized carriers of the sound-broadcasting stations RV-166 (Irkutsk) – 198kHz ——— with a carrier power of 40 kW, and RV-76 (Novosibirsk) – 270 kHz, ——— which use class of emission A3EGN (double sideband, single channel, amplitude-modulated with sound of broadcasting quality (monophonic)).

The emitted signals have a frequency uncertainty of 5×10^{-12}.

The usefulness of stabilizing the carriers of broadcast stations is enhanced by the fact that existing frequency allocations and transmitters are used without degrading their primary purpose. In addition, these stations usually provide a field intensity large enough to ensure a good signal-to-noise ratio.

REPORT 577-3

DISSEMINATION OF TIME SIGNALS AND TIME CODES BY ADDITION OF PHASE MODULATION ON AMPLITUDE-MODULATED SOUND BROADCASTING TRANSMITTERS

(Study Programme 4B/7)

(1974-1978-1982-1990)

Dissemination of time signals, with an accuracy meeting the requirements of many users, can be achieved without increasing the congestion in the bands allocated to standard-frequency and time-signal emissions, by use of existing transmitters designed for other services. In particular, it is possible to superimpose a phase modulation, simultaneously carrying second markers and date information (minute, hour, day, month, year) in coded form, on the conventional amplitude modulation of a sound broadcasting station.

A suitable receiver can operate as a remotely controlled time display, the accuracy of which depends only on the accuracy of the time scale at the emission.

This technique is now operational in France, modulating a sound broadcasting transmitter in band 5 (France Inter transmitter Allouis on 162 kHz with a power of 2 MW).

The coded date information is transmitted by the "slow code" of one bit per second, the complete cycle taking one minute.

The code DCF77 is used with certain peculiarities incorporated (see Report 578 and the Note (2) to Table II of Report 267.

The phase modulation model for time signals is given below:

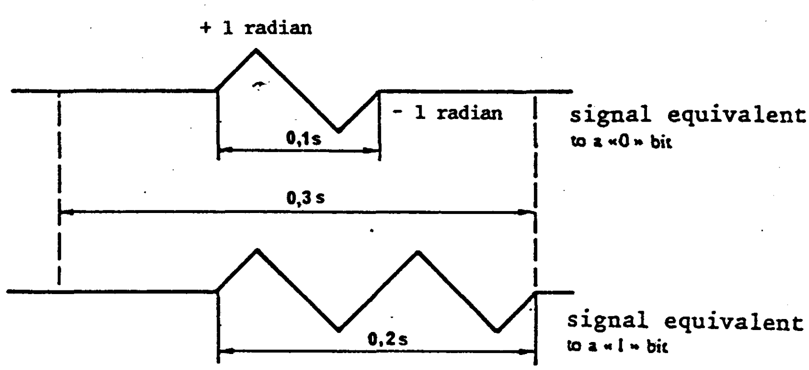


FIGURE 1

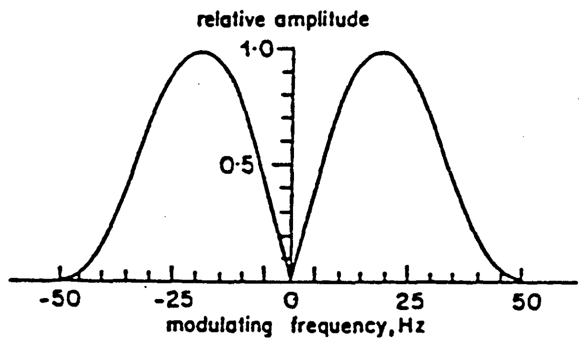
Apart from the 0.3 s used for time code modulation in each second, the phase can also be modulated to transmit other information.

The last second in each minute is free of phase modulation and is used as a minute frame marker.

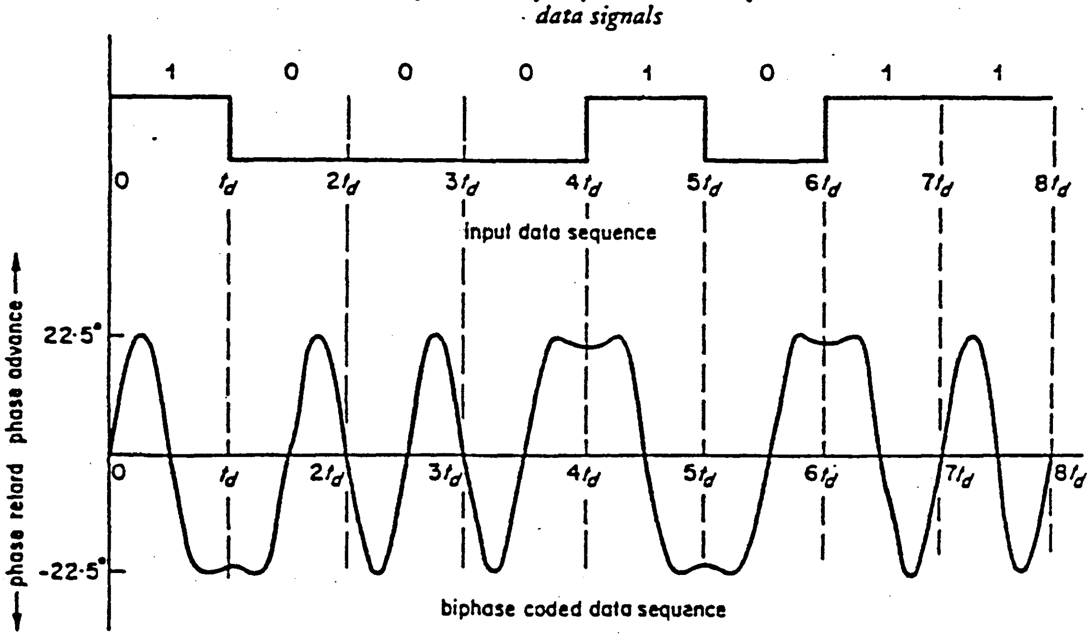
The time signal obtained (on French territory) has an accuracy of 1 ms and a standard deviation of about 0.2 ms.

In the United Kingdom time codes are phase-modulated on the 198 kHz carrier of the BBC Radio 4 transmitters [Wright, 1984] in the data channels established to meet the needs of the United Kingdom electricity supply industry and other potential users. The data rate in this case is 25 bit/s and data transmission is divided into 50-bit blocks each lasting two seconds. The block immediately preceding the minute marker is reserved for the transmission of a time code giving week number, day number, UTC hour, minute and the offset of local time from UTC. The transition to the next block takes place on the minute. Time, and the data clock, are derived from a rubidium standard and maintained in overall agreement with UTC(NPL).

Reflecting the widespread use of 198 kHz as a frequency reference the data are bi-phase (Manchester) encoded; this code has no dc component and therefore there is no net shift of the carrier phase. Figure 2 shows the phase excursions of $\pm$ 22.5 deg during a data sequence and the resulting spectral distribution after suitable shaping filters, with most of the energy falling in the region of the bit rate. This time code is carried by all three Radio 4 stations on 198 kHz, the emitted signals being so timed that they arrive with a time difference of less than a millisecond in the equisignal areas, to ensure error-free decoding.



Spectrum of biphase coded l.f. radio-data signals



Phase of data modulated carrier as a function of time

FIGURE 2

REFERENCE

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REPORT 578-3

TIME CODES

(Question 7/7)

(1974-1978-1982-1990)

Developments in recent years have emphasized the need for the transmission of more complete time information than is provided by the normal second and minute signals as part of the standard-frequency and time-signal services. Requirements for more complete coded time information, which may include the minute, hour and day of the year, arise in various fields – for example, in providing a common time base for geographically widespread monitoring systems making use of the unattended equipment. An increasing number of applications in science, industry and administration is expected and to that end the provision of a time plus calendar reference as part of the Radio Data Systems on general broadcast services (See Report 1061) is foreseen.

In the United Kingdom the British Broadcasting Corporation (BBC) operates four national VHF radio services plus a network of local radio stations. As the first phase of the implementation of RDS in the UK a partial realisation of a full system was introduced in October 1987 covering the transmitters in England and providing a clock time and date code [Shute, 1987]. This takes the form of binary-coded dissemination of time and date based on UTC (Universal Coordinated Time) but with provision for an offset enabling the RDS receiver to indicate an appropriate local time. The data group containing the clock time (CT) is radiated once per minute following the practice already adopted for the similar code provided in the transmissions of the BBC Radio 4 service on 198 kHz.

At each of 48 encoding sites the RDS time is derived from a clock which is referenced to the received MSF 60 kHz signal which, in turn, is maintained in agreement with UTC(NPL). A coherent service of time and time code distribution thus exists at present in England and is being progressively extended to other regions of the UK in a second phase in the period 1988-1989 [Marks, 1988].

Through a joint effort between the various user groups in the United States, a series of time codes was standardized and adopted. These codes became known as serial decimal (SD) and binary coded decimal (BCD) time codes [IRIG, 1987, 1989].

The parallel grouped binary time code, as the name implies, consists of groups of binary numbers, each of which is designated a time unit. The groups of binary numbers are adopted (in preference to a single group) to accommodate not only the SI units of time but also the users' needs for different precisions and accuracies. The PB5 code which is shown in Fig. 1 illustrates this concept.

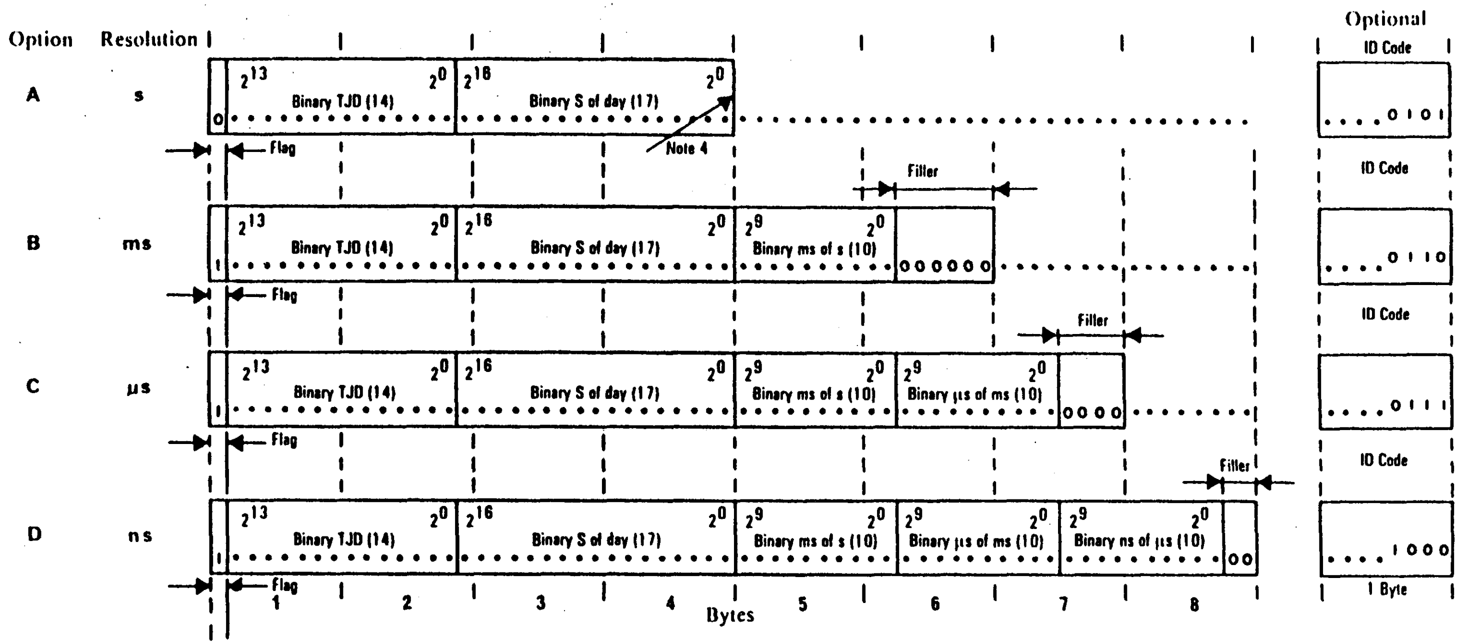

FIGURE 1 – *Parallel grouped binary time code PB5 and resolution options*

Note 1. – Dots represent bit positions.

Note 2. – The number in parenthesis represents bits in each group.

Note 3. – Filler bits may be added to the least significant sub-second group in option B, C, or D, as shown, to maintain integral byte boundaries.

Note 4. – The Truncated Julian Day, (TJD) and second-of-day groups are right-justified to this boundary ; the remaining groups are left-justified to this boundary.

TJD = MJD – 40000 (see Recommendation 457).

Figure 2 shows a typical BCD time code which consists of a time frame comprising a sequence of square waves or pulses. The sequence of pulses is so arranged in a time frame that their positions are used to designate a time unit. Within each time unit or sub-frame, a group of four pulses is used as a counter. The width of each pulse is used to designate a binary state. The four pulses in the sub-frame are given the binary weights of 1, 2, 4 and 8 to code a digit from 0 to 9. Each sub-frame is separated from the other by a sub-frame reference marker and each major frame is separated from the other by a frame reference marker at the end of each major frame.

Standard-frequency and time-signal station WWV was the first to add complete coded time information to its modulation schedule in 1960. Time codes were later extended to transmissions from stations WWVH and WWVB (60 kHz). The time codes on the high-frequency (HF) stations are radiated on a 100 Hz sub-carrier. For WWVB the carrier level is reduced by 10 dB for each binary digit.

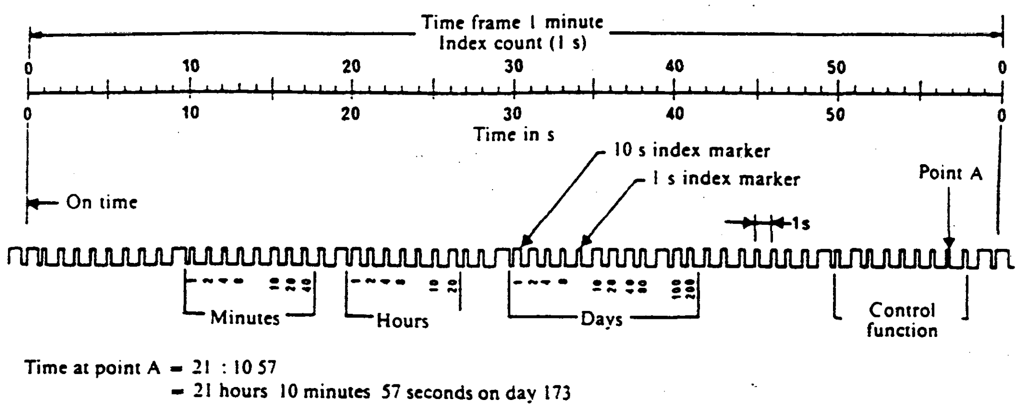

FIGURE 2 – *A typical BCD time code format*

Having regard to new satellite time-transfer techniques, dating requirements on board satellites, space stations, space shuttles and space probes and the corresponding ground requirements, the space agencies Members of the CCSDS recommend the use of binary time codes as defined in CCSDS Document 301-0-B-1 (January 1987).

Three codes are recommended:

- CCSDS UNSEGMENTED TIME CODE (CUC);
- CCSDS DAY SEGMENTED TIME CODE (CDS);
- CCSDS CALENDAR SEGMENTED TIME CODE (CCS).

An 8-bit preamble (P-field) identifies the code and specifies the origin (1 January 1958 0^h or as defined by the space agency) and the resolution (second, millisecond, microsecond, nanosecond or picosecond).

This is followed by the binary time coding (T-field) segmented in 8- or 16-bit words. See Figure 3.

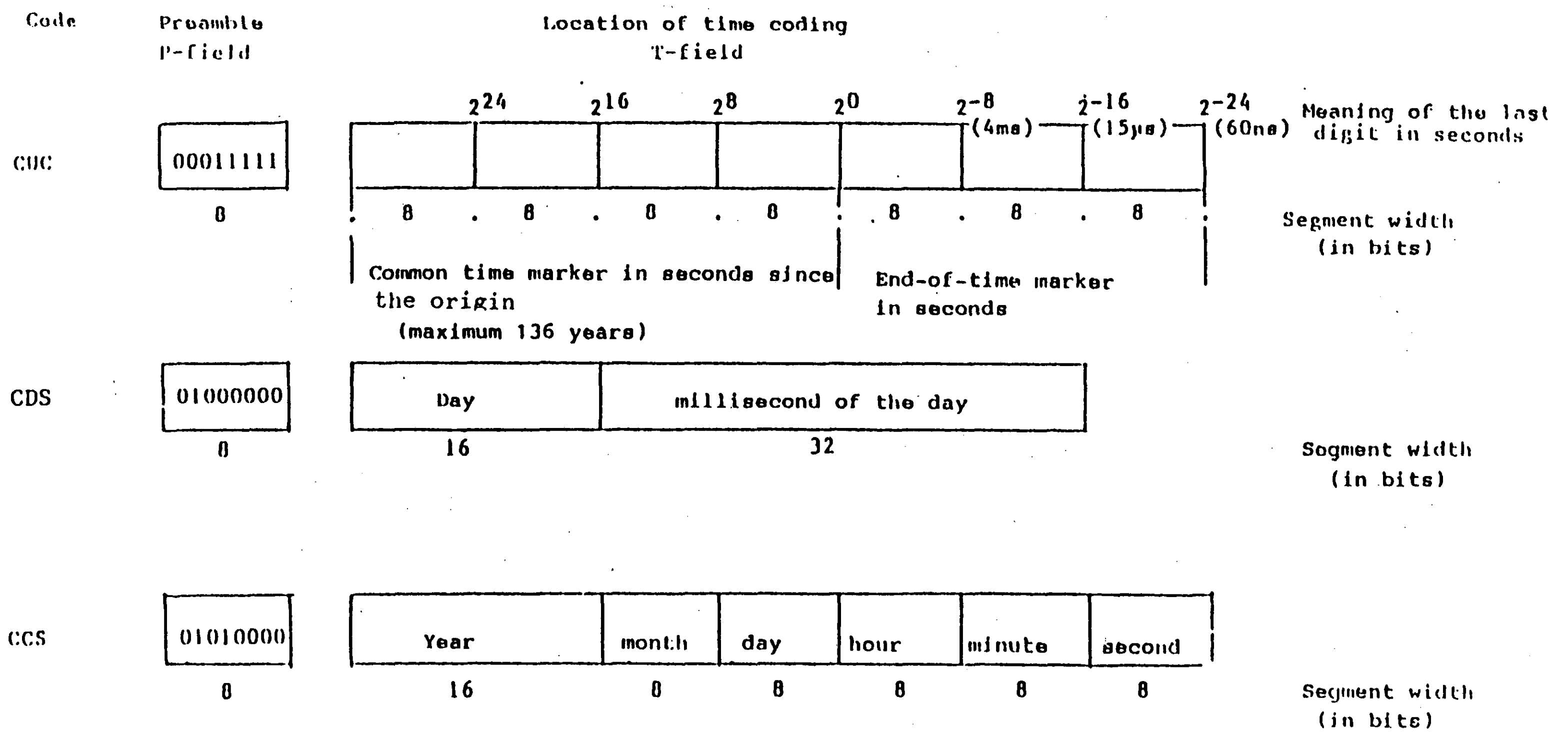

FIGURE 3

Examples of time codes recommended by the CCSDS

An FSK time code is included on the 31st to 39th seconds pulses of CHU, giving the day, hour, minute and second. The FSK 300 Bd system was chosen because of its proven utility in the transmission of commercial data, and the ready availability of commercial equipment. Under severe noise conditions, the decoding has proved much more reliable than equivalent amplitude modulated codes.

Starting with DCF77 in 1973 [Becker and Hetzel, 1973] a number of European stations transmitting standard frequencies and time signals in band 5, have added coded time information to their emissions. Two approaches have been used, depending on the bandwidth available and on the degree of noise immunity in the decoder. For maximum security the so-called "slow code" at a bit-rate of 1 Hz has been adopted, first by DCF77, then by MSF 60 kHz, the complete information thus extending over most of one minute. This coding method is considered to have two essential advantages: the necessary bandwidth is small (less than 30 Hz) and the low transmission rate permits decoding by the use of simple decoders. These features are especially useful for remote and unattended stations. Receiving and decoding equipment for DCF has been described by [Hetzel and Rohbeck, 1974] and for MSF 60 kHz, by [Cross, 1976].

If a larger bandwidth is available at the transmitter, the so-called "fast code" can be employed in which the data rate is chosen to give complete information in about 0.5 s. Such a fast code is transmitted by MSF 60 kHz and OMA 50 kHz. A similar fast code is also broadcast in Italy by RAI on AM and FM networks, about 25 times a day. [Leschiutta and Pettiti, 1979] The code formats in use generally can include information on the second, minute, hour, calendar day, day of the week, month, year, the modified Julian day and, in some cases, DUT1 and an indication if the transmitted time differs from the zonal time. A simple code to distinguish the hours is implemented in the broadcasting stations of the USSR, by a sequential lengthening of the sixth pulse of the standard time signals.

A common feature of the DCF77, MSF 60 kHz and Allouis 162 kHz services is that they all use BCD codes and have the same modulation width for representing binary zeros (0.1 s markers) and binary ones (0.2 s markers). Not all the codes and modulation types are identical: amplitude modulation is used for DCF77 and MSF 60 kHz; and phase modulation for Allouis 162 kHz and the Radio 4 transmitters on 198 kHz (See Report 577). The DCF77 and Allouis 162 kHz codes are similar from the 15th second code to the 59th second code and, in particular, the 17th and 18th second codes indicate whether the broadcast time is UTC or UTC plus 1, 2 or 3 hours [Becker and Hetzel, 1981]. Additional information is given on Allouis 162 kHz concerning the nature of the day, the 14th second code indicating whether it is a public holiday and the 13th second code whether it is the eve of a public holiday. Information is also given on the possible readjustments to UTC - this is indicated by the 1st or 2nd second code during the hour preceding the readjustment. Lastly, the code of seconds 3-6 indicates the number of "1" bits (control sum) to be transmitted per minute [Dubouis, 1986].

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REPORT 731-2

SURVEY OF USERS OF STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS

(Question 1/7)

(1978-1982-1990)

1. Introduction

Report 731-1 (1982) contains extensive information from a 1975 survey of users of the WWV and WWVH services operated by the United States National Institute of Standards and Technology (formerly the National Bureau of Standards) as well as some similar information on services operated by the United Kingdom and the USSR. In 1987-1988 NIST conducted another user survey, expanding the coverage in this case to the WWVB LF and the GOES satellite time code services as well as the HF services. The present revision includes comparisons between the 1975 and 1987 United States results for the HF services, new survey results for the NIST LF and satellite services, and retains the previous contributions from the other administrations.

1.1 High-frequency Services

In 1975 and again in 1987 the U.S. National Institute of Standards and Technology (NIST) (formerly, the National Bureau of Standards) conducted extensive surveys of users of its WWV and WWVH HF time and frequency services. The two surveys produced about 12,000 and 6,000 responses, respectively, to detailed questionnaires that were designed to characterize the users and applications as well as to determine the level of use and satisfaction with the various components of the WWV and WWVH broadcasts. It is important to realize, however, that the two different sets of responses are from two different user populations. They differ not only due to actual changing trends in the use of WWV and WWVH (and HF services in general) but also because the questionnaire distribution channels were significantly different for the two surveys. As a result, some caution should be exercised in drawing conclusions from comparisons of the two surveys.

The following information summarizes the results from the two NIST surveys and also includes related results from surveys conducted in the United Kingdom, the USSR, and Italy.

In 1977 the Main Metrological Centre of the Time and Frequency Service of the USSR carried out a survey by questionnaire among the users of standard frequency and time signals to collect information on the use by the existing radio stations of LF, MF and HF bands and on the requirements of the users with regard to accuracy and to the technical and information characteristics of signals.

In 1979-1980, in one of its periodic surveys, the National Physical Laboratory (NPL) conducted an inquiry of the users of MSF services, with specific reference to the HF emissions. A similar survey was carried out in Italy in the same period in order to learn the needs of users and in connection with the introduction of a time code via the broadcasting stations.

1.2 Characterization of the Users and Applications

Participants in the 1975 and 1987 NIST surveys were asked to characterize themselves into one or more categories of users and into one or more categories of applications. A summary of the results for each survey are shown in Figures 1-4. Even though twice as many responses were received for the earlier survey, the data for each category are shown as a percent of total responses received so that comparisons can be made over the twelve year intervening period. The difference between the total number of responses received in the two surveys (12,000 in 1975 and 6,000 in 1987) is thought to reflect primarily differences in the questionnaire distribution channels employed rather than an actual significant change in the number of WWV and WWVH users. In the earlier survey the questionnaire was announced and/or published in many more publications than in the 1987 case, thus stimulating many more responses. In both cases, however, the publications which did choose to publicize the survey and encourage reader participation tended to be weighted toward those appealing to amateur radio enthusiasts, which in turn helped to produce the relatively large number of responses in categories related to amateur radio.

A more detailed analysis of the results indicates that the "Other" user category in 1975 was made up largely of amateur radio operators, since there was no explicit "Amateur radio" category provided on the questionnaire. This result, together with the results in the more explicit 1975 Applications and 1987 User Categories, confirm that radio amateurs are the single largest user group for the WWV and WWVH services. Other significant user groupings in both surveys include boaters; communications systems, including radio and TV operations; standards labs; civilian and military government; aviation/aerospace; universities; equipment manufacturing; and scientific data monitoring. Although the user categories offered on the 1975 and 1987 questionnaires were not exactly the same, it appears that the "typical" user of the WWV and WWVH services has not changed appreciably during the intervening period.

The "Application" category results shown in Figures 3 and 4 further support the importance of these services in applications of interest to amateur radio operators and indicate that the most widely used application for such HF services is "Watch/clock setting". Among the others it is interesting to note that more than 10% of the 1987 survey participants indicated "Time base for Computers" as an important application. Based on this result along with other independent information, NIST initiated a new Automated Computer Time Service in March, 1988 which provides an ASCII time code via dial-up telephone links for applications needing direct interfacing of a timing signal to computers and other automated systems.

CLASSIFICATION OF WWV USERS: 1975

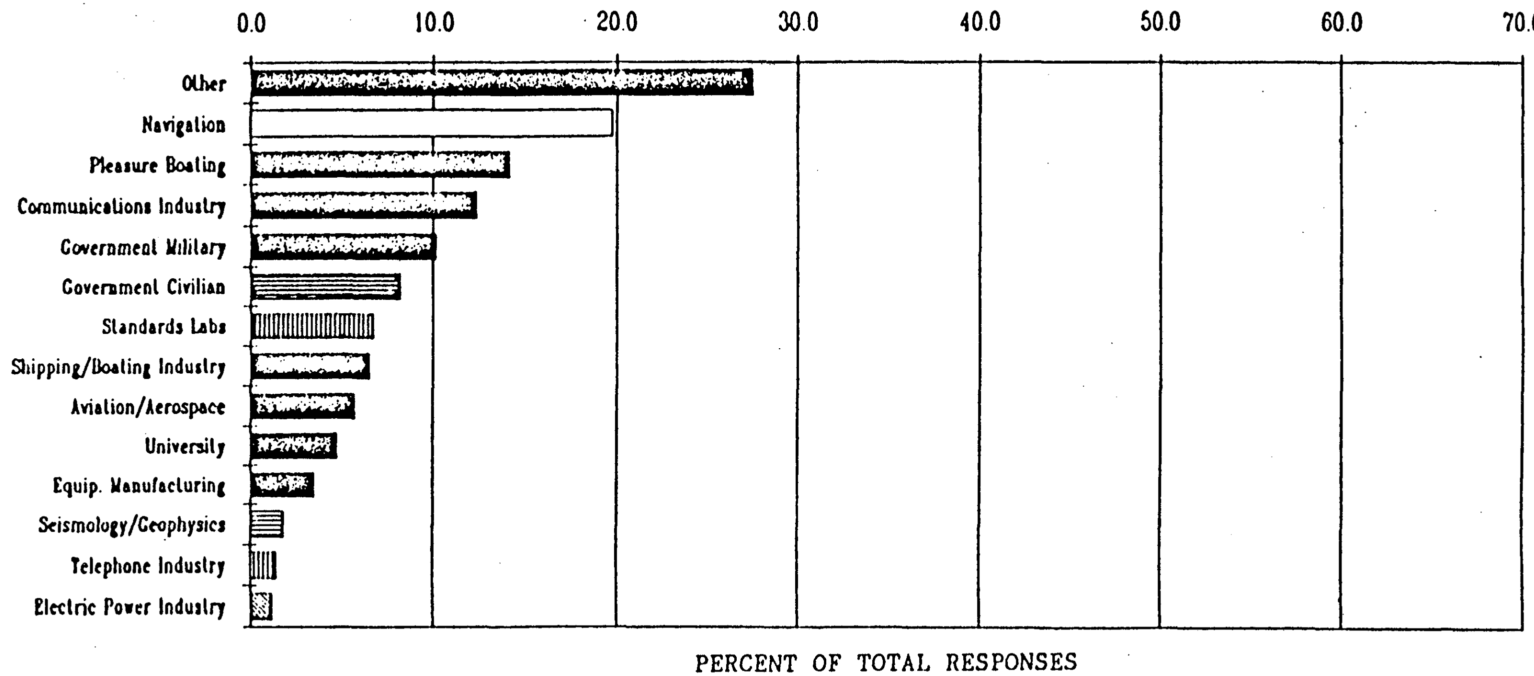


FIGURE 1

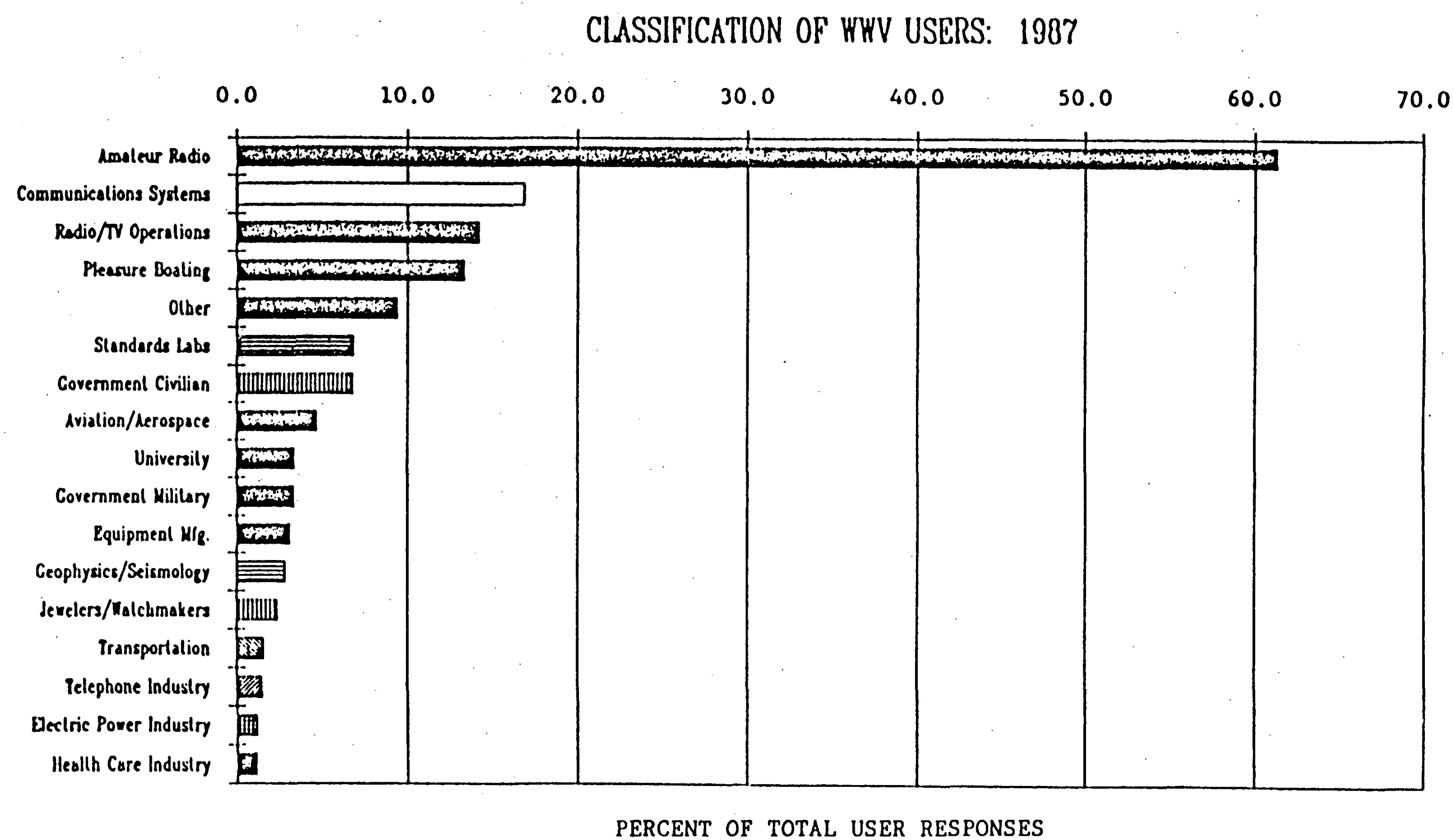

CLASSIFICATION OF WWV USERS: 1987
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
Amateur Radio
Communications Systems
Radio/TV Operations
Pleasure Boating
Other
Standards Labs
Government Civilian
Aviation/Aerospace
University
Government Military
Equipment Mfg.
Geophysics/Seismology
Jewelers/Watchmakers
Transportation
Telephone Industry
Electric Power Industry
Health Care Industry
PERCENT OF TOTAL USER RESPONSES

FIGURE 2

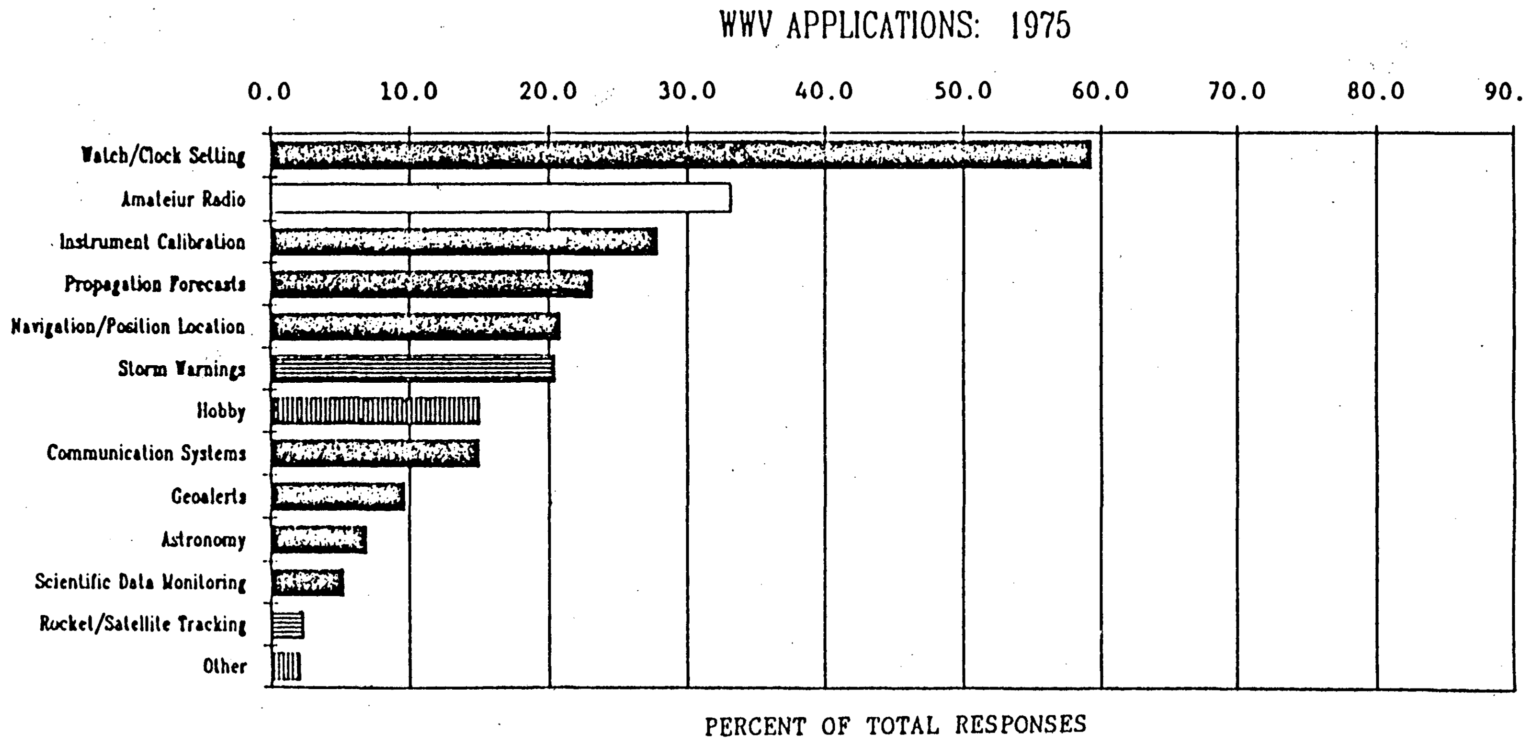

WWV APPLICATIONS: 1975
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
Watch/Clock Setting
Amateiur Radio
Instrument Calibration
Propagation Forecasts
Navigation/Position Location
Storm Warnings
Hobby
Communication Systems
Geoalerts
Astronomy
Scientific Data Monitoring
Rocket/Satellite Tracking
Other
PERCENT OF TOTAL RESPONSES

FIGURE 3

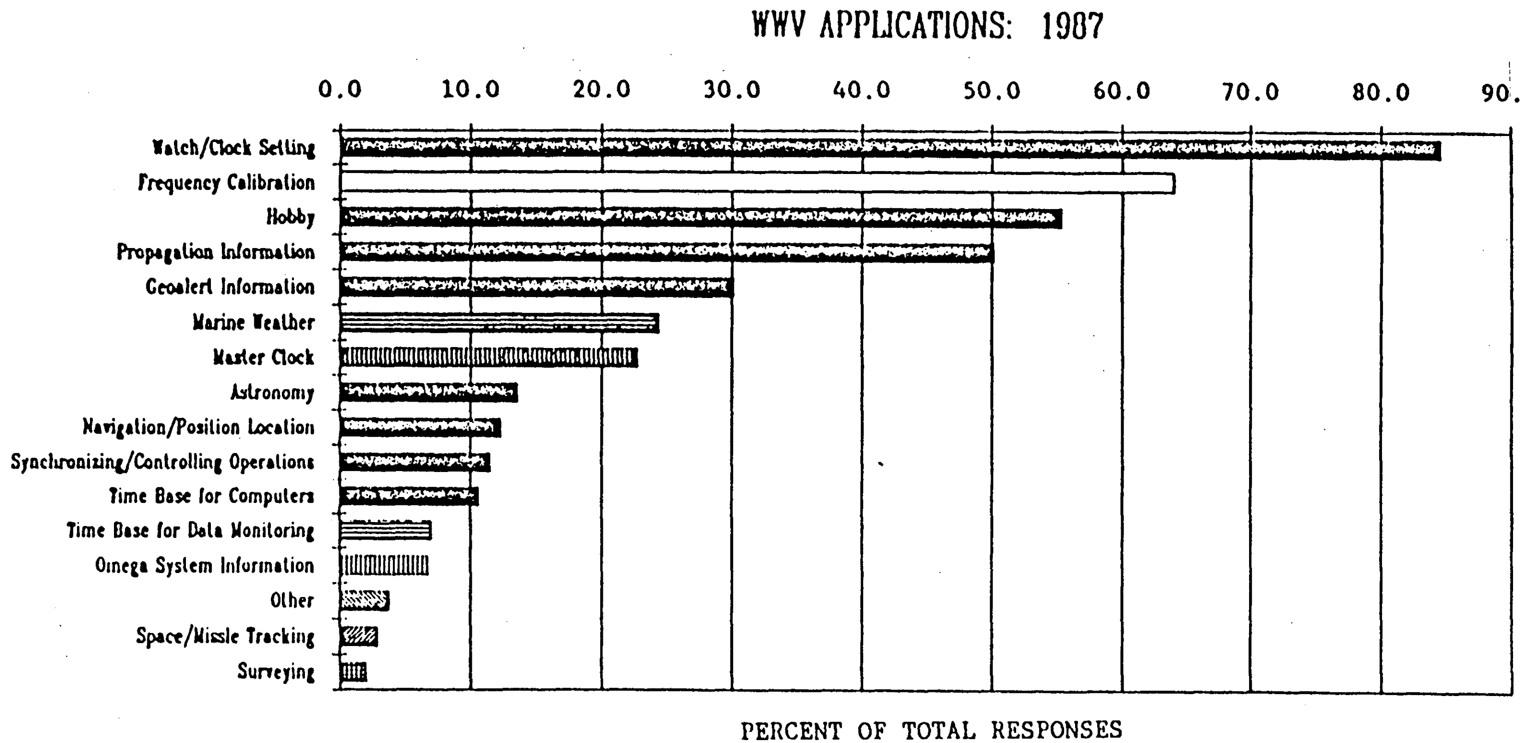

WWV APPLICATIONS: 1987
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
Watch/Clock Setting
Frequency Calibration
Hobby
Propagation Information
Geoalert Information
Marine Weather
Master Clock
Astronomy
Navigation/Position Location
Synchronizing/Controlling Operations
Time Base for Computers
Time Base for Data Monitoring
Omega System Information
Other
Space/Missle Tracking
Surveying
PERCENT OF TOTAL RESPONSES

FIGURE 4

1.3 Relative Use of the Various HF Frequencies

Figure 5 compares the 1975 and 1987 WWV results with respect to which of the transmitted frequencies are most widely used. In the case of 25 MHz results are shown only for 1975, since that frequency was discontinued from WWV shortly after the earlier survey. The scale on the "Relative Use" axis is to be interpreted as follows: "0" = "never use"; "1" = "use rarely"; "2" = "use sometimes"; and "3" - "use frequently". Each plotted result is a weighted average of all responses for that particular frequency.

The 5, 10, and 15 MHz frequencies continue to be used the most. These three transmissions are also higher power (10 kW versus 2.5 kW) than the 2.5 and 20 MHz frequencies. For each of the five frequencies available both in 1975 and 1987, the weighted-use result is lower in 1987 than in 1975.

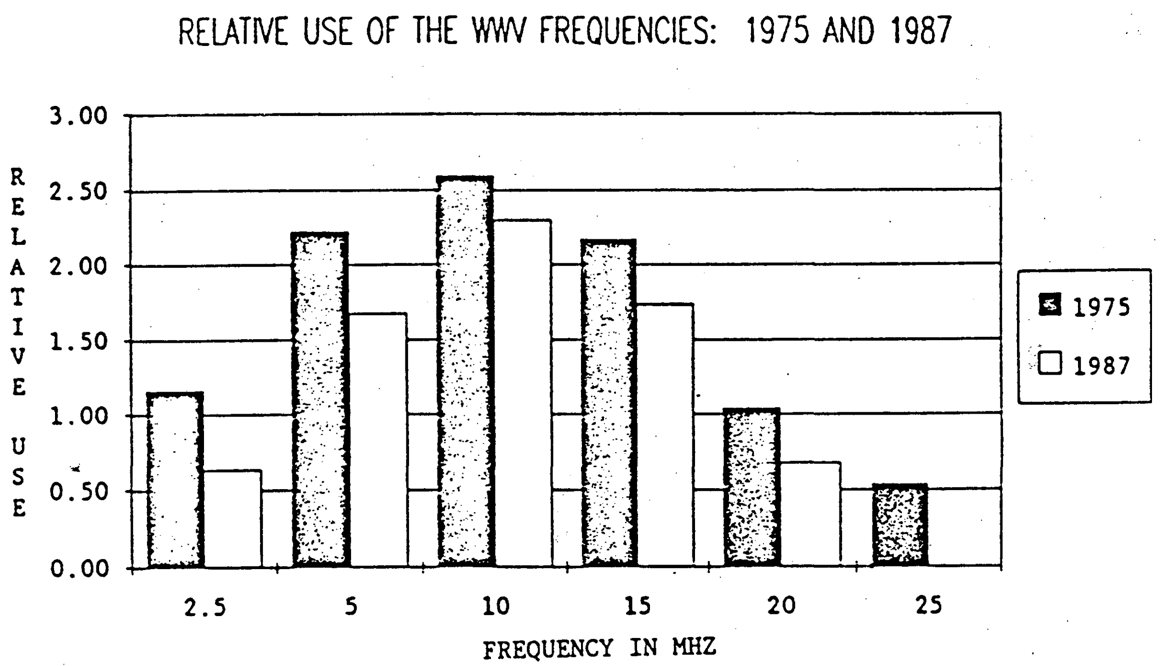


FIGURE 5

Figure 6 shows the relative use of standard signal carrier frequencies of USSR radio stations operating in the bands 2.5, 5, 10 and 15 MHz. Over 70% of standard signal users receive signals where the carrier frequencies are offset by ± 4 kHz from the standard values.

In the United Kingdom survey, only 21% of the total replies received indicated any use of the HF service. It was clear that within the United Kingdom many alternative sources of time/frequency reference were available, either from other HF stations or from the several LF broadcasts, e.g. MSF itself on 60 kHz, DCF77 and HBG. As the results of this most recent survey confirmed that the MSF HF service had only a secondary role to play in the dissemination of a time and frequency reference within the United Kingdom and adjacent sea areas, the service was later discontinued. The main burden for this purpose is now carried by MSF emissions on 60 kHz which provides greater accuracy and reliability, relative freedom from propagation effects and carries a time code designed for automatic date and time indication.

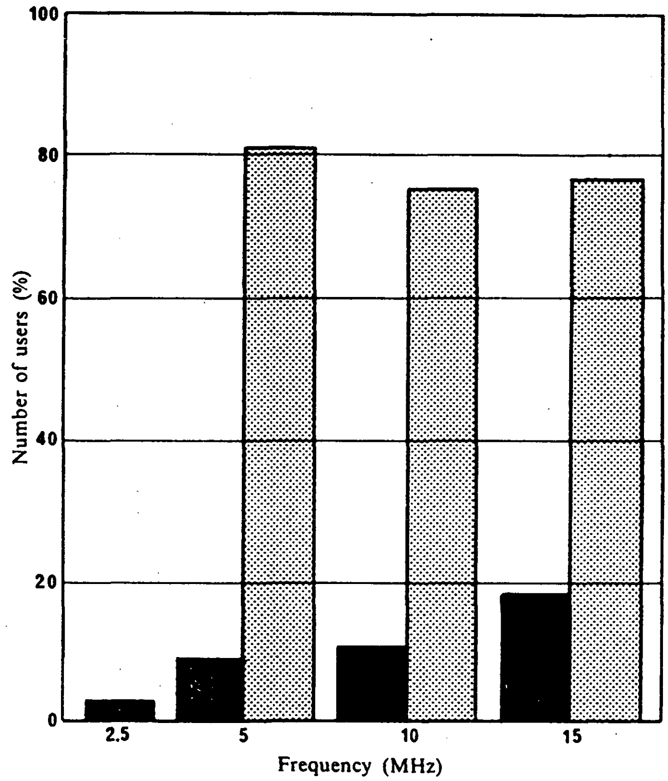
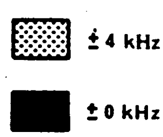


FIGURE 6 – *Use of frequencies according to USSR survey*

(The list of the USSR transmitters is contained in Report 267, Table I)



1.4 Relative Importance of Types of Broadcast Information

WWV and WWVH broadcasts include the following types of information: voice time-of-day announcements (once per minute), a BCD time code on a 100 Hz subcarrier, 1-second "ticks" for precise time intervals, standard frequencies, DUTI corrections, marine weather advisories, Omega Navigation System status reports (after 1975 only), and geoalert reports (WWV only). In addition, at the time of the 1975 survey explicit radio propagation information was included on WWV. This information, in part, is now integrated into the geoalert announcements. Figure 7 summarizes and compares survey responses for 1975 and 1987 with respect to the relative importance users regard the various types of information broadcast on the NIST HF services.

RELATIVE IMPORTANCE OF TYPES OF INFORMATION

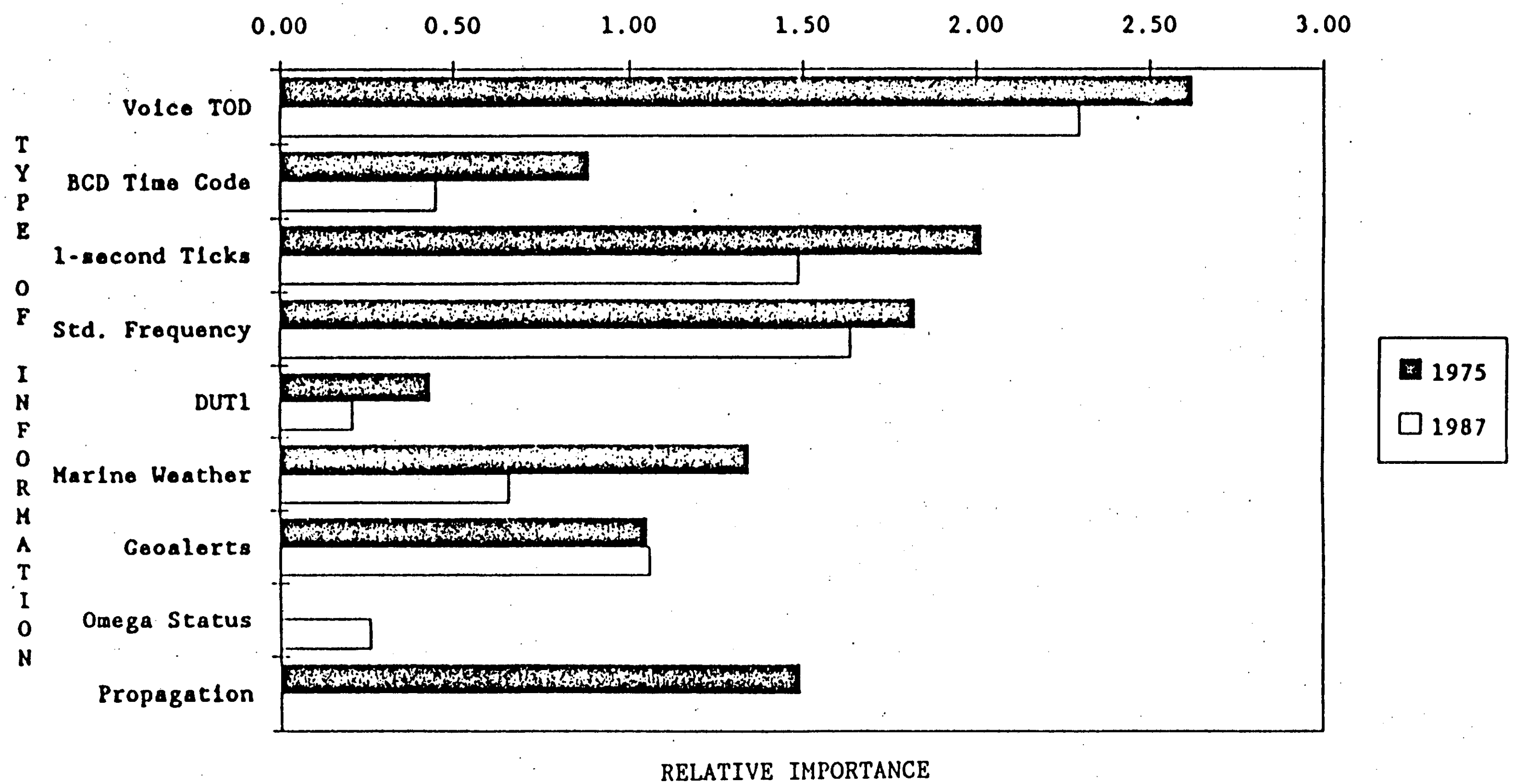


FIGURE 7

The results are plotted on a "Relative Importance" scale where the numbers have the following meaning: "0" = "not important"; "1" = "marginally important"; "2" = "important"; and "3" = "very important". Each plotted value is a weighted average of all responses for that particular type of information on the broadcast. The most important aspects of these services continue to be the voice time-of-day announcements, the 1-second "ticks", and the standard frequencies in that order. The least important aspects appear to be the DUTI corrections and the Omega System Status announcements. It is interesting to note that even though the survey participants rated the BCD time code as only "marginally important" on the average, more than 50 million U.S. residents are served by accurate telephone time-of-day services that maintain their accuracy by receiving the WWV BCD time code. Once again, with the exception of the geoalerts, users in 1987 seem to view each of the types of information as being of somewhat lesser importance than users in 1975.

In the USSR, 75% of users employ the standard frequency and time signals emitted by radio stations for frequency measurements. The LF signals are the most popular in this respect. The measurement accuracy required by users can be divided into three classes: low (measurement uncertainty $\sigma > 10^{-7}$), medium ($10^{-7} \geqslant \sigma > 10^{-10}$) and high ($\sigma \leqslant 10^{-10}$) accuracy. The low and medium accuracy classes account for more than 90% of users. About 50% of the users of standard signals employ them to measure time. The degree of accuracy required by users can be divided into three classes as follows: low ($\Delta t > 0.1$ s), medium ($0.1\text{ s} \geqslant \Delta t > 0.01$ ms) and high ($\Delta t \leqslant 10$ µs). The overwhelming majority of users (more than 90%) require an accuracy of 1 s to 0.1 ms. The most popular time signals are those emitted by HF radio stations RWM and RID. Among all the users of standard signals to synchronize time scales, 60% need the UT1 time scale and therefore use UT1 – UTC information. 80% of the latter additionally use DUT1 information. In order to receive information on the differences between UT1 – UTC scales, more than 90% of users employ the position code while the Morse code is preferred by fewer than 10%. For this reason, in 1978 UT1 – UTC information broadcasts in Morse code were discontinued in the USSR.

In Italy the survey showed a marked interest in the complete time code that is provided, one particular requirement for general users being the day-of-the-week information.

1.5 Accuracy Adequacy, Reception Reliability, and Harmful Interference

The questionnaires also included questions related to other miscellaneous aspects of the WWV and WWVH HF services. In spite of the limitations of HF services, the delivered accuracy is judged to be "adequate" by 89% of all users in 1987 as compared to more than 95% in 1975. About 88% of WWV users and 75% of WWVH users report generally adequate reception, particularly on the 5, 10, and 15 MHz frequencies. Similar results were obtained in the 1975 survey.

About 35% of WWV users and 32% of WWVH users in 1987 reported experiencing harmful interference at least some of the time, and about 10% of all users report frequent interference problems. The 10% figure is fairly comparable to the 1975 results, so the interference environment does not appear to be obviously deteriorating.

2. Low-frequency Services

The 1987 user survey conducted by NIST included several questions designed to assess the use and importance of the NIST 60 kHz service from WWVB. Questionnaires were publicized and distributed by using announcements in the technical and trade press, NIST mailing lists, and mailing lists provided with the cooperation of interested standards organizations and equipment manufacturers. About 900 responders indicated at least some use of WWVB.

Since a high percentage (about 80%) of WWVB users also report being WWV/WWVH users, it is difficult to use the survey results alone to characterize the principal WWVB user and application categories. However, it is possible to conclude, considering all available evidence, that the major user groups include standards labs, radio and TV operations, scientific data monitoring, and the electric power industry.

The WWVB format consists of the stabilized 60 kHz carrier, useful for frequency and phase comparisons and a complete time-of-year code. About 73% of the responders consider WWVB's frequency measurement capabilities as "important" or "very important", while about 45% rate WWVB's time code in one of these categories.

More than 70% of WWVB users reported its accuracy capabilities and reception reliability to be at least "generally adequate". About one-third of the users experience harmful interference "sometimes" or "frequently".

3. GOES Satellite Time Code

NIST has disseminated a satellite-based time code using the GOES (Geostationary Operational Environment Satellite) system since 1974. The 1987 NIST user survey included several questions about this dissemination activity. About 370 survey participants reported using the GOES time code. From the survey results and other sources of information about use of GOES, major user categories include standards labs, electric power companies, the communications industry, scientific data monitoring, and various government activities.

Users report that GOES accuracy and reception reliability are adequate or generally adequate in all but about 5% of the cases. In view of the potential interference between the GOES time code and certain land-mobile frequency channels that share the same allocations, users were asked about their interference environment. Although 24% of users reported harmful interference sometimes or frequently, only about 15% felt that this hindered their use of the GOES signals significantly. About 42% of users report using the time code at its full 100 microsecond accuracy capability (by using receivers that automatically correct for the path delay variations) while the remaining 58% of users are apparently satisfied with the approximately 1 millisecond accuracy capability available from GOES without processing the satellite position information provided in the signal format.

At times of satellite maneuvers it is sometimes possible for time code errors to occur that exceed the normal 100 microsecond level for periods of several hours until updated satellite position information becomes available to NIST from the satellite operators. Only about 12% of users felt that these occasional larger-than-normal time code deviations were a significant problem.

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CCIR Documents

[1978-82]: 7/111 (United Kingdom); 7/130 (Italy).

REPORT 732-3

PROPOSED REDUCTION OF MUTUAL INTERFERENCE BETWEEN STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS IN BANDS 6 AND 7

(Study Programme 1A/7)

(1978-1982-1986-1990)

1. Operational procedures

This Report is based partly on the conclusions of Interim Working Party 7/3 which was set up to consider means of reducing mutual interference in the standard-frequency and time-signal services. It distinguishes the following procedures to help alleviate the problems of mutual interference.

1.1 *Time sharing (time multiplexing)*

This provides a practical, if partial, remedy for mutual interference. It requires no change in receiving arrangements beyond a knowledge of the station schedules, if it is required to correct for propagation delay. In an ideal situation time sharing could be applied world-wide to embrace a number of multiplexed transmissions, operating compatibly. Such a system was conceived some 20 years ago by the then Chairman of Study Group 7 as a means of alleviating the problems of mutual interference between WWV, then radiating from Beltsville, Maryland, and several European standard-frequency and time-signal (SFTS) transmitters.

Time-sharing continues to be applied in a geographically small area of Western Europe and applies to the transmissions of IAM, IBF ~~   ~~ and OMA (modulation only) on 2.5 MHz. While accepting the usefulness of such local arrangements, this approach is not seen as the major solution to the present difficulties. Due to diurnal and seasonal variations in propagation it is not possible to guarantee continuity of reception on any one frequency and this must be considered a serious disadvantage of this system for some users. There is also the difficulty that the access time for the desired transmission is increased and problems may arise in identifying the signals of different stations.

An alternative approach to time multiplexing making use of a shorter cycle of alternation, can be envisaged in which, for example, six potentially interfering stations are each allocated successive and unique 10 second segments in each minute for their sole operation without interference from the other five. Such a system would, of course, require coordination between the participating stations but this should not be difficult to achieve since all stations adhere to UTC to within 1 ms.

An extension of the concept of time-sharing was also considered in which two potentially interfering stations would transmit carrier continuously but suppress, respectively, odd and even pulses, thereby enabling their time signals to interlace, but this appears to require somewhat exceptional conditions of continuity and stability of propagation to be effective.

An alternative form of time-sharing is to offset by an appropriate amount the emissions of the second pulses; such a procedure is followed by the station BPM in the People's Republic of China, for the UTC pulses.

1.2 *Audio frequency tone modulation*

This form of modulation, except to the limited extent necessary for station identification, is wasteful of valuable spectrum space and the aim should be its virtual elimination from the SFTS service.

1.3 *Frequency discrimination*

1.3.1 *Pulse sub-carrier*

At present most of the stations in bands 6 and 7 make use of A2X emission to transmit the time signals. Stations such as WWV, WWVH, JJY and others transmit seconds markers on seperate sub-carrier frequencies chosen in accordance with the formula:

$$f_{sc}(n) = 0.2n \qquad \text{kHz} \tag{1}$$

where n is an integer chosen to be $n = 5$ for WWV, $n = 6$ for WWVH and $n = 8$ for JJY.

The use of A2X emission for the time signals makes it relatively simple to separate potentially interfering signals on the same carrier frequency by means of suitable audio filters, although at the expense of increased delay in the receiver.

1.3.2 *Single-sideband (SSB) operation with full carrier*

The merits of SSB operation are evident in militating against the effects of interference while providing some spectrum economy and protection against fading. At the same time, it is understood that administrations might not wish to make the necessary capital investment in existing transmitting stations to convert to SSB operation when a finite term of, say, 15-20 years can be envisaged for the SFTS service in bands 6 and 7.

The same consideration applies to the introduction of more exotic systems of phase or frequency modulation which might allow several stations to co-exist with reduced mutual interference but only at the cost of additional complexity in both transmitters and receivers. To be acceptable, any modification of the existing network of SFTS stations must be simple to implement and require little or no modification of presently available equipment for radiation and reception.

1.3.3 *SSB with full and/or suppressed carrier-frequency offset operations*

This is seen as a hopeful method for the satisfactory co-existence of both present and possible future transmissions in the allocated MF and HF bands. It presupposes that the carrier frequencies are no longer confined to the values 2.5, 5, 10, 15, 20 and 25 MHz but instead may have, in addition to these, the values specified by the formula:

$$f(N) = (X + 4N) \qquad \text{kHz} \tag{2}$$

where X is 2500, 5000, 10 000, 15 000 and 20 000, and N may take the values 0 or ± 1 for $2500 \leqslant X \leqslant 20\,000$.

This technique of carrier offset is already applied successfully in the USSR in the frequency range up to 15 MHz, with N chosen to be either 0 or $\pm$ 1. A plot of the disposition of SFTS stations within the Soviet Union is shown in Fig. 1 with the appropriate frequencies of operation (based on Report 267). Also shown are the locations of stations in other countries which operate simultaneously on at least 3 frequencies (i.e. ATA, BPM, LOL, ——— WWV and WWVH) in the frequency range 2.5 to 15 MHz. The Soviet stations RWM and RID with offsets of plus and minus 4 kHz, respectively, are extremely widely used

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[Cherenkov, 1978] as shown in Report 731 by virtue of the high degree of protection they afford from disturbances by other SFTS stations operating at the centre of the allocated bands. These signals can be received in two ways: either as J2X signals by mixing with a local 5, 10 or 15 MHz carrier followed by linear or non-linear detection and filtering, or in the usual manner as A1X signals on carrier frequencies removed from the standard values.

In view of the considerable advantages of single-sideband operation in solving the problems of regional interference it is appropriate to recommend the consideration of the use of H2X (single-sideband, full carrier) and J2X (single-sideband, suppressed carrier) emissions only with the standard frequency carriers in the assigned bands. In order to simplify its receiver and enhance its noise immunity the upper ($f_{sc}+$) and lower ($f_{sc}-$) values of the sub-carrier frequencies could be chosen according to the following relations:

$$\left.\begin{aligned} f_{sc}+ &= 0.4\,(n + \tfrac{1}{2}) \quad \text{kHz} \\ f_{sc}- &= 0.4\,(n + 1) \quad \text{kHz} \end{aligned}\right| \qquad (3)$$

For H2X emissions the proposed values of n are: $n = 1, 2, \ldots 5$ and for J2X emissions $n = 6, 7, \ldots 11$, e.g., $n = 9$ corresponds to an upper frequency offset of $+3.8$ kHz and a lower offset of -4 kHz (see equation (3)).

1.3.4 *Total bandwidth required for the SFTS service*

In order to embrace the modulation sidebands under the new system of carrier frequency allocation some extension in the total bandwidth available to the SFTS service is required.

At 2.5, 5 and 10 MHz the total bandwidth available should be ± 8 kHz to embrace three possible transmissions, corresponding to values of N of -1, 0 and $+1$. At present the so-called "guard bands" are at ± 5 kHz, except at 2.5 MHz in Region 1 where the frequency limits are only ± 2 kHz.

At 15 and 20 MHz the total bandwidth available should be ± 12 kHz, corresponding to values of N of -2, -1, 0, $+1$ and $+2$. In view of the remote possibility that 25 MHz will be re-activated as part of the SFTS service, it is further proposed that this frequency be relinquished for future operations of the SFTS service.

1.3.5 *Use of the new allocated frequencies*

By decision of the World Administrative Radio Conference (Geneva, 1979) standard frequencies and time signals can be transmitted in three bands at 4, 8 and 16 MHz, in Region 3. This decision could alleviate the mutual interference problem on the other frequencies in Region 3. Station JJY in Japan has started operation on 8 MHz.

1.4 *Nearest neighbour concept*

The frequency plan described in the foregoing paragraphs would allow a number of SFTS emissions to co-exist with minimal mutual interference. How the plan should be implemented and the several frequencies available applied to the best advantage will depend on the relative geographical disposition of potentially interfering stations. It is advocated that when two stations are "nearest neighbours" and are separated by less than 3000 km, then it should be mandatory that there be a frequency difference of at least ± 4 kHz between their respective carrier frequencies: the exact frequency disposition will depend also on the "next nearest neighbour" situation but basically it is a bilateral problem to be resolved between pairs of nearest stations.

By way of illustration, a possible implementation of the proposed frequency plan is considered by reference to Fig. 1. The relative offsets of the stations within the USSR are accepted as the kernel of the plan and the appropriate values of N are indicated. Corresponding values of N for ATA, BPM, LOL, —— WWV and WWVH can be selected in conformity with the frequency plan to minimize the extent of mutual interference, although it should be emphasized that the examples below are not intended in any way to preempt the interests of administrations in arriving at suitable choices of N in bi-lateral or tri-lateral discussions.

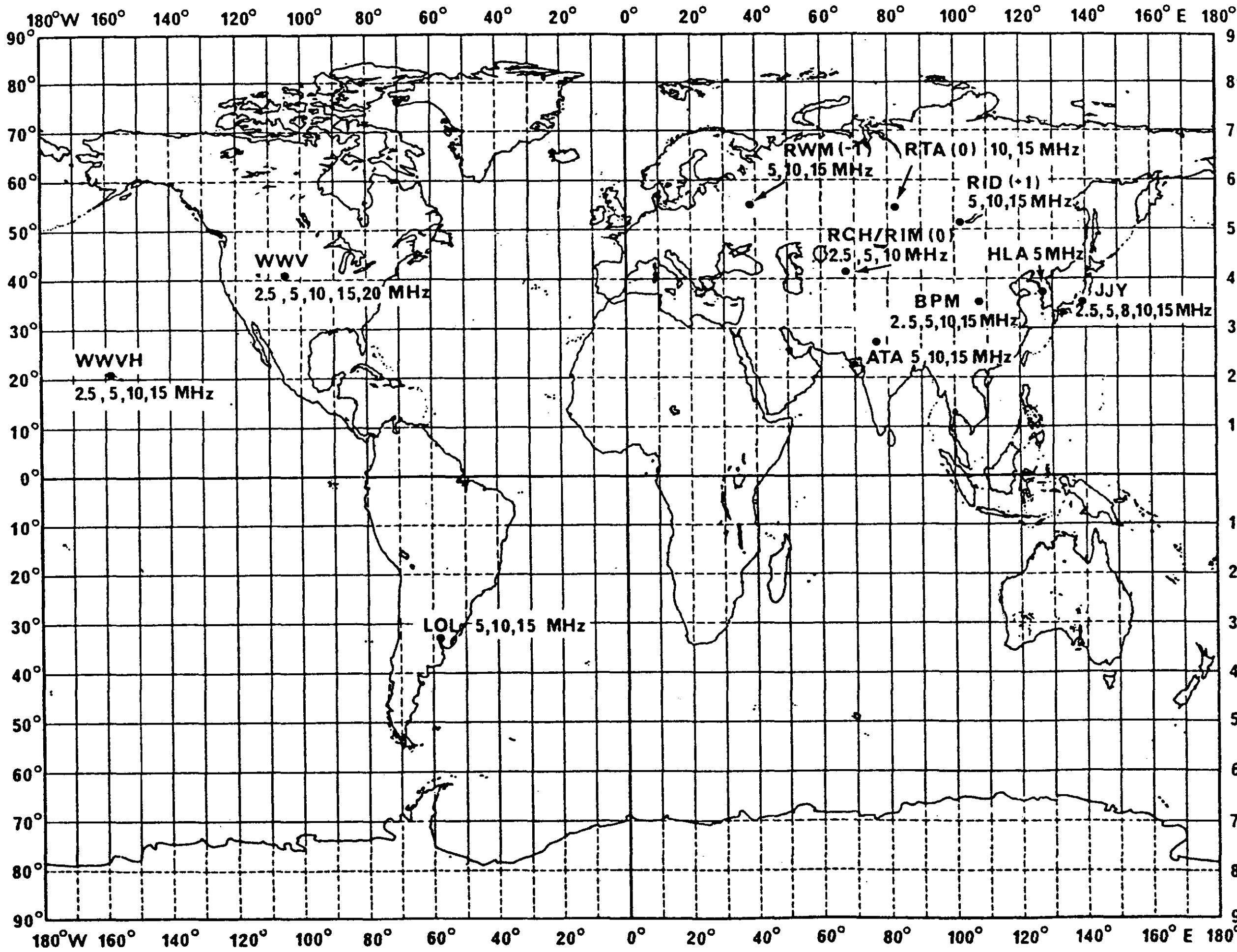

FIGURE 1 – *Carrier frequency offsets of standard-frequency and time-signal stations*

Turning attention to the Western Pacific, it is evident that there is severe conflict between the transmissions of BPM, JJY and WWVH on 2.5, 5, 10 and 15 MHz. This could be much reduced if JJY were to operate with $N = -1$ bearing in mind that RID, Irkutsk has $N = +1$. An alternative would be for WWVH to accept $N = +1$; JJY, $N = 0$; and BPM, $N = -1$. A more thorough recasting of the world-wide operation of these "base" stations operating on at least two frequencies would be possible with some re-allocation of the N values within the USSR. From Fig. 1 it appears that an interchange of the N values for RTA and RID would be advantageous and would conform, moreover, with the "nearest neighbour" principle involving station RCH/RIM, Tashkent. Such a change would also allow a larger frequency difference to be adopted between BPM and JJY which are in relatively close proximity, with $N = -1$ for BPM and $N = +1$ for JJY. In the Americas station LOL is sufficiently remote from WWV and other transmitters that it could continue with $N = 0$ although the proposed system could also be exploited here by choosing $N = \pm 1$ for LOL.

It will be seen that the implementation of the proposed frequency plan is to a large extent self-determining and that once a value of N is selected for a given station it is not readily changed without affecting other parts of the SFTS network. Nevertheless, given as a starting point the frequency values adopted in the USSR, it is possible to devise a self-consistent and compatible network of SFTS stations with the minimum extent of mutual interference and with the least possible dislocation in the normal use of such stations.

1.5 *Control of vertical and horizontal radiation pattern*

While it has been suggested that the main control of mutual interference should be achieved by the appropriate choice of relative frequency offset, this should not detract from the need to examine the spread of radiation in both the horizontal and vertical planes from the transmitter. In particular, in geographically small areas it may be necessary to confine the vertical polar diagram to angles greater than 30° elevation with a preponderance of high angle radiation. This is conveniently achieved by arrangements of horizontal dipoles and a relevant Report 301 of Study Group 10 gives the characteristics of such systems designed for broadcasting in tropical regions. Other information is also contained in the CCIR Handbook on Directional Antennas [ITU, 1966].

2. Administrative measures

2.1 It is proposed, also, that this Report be transmitted to the Chairman, Study Group 2, since the present allocated standard frequency bands are partially shared with the radio astronomy and space-research services.

2.2 Furthermore, although Report 731 has shown a strong and continuing need for the transmissions in bands 6 and 7 it is suggested that administrations periodically review the need for such services in view of the desirable savings in power and spectrum usage which would result from their curtailment.

REFERENCES

CHERENKOV, G. T. [1978] The use in the national economy of standard frequency and time signals transmitted by the USSR HF signal generator stations. Studies by the All-Union Scientific Research Institute of Physical and Radio Measurements. Studies on time and frequency measurement (in Russian), Vol. 37, **67**, 15.

ITU [1966] Handbook on high-frequency directional antennas. ITU, Geneva.

REPORT 735-1

IMPORTANCE OF STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS IN BAND 5

(Study Programme 2B/7)

(1978-1982)

1. In band 5, a number of stations are emitting standard-frequency and time-signals on a continuous basis; some of these stations are radiating a time code with complete date information, such as the minute, hour, calendar day, day of the week, month and the year.

This kind of service is particularly well represented in Europe, where the emissions on band 5 are generally more used than the services on the bands allocated for the existing standard-frequency and time-signal emissions.

2. The segment of band 5 is particularly well suited for time-and-frequency distribution for the following reasons:

- the ground wave covers a wide range and is stronger than the sky wave up to distances of several hundred kilometres;
- the sky wave propagates via the ionospheric D layer and its propagation is stable especially in the daytime;
- the radiation efficiencies of the antennas in band 5 are considerably higher than the efficiencies that can be obtained in band 4 and relatively broad bandwidths can be secured.

As a consequence of these propagation and technical factors, the following features can be pointed out:

- for frequency comparisons, the phase time of the carrier is reproduced with good accuracy at the receiving station, e.g. with a standard deviation of less than 1 μs at a distance of 700 km during the day. At 300 km distance from the transmitting station the standard deviation of the recorded carrier phase time for the long-term average value has been found to be < 0.2 μs in the daytime. This allows a large geographic area to be supplied with standard frequencies with a relative uncertainty of less than 1×10^{-12} if appropriate averaging procedures are used. Secondary frequency standards, e.g. rubidium vapour standards can thus be locked, with suitable techniques, to these standard-frequency emissions, in order to improve their long-term frequency stability;
- for time comparisons, an uncertainty of less than 0.1 ms can be achieved during the day at distances of several hundred kilometres, using simple and inexpensive equipment. With some degradation of precision, slave clocks can be used at distances of up to 2000 km.

3. The following applications and classes of users have been identified as regards this kind of service on band 5:

3.1 *Standard frequency*

Industrial laboratories; scientific centres; time comparisons among time services of neighbouring countries; support of the time services of countries having no advanced technical facilities; control of the carrier frequency of transmitters used by various radio services; telecommunication networks (e.g. for synchronous or semi-synchronous digital networks); watch and chronometer calibration.

3.2 *Time signals*

Public clocks; speaking-clock services; public utilities such as television and broadcasting; postal services; railways and other means of transport including air traffic control; master clocks for industrial firms and public institutions.

Dating of events: traffic; geoscience (e.g. for seismic measurements and geoseismic investigations); medicine (for the chronology of medical examinations).

Common time reference for electronic data processing systems (e.g. processors) and for the process controllers in production plant.

Time reference for the dispatching of electrical energy, e.g. at time-dependent charges and studies on the dynamic behaviour of electric power network.

REPORT 736-1

FREQUENCY SHARING BETWEEN THE TIME-SIGNAL SERVICE AND THE RADIOLOCATION SERVICE, THE FIXED-SATELLITE SERVICE AND THE FIXED AND MOBILE SERVICES NEAR 14, 21, 26 AND 31 GHz

(Study Programme 2A/7)

(1978-1982)

1. Introduction

This Report examines the problems of frequency sharing between a proposed satellite time dissemination system and the radiolocation service, the fixed-satellite service, and the fixed and mobile services in the vicinity of 14, 21, 26 and 31 GHz (see Table I). An evaluation is made of co-channel operation of a satellite time dissemination system, a radiolocation system, fixed-satellite communications equipment, and fixed and mobile terrestrial radio relay equipment. Typical parameters for the general classes of equipment have been assumed to allow completion of the analysis.

2. The satellite time dissemination system

Figure 1 illustrates a proposed satellite time dissemination system intended to provide a means for high-precision comparisons of time and frequency at widely separated points on the Earth. A pseudo-random noise (PRN) coded signal is transmitted from a ground transmitter to a spacecraft receiver. The spacecraft receiver decodes the transmitted signal and makes a comparison with a precision clock located onboard to determine the time of arrival referred to the spacecraft time standard. A spacecraft transmitter then uses a PRN modulated signal to relay data on the ephemeris and epoch of earth signal reception to the earth station. The earth receiver decodes this signal and a comparison can then be made between the spacecraft time standard and the ground clock. Two earth stations can be used with the spacecraft in such a way that stations one and two can compare clocks. The spacecraft clock can also be compared with a calibration time standard at an appropriate earth station in order to assess its accuracy. The radio frequency operating bands proposed for use by the satellite time dissemination system are listed in Table I. The operating characteristics are summarized in Table II. PRN coding is used to assure good S/N ratios with minimal interference power received by other stations sharing the bands.

3. Sharing with the radiolocation service

The radio frequency band proposed for timing dissemination up-link transmissions near 14 GHz must be shared with the radiolocation service. Typical operating characteristics for a radiolocation system which might operate in this portion of the spectrum are given in Table III. Interference between a timing dissemination system earth station and a radiolocation system can be prevented by coordination of siting, antenna orientation, antenna heights, etc., between the two installations. For example, if the two stations are separated by a distance (in kilometres):

$$d \leqslant \sqrt{17\,h_1} + \sqrt{17\,h_2}$$

where

h_1 : height of antenna 1, metres,

h_2 : height of antenna 2, metres,

they will be below each other's radio horizon and main beam coupling will not occur regardless of orientation. To illustrate this, if the two antennas are 15 m high, the two stations need only be separated by approximately 32 km to be below each other's radio horizon. Furthermore, the directivity of the timing dissemination system transmitting antenna can also be used to limit further the interference flux at the radiolocation system antenna site.

The Radio Regulations (RR 2540 to 2548) require that the effective isotropically radiated power transmitted in any direction towards the horizon by an earth station operating between 1 and 15 GHz shall not exceed:

$+40$ dBW in any 4 kHz band for $\theta \leqslant 0°$,

$+40 + 3\,\theta$ dBW in any 4 kHz band for $0° < \theta \leqslant 5°$,

where θ is the angle of elevation of the horizon viewed from the centre of radiation of the antenna of the earth station and measured in degrees as positive above the horizontal plane and negative below it. For the postulated system,

$$\text{e.i.r.p.} = P_t + G_t + B$$
$$= 20 + 53 - 48 = 25 \text{ dB(W/4 kHz) maximum,}$$

where:

P_t : transmitter power dBW,

G_t : transmitter antenna gain, dB,

B : bandwidth correction factor

$$10 \log \left(\frac{4 \times 10^3}{250 \times 10^6}\right)$$

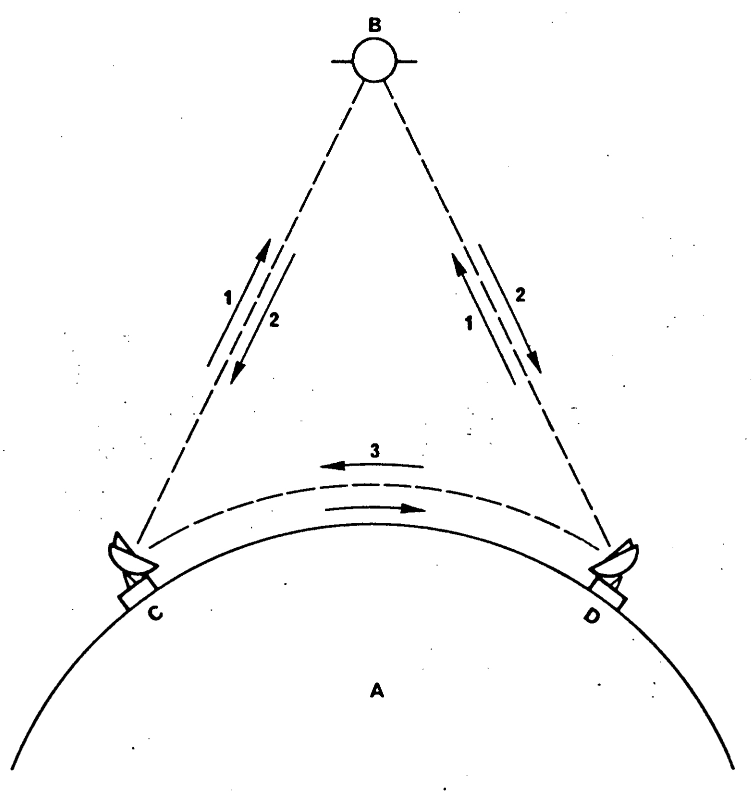

FIGURE 1 – *Satellite time dissemination system*

A	Earth
B	Time dissemination satellite
C	Earth station number 1
D	Earth station number 2
1	Earth-to-space link
2	Space-to-Earth link
3	Terrestrial path

TABLE I – *Proposed frequencies – satellite time dissemination system*

Proposed Centre Frequency Operating Band (GHz)	Proposed RF Bandwidth (GHz)	Other Allocations (Existing and Possible)	Operating Limitations (ITU Radio Regulations)
13.4-14.0 (up-link)	± 0.125 (0.25)	**Radiolocation** Earth Exploration Satellite (Active Sensor) Space Research (Earth-to-space)	e.i.r.p. +40dB(W/4 kHz) $\theta \leq 0°$ e.i.r.p. (+40+3θ) dB(W/4 kHz) $0° < \theta \leq 5°$ No limit on radiolocation
20.2-21.2 (down-link)	± 0.125 (0.25)	**Fixed satellite** (space-to-Earth) **Mobile satellite** (space-to-Earth)	No limit specified
25.27-27.5 (up-link)	± 0.6 (1.2)	**Fixed** **Mobile** EES (space-to-Earth)	e.i.r.p. $\leq$ +64 dB(W/MHz) $\theta \leq 0°$ e.i.r.p. $\leq$(+64 +3θ) dB(W/MHz) $0° < \theta \leq 5°$
30.0-31.3 (down-link)	± 0.6 (1.2)	**Fixed-satellite** (Earth-to-space) **Fixed** **Mobile** Space Research **Mobile satellite** (Earth-to-space)	Not yet specified

TABLE II – *Satellite time dissemination system – summary of characteristics*

Earth station	
Transmitter power	100W
Antenna gain (assumed)	53 dB
Type modulation	PRN code
Receiver noise temperature	1000 K (~6 dB NF)
Predetection bandwidth	250 MHz, 1.2 GHz
Post detection bandwidth	1 MHz
Processing gain	24 dB, 30.8 dB
Post detection S/N ratio	18 dB
Satellite	
Transmitter power	50W
Antenna gain	4 dB (over Earth angle)
Type modulation	PRN code
Receiver noise temperature	1000 K
Predetection bandwidth	250 MHz, 1.2 GHz
Post detection bandwidth	1 MHz
Processing gain	24 dB, 30.8 dB
Post detection S/N ratio	18 dB

TABLE III – *typical radiolocation system operating characteristics*

Peak pulse power	25 kW
Pulse width	32 ns
Pulse rise time	12 ns
PRF	15 kHz
Average power	12 W
Frequency (carrier)	~14 GHz
Receiver sensitivity	−85 dB (m)
Receiver noise figure	11 dB ($T_s \sim$ 3400K)
Signal-to-noise ratio (required for operation)	12 dB
Receiver IF bandwidth	40 MHz
Antenna gain over isotropic	35 dB
Side lobes	25 dB below main lobe
Antenna tilt	0 deg.
Antenna scan rate	135 r.p.m.
Antenna pattern	10 deg. vertical beamwidth 0.34 deg. horizontal beamwidth

The emissions from the radiolocation system transmitter main beam may occasionally be directly coupled into the satellite receiver antenna when the timing dissemination satellite is in view and less than ten degrees above the radiolocation system horizon (due to assumed ten degrees vertical beamwidth). In this case the interference power density at the satellite receiver is:

$$D_r = P_t + G_t - B_t - 10 \log (4\pi R^2) + 10 \log \left(\frac{G_r \lambda^2}{4\pi}\right)$$

D_r: -179 dB(W/Hz)

where:

D_r: interference power density, dB(W/Hz),

P_t: average transmitter power, dBW,

G_t: transmitter antenna gain, dB,

B_t: transmitter bandwidth, dB (1 Hz),

R: distance between transmitter and receiver antennas, m (3709×10^3 m for a 1000 km satellite),

G_r: receiver antenna gain, dB,

λ: operating wavelength, m.

The estimated signal power density (given by the same relationship plus the processing gain, 24 dB) is -169 dB(W/Hz), thus yielding a carrier-to-interference ratio of 10 dB, in the worst case. This C/I ratio is adequate to protect the timing dissemination system during all operations.

4. Sharing with the fixed-satellite service (space-to-Earth)

The satellite time dissemination down link proposed in the vicinity of 21 GHz must share a band with fixed-satellite and mobile-satellite service down links (space-to-Earth). For sharing to be permissible in this band, the power flux-density at the Earth's surface must be less than the limits specified in the Radio Regulations (RR 2577 to 2585) (see Table I). Furthermore, the angular discrimination due to the directivity of the fixed-satellite antenna can be used to provide additional isolation by constraining satellite transmissions within a minimum angular separation from the fixed-satellite earth station antenna axis.

The power flux density at the fixed-satellite earth station is given by:

$$\begin{aligned} PFD &= P_t + G_t - B_t - 10 \log (4\pi R^2) \\ &= -145 \text{ dB(W/(m}^2\text{ MHz))} \end{aligned}$$

The interference criteria developed at the WARC-BS-77 specify a maximum single entry interference-to-carrier ratio of -35 dB for protection of fixed-satellite communication systems. Report 561 predicts a fixed-satellite down-link carrier PFD at the Earth's surface on the order of -124.0 dB(W/(m^2 MHz)). This value for PFD results in a carrier-to-interference ratio of 21 dB. The additional 14 dB of isolation required (assuming a 60 dB FSS antenna gain and ITU standard side lobe envelope) can be obtained by preventing transmission within 0.3 degree of the FSS earth station antenna axis. This angular separation is obtained from:

$$G = 32 - 25 \log \theta$$

where:

G = maximum antenna gain at an angle θ from the axis.

Thus:

$$(60 - 14) = 32 - 25 \log \theta$$

$$\theta = 0.3 \text{ degree}$$

The possibility exists that fixed-satellite earth stations with higher sensitivities than those described in Report 561 will be implemented. If for example, a fixed-satellite earth station had the following characteristics:

– earth station noise power referred to receive input:	−143.6 dB(W/MHz)
– wanted down-path carrier-to-noise ratio:	15 dB
– earth-station antenna gain:	65 dBi

the fixed-satellite pfd on the Earth's surface would be −146 dB(W/(m^2 · MHz)). This value is approximately the same as that of the time dissemination satellite system. In order to provide this sensitive fixed-satellite system with protection (i.e., a carrier-to-interference (C/I) ratio of 35 dB) the satellite time dissemination down link would be constrained from operation while it was within approximately 1.2° of the earth-station main beam.

A sensitive earth station of the type mentioned above would have a beamwidth on the order of 0.048°. Under the worst-case conditions, in which the time dissemination satellite control system failed but the satellite remained transmitting, the sensitive fixed-satellite earth station could receive main beam interference for about 1.7×10^{-7}% of the time or approximately 5 s a year. The longest possible occurrence of a single pass main beam coupling for this case is on the order of 0.4 s. Taking the entire 1.2° cone about the earth-station bore site into account a C/I of less than 35 dB could possibly occur for about 0.01% of the time until the failure of the time dissemination satellite was remedied.

5. Sharing with the fixed-satellite service (Earth-to-space)

The proposed satellite time dissemination system down link near 31 GHz would share a portion of a band allocated for fixed-satellite service up links. Interference between fixed-satellite service earth-station transmissions and time dissemination earth-station receivers can be prevented by coordination of station parameters, station locations, antenna orientations, etc. Interference between the satellite-borne time dissemination transmitter and the fixed satellite service spacecraft receiver is very unlikely because of the relatively low e.i.r.p. and relatively long distances involved. For example, the interference power flux density at the fixed-satellite receiver is given by:

$$\mathrm{PFD_I} = P_t + G_t - B_t - 10 \log (4\pi R^2)$$

$$\leqslant 17 + 0 - 84 - 11 - 151 = -229 \text{ dB(W/(m}^2\text{ Hz))}$$

Similarly, the carrier power flux density is:

$$\mathrm{PFD_C} = P_t + G_t - B_t - 10 \log (4\pi R^2)$$

$$\leqslant 8.3 - 11 - 152 = -155 \text{ dB(W/(m}^2\text{ Hz))}$$

$$(\text{for e.i.r.p. density} = 8.3 \text{ dB(W/Hz) and } R \simeq 41\,500 \text{ km})$$

Thus the carrier-to-interference ratio would be approximately +74 dB.

6. Sharing with the fixed and mobile services

Sharing between the satellite time dissemination up link (~ 26 GHz) and the fixed and mobile services will be feasible if two requirements are fulfilled. The first is that the time dissemination transmitter e.i.r.p. fall within limits specified by the Radio Regulations (RR 2542). The second is that there be sufficient carrier-to-interference margin to preclude harmful interference to each other.

The requirement on e.i.r.p. density for earth stations operating above 15 GHz is:

$$64 \text{ dB(W/1 MHz) } \theta \leqslant 0°$$

$$64 + 3\,\theta \text{ dB(W/1 MHz) } 0° < \theta < 5°$$

The time dissemination earth station

$$\text{e.i.r.p.} \leqslant 20 + 71 + - 24 = 67 \text{ dB(W/MHz)}$$

Thus, if $\theta \geqslant 1.0°$, the first limitation is satisfied.

The second restriction, i.e., C/I margin, can be handled by coordination of station parameters (i.e., gain, power, etc.) siting, antenna height, antenna orientation, etc. As an example, if two stations sharing a band have antenna heights of 15 m, for

$$d \geqslant \sqrt{17 \times 15} + \sqrt{17 \times 15} \geqslant 32 \text{ km}$$

they are below each other's radio horizons.

Sharing near 31 GHz between the time dissemination down link and the fixed and mobile services will be determined by a trade-off between interference level and the percentage of operating time during which it occurs.

The interference power density in the receiver front end is:

$$P_I = E_T + G_r - L$$

where:

$$E_T = \text{transmitter e.i.r.p. density} = P_T + G_T - B_T$$
$$= 17 + 4 - 84 = -63 \text{ dB(W/Hz)}$$

L: propagation loss $= 92.5 + 20 \log f + 20 \log R$,

f: operating frequency, GHz,

R: distance, km.

For $R = 3709$ km ($L = 193.7$ dB) and $G_R = 60$ dBi, $P_I = -196.7$ dB(W/Hz).

From Report 686 for a relay network of 5 stations:

$$P_I = -196.2 + 10 \log \left(\frac{X}{1250}\right)$$

where:

X = allowable interference, psophometrically weighted, (pW0p)

Solving for $P_I = -196.7$ gives

$$X = 1114 \text{ pW0p}$$
$$\text{or } -59.5 \text{ dBm0p}$$

According to Recommendation 357, this level of interference power can be withstood by an analog angle-modulated radio relay system for nearly 20% of the operating time. Report 684 which investigates low-orbit satellite visibility statisitics, shows that a single station would find a low orbit satellite within its main beam less than 1.0% of the time. Thus, the time dissemination system is capable of frequency sharing with fixed and mobile radio relay systems without causing harmful interference. Interference to time dissemination earth station receivers by fixed and mobile transmitters can be eliminated by coordination of station parameters, sites, antenna orientation, etc.

7. Conclusions

Sharing between a satellite time dissemination system and the radiolocation service near 14 GHz is feasible. Interference to radiolocation system operations by a time dissemination earth station can be prevented by coordination between the two installations. This effective isotropically radiated power of the time dissemination system earth stations should conform to the limitations of RR 2541. Radio-frequency energy emitted by radiolocation system transmitters will not interfere with time dissemination system operations.

Sharing between a time dissemination system down link and fixed-satellite service space-to-Earth links near 21 GHz is also feasible. The time dissemination spacecraft transmitter must comply with RR 2578, limiting the power flux density at the Earth's surface. Furthermore, the time dissemination satellite should be programmed to preclude transmission near 21 GHz when its position is within 0.3 degree of the principal axis of a fixed satellite earth-station receiver antenna operating near 21 GHz.

Sharing between a satellite time dissemination system down link and fixed-satellite up links near 31 GHz is feasible for the timing system parameters given in this Report. Coordination between fixed-satellite and time dissemination earth stations will be necessary to protect the time system from harmful interference.

Frequency sharing between a time dissemination system up link and fixed and mobile services near 26 GHz is feasible provided that the transmitter power is no more than 100 W when using an antenna of no more than 71 dB gain elevated at least one degree above the horizontal plane. Coordination of earth station and relay station installations will be required.

Sharing between a time dissemination system down link and fixed and mobile services near 31 GHz is feasible provided the satellite transmitter power is no greater than 50 W and the satellite antenna gain is no greater than 4 dB. PRN coding should be used to improve signal-to-noise ratios without increasing interference power levels.

REPORT 896-1

DOCUMENTATION OF CHANGES IN TRANSMITTED TIME SIGNALS

(Question 1/7)

(1982-1986)

1. Introduction

The transmitted time signals of the different standard time stations have been maintained close to the time determined from the rotation of the Earth by either steps or changes in rate of the time signals. Now most countries transmit UTC.

2. USA time signals

Time and frequency steps by WWV of the National Bureau of Standards and the Master Clock (MC) of the US Naval Observatory (USNO) have been reported for 1956-1971 [CCIR, 1978-82]. Corrections to UTC have been made since 1972.

3. JJY time signals

Time and frequency steps by JJY of the Radio Research Laboratories (RRL), Japan, have been reported in [CCIR, 1982-86]. From January 1955 to August 1961, the time and frequency of JJY were maintained to be nearly in agreement with UT2 which was determined by the Tokyo Astronomical Observatory (TAO). The UTC system has been introduced since 1 September 1961.

4. Prior to the introduction of the present UTC system (according to Recommendation 460), various methods of time-signal adjustments have been in use. The details of these adjustments should remain accessible for archival purposes. The Administrations of the Federal Republic of Germany, France, Japan, the United Kingdom and the United States of America have sent this information to the Bureau international des poids et mesures (BIPM) which, following the suggestion expressed in Opinion 71, has agreed to keep such information on record. Additionally, the respective World Data Centres would also be possible sources for this information.

REFERENCES

CCIR Documents

[1978-82]: 7/103 (USA).

[1982-86]: 7/4 (Japan).

REPORT 897-2

METHODS FOR SHORT RANGE PRECISION TIME TRANSFERS

(Study Programme 3C/7)

(1982-1986-1990)

1. Introduction

There is a need for comparisons between time scales maintained at separate locations within a short range of each other, typically less than 100 km. This Report deals with separate locations that are considered to be local in the sense that they share a common environment of propagation medium. This includes sites within line-of-sight, within reach of coaxial cables or optical fibres, or within convenient reach by portable clocks.

2. Common view method

A widely used method of synchronization in frequency and time (see Report 363) is the common monitoring of a radio signal that both sites can receive (i.e., Loran-C, television-line, television-carrier, HF, LF, VLF stabilized carriers, Omega); comparing the differences observed between the external signal and an internally generated signal for each site. The simultaneous observation of signals from a satellite by independent ground receivers is one of the most promising examples [Taylor, 1974] although the method has the disadvantage that the propagation path difference must be calibrated.

3. Cable including optical fibres

For those distances in which coaxial cable can be used to join the sites, two-way propagation of signals provides a means of calibrating the path length and direct comparison of signals for frequency and time synchronization [Rueger and Bates, 1979].

An experimental T/F transfer link using fibre optics at 850 nm and 100 MHz modulation was tested at the Jet Propulsion Laboratory. Over a 3-km path, a stability of 3×10^{-15} at 100 s and 1×10^{-16} at 1000 s was attained. The link operated by continuously measuring the round-trip delay in a single fibre and correcting the input phase to compensate for the variations in the delay, thus achieving constant phase at the receiving end. Subsequent measurement of an uncompensated, 14 km, single-mode, 1 400 nm fiber optic link demonstrated a stability of $\sigma_y(\tau) = 1.2 \times 10^{-15}$ at $\tau = 1\,000$ seconds. This cable was buried 1.5 meters in the ground between two stations of the NASA/JPL Deep Space Network at Goldstone, California [Lutes, 1982; 1987].

At the Technical University, Graz, a multi-mode fibre optic T/F distribution system for distances up to several hundred metres has been developed and built with off-the-shelf components. The system is comparable both in price and performance with standard equipment used in time-keeping laboratories. The jitter (output versus input, standard deviation of 100 samples) is well below 50 ps and the temperature-induced changes of the propagation delay of the transmitter and receiver are below 30 and 50 ps/°C respectively. The signal delay variations of the cables used are between 5 and 17 ps/°C for cables of 100 m length [Kirchner and Ressler, 1984].

4. Line-of-sight links

For some distances, line-of-sight propagation links using radiowaves including microwaves or laser beams, are an economical choice for transferring signals on either a one-way or reflected two-way propagation path. The two-way approach permits control of variables resulting from the propagation path such as temperature, humidity, clouds, smoke, or rain, but is subject to multipath problems depending on the sending and receiving antenna design parameters and location relative to obstructions or reflecting surfaces near the line-of-sight path.

A horizontal two-way time comparison link in air using the University of Maryland's user ranging and time transfer equipment has been established between the Goddard optical research facility (GORF) 1.2 m telescope and the Time Services Division of the United States Naval Observatory (USNO). The bent path has a one-way distance of 26 km. Two optical corner reflectors at the USNO, identical to those placed on the Moon during the Apollo programme, reflect the laser pulses back to the GORF. Light pulses of 100 ps duration and an energy of several hundred microjoules from a neodymium-YAG laser, frequency doubled to a wavelength of 532 nm (green), are sent at a rate of 10 pulses per second. The detection at the USNO is by means of an avalanche photodiode and the timing is accomplished by a computing counter and a computer with respect to a 10 pulses per second pulse train from the master clock. The standard deviation for 100 comparisons is typically 200-400 ps. The corresponding standard deviation of the mean is 20-40 ps. The calibration accuracy, at present, is 1-2 ns, established with a portable clock [Alley *et al.*, 1982].

In 1982, similar techniques were used in time comparison experiments via laser pulses between the two sections of the Shanghai Observatory, Zi-Ka-Wei and Zo-Se, separated by 25.2 km. Time fluctuations of clock difference between two sections were about ± 8.0 ns (r.m.s.) for single measurement and about ± 1.3 ns for the average value of two minute measurements respectively [Yang *et al*, 1983].

5. General remarks

Timing signals for synchronization purposes are characterized by the signal rise time, the bandwidth available and the stability of phase time delay as the signal passes through the propagation medium and measuring instruments.

It has been a common practice to calibrate differential propagation path lengths by carrying a precision clock between two sites assuming corrections can be made for the portable clock rate as determined from aging data, velocity and gravitational corrections [Allan and Ashby, 1979].

A range of capabilities for high quality performance realized by several methods is shown in Table I for a distance of about 100 km or less.

TABLE I – *Uncertainty of short range time transfer*

Method of time transfer		Uncertainty of time transfer	Utilization status	Calibration (1)
Portable clock	[Rogers *et al.*, 1977]	2 ns	Routine	
Television line	[Lavanceau and Shephard, 1978]	10 ns	Routine	X
Television carrier	[Lavanceau and Shephard, 1978]	0.1 ns	Routine	X
Microwave relay	[MacConnell *et al.*, 1977 ; Norton *et al.*, 1962]	2 ps 2-50 ps	Experimental	X (2)
Coaxial cable	[Rueger and Bates, 1979]	0.2 ns	Routine	X (2)
Loran-C	[Winkler, 1972]	0.1 µs	Routine	X
VLF (Omega)	[Cooper and Chi, 1979]	1.5 µs	Experimental	X
HF time signals		1 ms	Routine	X
Telephony 10 kHz		10-100 µs		X
Optical				
Optical fibres		10 µs	Experimental	X (2)
Laser	[Besson, 1970]	0.1 ns	Experimental	X
Geodimeter	[Levine, 1978 ; Faller and Faller, 1977]	2 ps	Experimental	
Satellite links				
GOES	[Beehler *et al.*, 1979]	1 µs	Routine	
Transit	[Laidet, 1972 ; Beehler *et al.*, 1979]	1-5 µs	Routine	
Transit improvement program	[Taylor, 1974 ; Rueger and Bates, 1979]	10 ns	Experimental	
Global positioning system	[Schuchman and Spilker, 1977]	10 ns	Design potential	
Radio broadcast	[CCIR, 1970-1974 a]	6 µs	Routine	X
50-60 Hz power line	[CCIR, 1970-1974 b and c]	0.25 ms	Routine	X

(1) Calibration of both the instruments and the installation is required to achieve the indicated uncertainty of time transfer. The methods indicated by an "X" require an independent propagation path calibration.

(2) No external calibration is required for two-way operation.

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REPORT 1016-1

TELEVISION METHODS FOR THE TRANSFER AND DISSEMINATION OF TIME AND FREQUENCY

(Study Programme 3C/7)

(1986-1990)

Television signals are well adapted for the dissemination of time and frequency at several levels of accuracy, and for the comparison of time scales; among the advantages are:

– their widespread availability with good signal strength;
– their time structured nature and wide bandwidth in frequency allocations which already exist;
– the low price of receiving equipment;
– the predictability of their propagation.

Several methods have been developed for television time comparisons. The original method of Tolman *et al.* [1967] involves simultaneous time of arrival measurements of selected synchronization pulses. This system is in wide use in the People's Republic of China [CCIR, 1974-78a], in Europe [Rovera, 1972; Allan *et al.*, 1970; Parcelier, 1976; Parcelier and Fréon, 1977; Becker and Enslin, 1972], in Japan [Saburi *et al.*, 1978] and in the United States of America [Allan *et al.*, 1972; Davis *et al.*, 1971], where it is known as "Line-10".

Television synchronization pulses are used as common reference markers for many national, and sometimes international, time comparisons. A determination of the propagation delays has to be made by portable clocks or other suitable methods. For line-of-sight comparisons, using the same television transmitter, the uncertainty of a time difference measurement can be 10 ns or less.

Television signals from different transmitters can —— be used for time or frequency comparisons only if the delay introduced by the links between the transmitters either remains constant or is restricted to a small number of constant and distinguishable values. It is also necessary that no frame synchronizer is used. Such frame synchronizers store a complete picture frame in digital form and release the frame in synchronism with a local clock. The uncertainty introduced by links between transmitters is usually less than 1 μs if they follow the same route, but may reach several microseconds. Much larger changes can be caused by the use of different routes through the linking network.

A method of measuring delays, section by section, to determine the total propagation delay has been employed by the Beijing Observatory in the People's Republic of China. This method used only simple apparatus and standard equipment. The results have been checked and compared with portable clocks and Loran-C timing; the systematic deviations of different methods were within 1 μs.

Variable and indefinitely large delays can be introduced by links containing satellites, or frame stores in which input and output are controlled by different clocks. These occur, for example, in frame synchronizers and in standards converters and their use is expected to increase. While this may limit the future usefulness of large television networks for time and frequency dissemination it may also simplify such use locally by permitting active and independent control of signal timing within a sub-network or after passage through a satellite link.

Experiments with portable clocks indicated that the accuracy of a technique using television line 6 synchronization pulse for seven years on a routine basis by Shaanxi, Shanghai and Beijing Observatories achieved 2 μs or better, and a daily frequency calibration precision of about $(2 - 20) \times 10^{-13}$ over a distance of 2000 km.

Improvements in the stability of measuring equipment for use with this method have been achieved in Japan by stabilizing the local oscillator frequency in the television tuner and by using a fixed setting of the automatic gain control in the intermediate-frequency amplifier with controlling voltage as high as possible. Improved short-term and long-term stabilities of about 10 ns and 30 ns, respectively, have been obtained [Inouye and Nara, 1978; CCIR, 1974-78b]. In addition, recent experiments have shown that significant improvement in the stability can be obtained by measuring the trailing edge of the synchronizing pulse rather than its leading edge. Thus, for purely differential measurements using the same synchronizing pulse, use of the trailing edge gives excellent results since the steeper trailing edge leads to better measurement precision [Saburi *et al.*, 1978].

It should be noted, however, that the time of occurrence of the *leading* edge of the pulse, with respect to a known time reference, is generally better controlled than that of the trailing edge. Thus, for time difference measurements between a local clock pulse and a particular synchronized television pulse, more accurate results may be obtained with the leading edge.

Several generations of receivers were specially built for daily comparison of the 15 clocks, in several laboratories in different parts of France, which contribute to TA(F) [Parcelier, 1976]. The measurements refer to a well-characterized pulse in a test line and are initiated automatically by the local clock. Tuning is adjusted for optimum shape of the received pulse, and automatic gain and level controls ensure that the results are unaffected by picture content. Simultaneous measurements over 30 minutes by two adjacent sets of equipment give a 1 σ dispersion of $\pm$ 5 ns about the mean; a precision of 40-50 ns is obtained in normal operation in a series of 15 or 30 consecutive measurements over distances of several hundred kilometres.

In the USSR, experiments have been carried out with insertion of seconds marker pulses in the sixth line of the video signal, with the possibility of remote control relative to UTC (S). In addition, a time code has also been inserted [Borisockin and Fedoton, 1982].

Two caesium clocks, one in Brittany and the other in Paris, were compared during one month through daily television measurements and six portable clock experiments [Parcelier and Fréon, 1977]. The standard deviation of the differences between the two methods of comparison over the period in question amounted to some 15 ns. A last portable clock experiment carried out 2½ months later gave a result 28 ns higher than that of the television experiment.

Clock comparisons by television signals on a routine basis and eight measurements by portable clock were made over seven years among three laboratories in Tokyo, all located within about 20 km of the television transmitter. The standard deviations of the difference between the two methods were about 50 ns. Receiver delay variations as determined by local calibrations have been taken into account.

A receiver developed in Switzerland measures the leading edge of a line synchronizing pulse and incorporates automatic frequency control and accurate stabilization of signal levels immediately before and after the edge. Measurements of signals from the same transmitter by co-sited receivers have shown 1 σ values below 1 ns for averaging times of 10 s and above, but for signals from different transmitters the 1 σ value rises from about 1 ns to 3 ns as the averaging time is increased from 50 s to 500 s [CCIR, 1974-78c].

A related method was reported by Lavanceau and Carroll, [1971] at the USNO. It involves stabilization of the colour sub-carrier by reference to a caesium beam frequency standard in the television studio. The line 10 synchronization pulse is also controlled and maintained in synchronism by referring to a "Table of coincidences" (TOC) issued by the USNO for use with the NTSC system, similar to the Loran-C TOC.

In contrast to a coherent TOC reference, as used in the weekly reports of the USNO (Time Service Announcements, Series 4), it has been proposed in Japan [Saburi *et al.*, 1978] to use the same TOC reference every day.

The NBS in the United States of America has developed and tested a method for time dissemination via television, by encoding data in particular lines of the television signal. First, lines 13 to 16, then line 1 and also line 21 were used. A 1 MHz reference signal was included in this system [Davis *et al.*, 1970; Howe, 1972].

Television systems used in Europe have nominal frame repetition rates of 25 Hz and UTC seconds markers can in principle be inserted in a fixed position in the frame.

The national television network in Yugoslavia is used in this way to disseminate time and frequency originating from a caesium clock in the Belgrade studio. Seconds pulses on the UTC (YU) scale, with hour and minute markers are inserted in the second half of line 19, while line 332 carries a code which gives the hour, minute and second and indicates the origin and status of the timing information. The first half of both lines carries a stabilized 1 MHz burst [Kovačević, 1973 and 1977]. Belgrade Television has carried these signals in its two programmes for the entire duration of the studio broadcasts since 1975.

In the United Kingdom the line and frame synchronizing pulses transmitted by the British Broadcasting Corporation in band 9 are generally controlled by a rubidium standard. Their drift relative to UTC is usually only a few microseconds per day, but there are also programme dependent reversible time steps. Signals from several transmitters serving many large centres of population and industry are monitored each working day with a precision of 0.1 µs. The measurements link the UTC scales maintained at the National Physical Laboratory (NPL) and the MSF/GBR transmitter site at Rugby [CCIR, 1974-78d].

Several methods have also been developed for using television transmissions as very stable frequency references. In the Federal Republic of Germany, precise frequency control has been extended to about 160 television transmitters at 82 locations operating in the frequency range 471.24 to 783.26 MHz. The transmitter frequencies are remotely controlled by a caesium standard that is adjusted relative to a central group of six commercial high performance caesium standards. The stations examined showed an average normalized frequency departure of 3×10^{-12}. The computed standard deviation is 3×10^{-11}. Signals received at distances of 46 to 125 km from the transmitter were found, over an interval of 30 s, to have phase fluctuations corresponding to frequency variations of about 1×10^{-11}, in the worst case.

In the German Democratic Republic the line and frame synchronizing pulses, transmitted by television are directly controlled by the national time and frequency service with an uncertainty of 6 ns and are used for frequency dissemination in the country and for time comparisons with the time services of neighbouring countries. The effect of reversible time steps greater than 200 ns due to changes in the delay time in the links of the television network can be eliminated by applying calculated corrections, leading to a reduction of the uncertainty of the time comparisons to less than 50 ns [Kalau, 1979].

In France a television carrier at 182.25 MHz has been used as a common reference in frequency comparisons between hydrogen masers in two laboratories 16 km apart. Synthesizers driven by the masers were used to generate voice-frequency beats with the carrier, and phase comparisons of the beats were made via a telephone link. Resolutions obtained were $4 \times 10^{-11}\tau^{-1}$ for $1\ \text{s} < \tau < 300\ \text{s}$ and 6×10^{-14} for $\tau = 1$ hour [Gabry *et al.*, 1977].

In Japan and the United States, the frequency stability provided by the television colour sub-carrier has been demonstrated. This high stability results from the use of atomic frequency standards by television networks to generate the sub-carrier frequencies.

Frequency comparisons were performed between Tokyo and Mizusawa (Japan) [Saburi *et al.*, 1978]. The colour sub-carrier was phase-compared with a locally generated colour sub-carrier signal. The precision obtained was 6.5×10^{-12}, 4×10^{-12} and 2.2×10^{-12} for averaging times of 10, 30 and 60 minutes respectively.

Frequency comparisons were performed by the National Institute of Metrology (NIM) of the People's Republic of China in 1979. The results show that using the television colour sub-carrier over the range of 2000 km, the precision of frequency calibration is better than $\pm 5 \times 10^{-12}$ in 30 minutes. At the same time, similar results were obtained by Beijing and Shaanxi Observatories.

A quite simple method that uses directly the colour sub-carrier pulse was tested in Shanghai Observatory. The precision of frequency calibration is about 1 to 2×10^{-11} in 15 minutes.

Since 1981, the NIM of the People's Republic of China has used a caesium clock to control the colour sub-carrier frequency and to insert a 1 MHz standard burst (20 cycles), seconds pulses and a time code in line 16 and line 329 of the Chinese Central Television (CCTV) signal. This standard frequency and time signal has been in service officially since 1984. Time comparisons have shown that the uncertainty, when the method is used for synchronization of second pulses, is less than 30 ns over a line-of-sight distance.

Based on earlier demonstrations of the excellent long-term stability of the 3.58 MHz television colour sub-carrier transmissions from the major television networks in the United States [Davis *et al.*, 1971], the National Bureau of Standards has recently initiated an improved nationwide frequency calibration service. A user nearly anywhere in the United States can now easily and inexpensively calibrate his oscillator to an accuracy of a few parts in 10^{11} in about 15 minutes with respect to the primary frequency standard at the NBS. This accuracy is made possible by the high stability of the network atomic frequency standards generating the sub-carrier signals and by the availability of regular NBS measurements of the sub-carrier frequencies.

The user must first measure the frequency difference between his oscillator and one of the major television network sub-carriers during a time when he is receiving direct network programming. The necessary television sub-carrier signal can be obtained easily from a slightly modified colour television receiver. Several versions of suitable user equipment have been designed and constructed at the NBS [Davis, 1975]. In the simplest form, called the colour-bar comparator, the measurement is made by manually timing the period required for a coloured bar on the television screen to cycle through a changing colour sequence.

In a more sophisticated version of user equipment the frequency difference between the local oscillator and the network sub-carrier is automatically measured, computed, and displayed directly in parts in 10^{11} on the television screen. The entire automatic measurement requires about 15 minutes and provides a precision of 1×10^{-11}.

NBS has also developed a versatile microprocessor-based data-logging system that automates both the line-10 sync pulse comparison and the colour sub-carrier frequency comparison measurement capabilities into a single, relatively inexpensive package. Time comparisons to 10 ns and frequency comparisons to 1×10^{-12} (averaged over 1 day) are being routinely obtained from unattended, remote units located at several points within the US [Davis, 1976].

One of the major networks in the US now uses caesium standards to generate the 3.58 MHz colour sub-carrier frequencies which are then distributed nationwide. The caesium standard virtually eliminates any long-term drift in the sub-carrier frequency.

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REPORT 1017

CHARACTERIZATION OF SIGNAL DELAYS IN ANTENNAS

(Question 9/7)

(1986)

1. Introduction

As greater resolution in time transfer becomes possible by the use of improved time and frequency generators with better short-term stabilities, the means of calibrating and measuring circuit delays between the standards to be compared may become a dominating source of error. Included in the intervening circuits are the delay contributions from the antennas used to emit and receive electromagnetic waves propagated over the path separating the precision time time generators. This Report addresses the related work in the published literature and is an initial attempt to present the state of the art in the present technology. Since means of performing these calibrations have not been standardized between administrations, it is appropriate to address guidelines for consideration that may lead to the adoption of acceptable procedures for these measurements.

2. Background

Time signal generators now exist with the potential for maintaining time scales with deviations of less than 1 ns for periods of hours to days. Electronic circuit delays can be measured and calibrated within a laboratory environment at the hundreds of femtoseconds (fs) level. Susceptibility of these circuits to environmental change, such as temperature, magnetic fields, and acceleration can be measured and provision made to sense and compensate or to allow for these perturbing effects. Antennas can be considered a subset of the possible electric circuits that can be serially connected. They may, however, require a more sophisticated treatment for measurement and calibration.

Large antennas used to emit Loran-C signals take 60 or more microseconds for the energy to build up the radiation fields at 100 kHz [Fujimoto and Fujiwara, 1981]. Likewise, the small inductive loop antennas used to receive these signals have delays associated with the build-up of the received signal. Signals such as used in Omega at 11-15 kHz, take tens of milliseconds to build up [Watt, 1967].

To a lesser degree, antennas used in satellites to emit 150 MHz and 400 MHz signals have delays of the order of 25 to 50 ns. Since these delays depend on factors such as bandwidth, frequency, physical length and directivity, time signals derived from a common time scale can develop time offsets, or delays that are the dominant errors in time transfers.

3. Measurements

Experiments have been performed to measure antenna signal delays by a substitution process. A section of cable comparable in length to the far field radiation distance, $2D^2/\lambda$, for electrically small antennas is selected and the total phase delay determined. The cable is divided into two parts; one part feeding a signal to one antenna; the other receiving the signal from another similar antenna. The total phase delay of this combination is determined. The difference between the two delay measurements, less the calculable propagation delay in the air dielectric medium between the two antenna phase centres, represents twice the delay associated with a single antenna.

For a situation where the antenna is of very large aperture, it may not be possible to have two nearly identical antennas sufficiently separated for the above measurement. Here the delay measurement can be made between two smaller nearly identical antennas, and then compared to the delay when one of the small antennas is replaced by the large antenna. Measurements of this kind have been carried out by the Jet Propulsion Laboratory, Pasadena, California [Otoshi, 1975; Cha *et al.*, 1978; Otoshi *et al.*, 1985].

In experiments with space probes, small variations in the delay of microwave signals have been measured in order to obtain data on planetary atmospheres and the distribution of gaseous matter in space. This work has led to investigations of the effect of discontinuities on the group delay in microwave transmission lines [Beatty and Otoshi, 1975] and has also led to the development of a set of group delay standards [Otoshi and Beatty, 1976] for 15, 30 and 60 ns. These delay standards have been calibrated at 2113, 2295 and 8415 MHz to ± 0.1 ns.

4. Conclusions

For antennas serving for the dissemination of precision time signals, calibration of the signal delay represents a new parameter or characteristic not normally specified or calculated in the initial design of a service antenna. Prior experimenters have performed substitution measurements to determine empirically antenna delay, but have not provided either an organized format or a common set of data across the radio spectrum. Families of antennas used for field-strength measurements are well developed and could represent a set of antenna designs suitably adaptable for standardization of this parameter.

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REPORT 1152

GENERAL SOURCES OF HIGHLY STABLE SIGNALS IN THE UHF-EHF BANDS USING SYNCHRONIZED OSCILLATORS

(Question 10/7)

(1990)

For a whole series of practical applications, sources are required which display not only high frequency stability but also the capability to vary the nominal frequency, forming networks of stable frequencies in the UHF-EHF bands, in some cases with rapid transfer from one frequency to another.

Such sources are constructed using various phase synchronization systems involving either continuous or pulsed phase-locked automatic frequency control loops [SHAKHGILDYAN and LYAKHOVKIN, 1972; Shakhgildyan and Belyustinaya, 1982; Shakhgildyan, 1989].

Potential signal stability and optimum frequency stabilization accuracy are limited by the presence of fluctuation interference in the components of the phase synchronization system, particularly in the UHF-EHF bands.

Research to enhance frequency stability is being pursued in two directions:

- improving the fluctuation characteristics of the different units and components constituting the phase synchronization system;
- optimizing the structures of phase synchronization systems.

Phase synchronization systems designed to form highly stable signals in the UHF-EHF bands are constructed on the basis of two principles [BALANOV and KABANOV, 1987; PATSYUK, 1988].

1) formation of a frequency network directly in the required portion of the band;

2) transfer of the frequency network formed in the low-frequency bands into the UHF-EHF bands.

The majority of phase synchronization systems operating in the aforementioned bands are of the multiloop type, which produces significantly better output signal spectral characteristics than single-loop structures.

The filtering properties of multiloop phase synchronization systems are such that for noise in a standard oscillator they are equivalent to a low frequency filter, for noise in a tunable oscillator in the last loop they are equivalent to a high frequency filter and for noise in other oscillators they are equivalent to a band-pass filter. By selecting appropriate parameters for the phase synchronization system, it is possible to "extract" the best sections from the spectral characteristics of the oscillators used, thereby minimizing output signal phase noise.

Typical values of the level of spectral density of phase noise for sources in the UHF-SHF-EHF bands using phase synchronization systems are given in Table I.

Figures for a source in the EHF band are given in Table II, which illustrates the gains in the level of output signal phase noise for a source with a phase synchronization system in comparison with a non-synchronized avalanche diode oscillator and an ideally multiplied 10 MHz quartz oscillator.

TABLE I

Analysis frequency	Spectral power density of output signal phase noise (dB/Hz)		
	UHF 1 GHz	SHF 10 GHz	EHF 100 GHz
100 Hz	-80	-70	-60
1 kHz	-90	-90	-70
10 kHz	-100	-90	-75
100 kHz	-120	-110	-90
1 MHz	-150	-130	-80

TABLE II

Analysis frequency	Spectral power density of output signal phase noise (dB/Hz)		
	Avalanche diode oscillator with phase sync. syst.	Non-synchronized avalanche diode oscillator	Multiplied quartz oscillator
100 Hz	-60	-40	-60
1 kHz	-70	-10	-70
10 kHz	-75	-20	-70
100 kHz	-90	-50	-70
1 MHz	-80	-80	-70

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SECTION 7D: CHARACTERIZATION OF SOURCES AND TIME SCALES FORMATION

REPORT 364-6

PERFORMANCE OF STANDARD-FREQUENCY GENERATORS

(Study Programme 3B/7)

(1966-1970-1974-1978-1982-1986-1990)

1. Introduction

In recent years, the results of a large number of studies have become available concerning the instability of standard-frequency generators. Theoretical treatments of the problem, definitions and experimental procedures for measurement have been widely investigated (see Report 580; specially for notations).

It has been shown [IEEE, 1966; NASA, 1964; Yasuda and Yoshimura, 1964] that the type of noise present in a standard-frequency generator may be classified by the form of the frequency (or phase) spectral density which it produces. Such densities are the Fourier transforms of the related auto-correlation functions and suitable mathematical techniques have been devised for operating on these functions [Blackman and Tukey, 1959; Davenport and Root, 1958]. The effect of the so-called "flicker noise" having a $1/f$ spectral variation is particularly important in the long-term operation of all forms of frequency standards and special studies have devoted to this aspect [NBS, 1974]. A $1/f^2$ spectrum has also been shown to be important in frequency generators [Jones and Tryon, 1983].

In both atomic sources and in quartz crystal oscillators, thermal and shot noise will contribute to the short-term instability and, depending on the mechanism, will produce either an f^2 or an f^0 variation in the phase spectral density. The intended use of the standard-frequency generator will determine the importance of these effects relative to the instability produced by flicker noise and other frequency disturbances.

With the increasing availability and use of commercial atomic frequency standards to generate very stable time scales in a number of laboratories throughout the world, a large amount of stability performance data has been accumulated. One conclusion is that commercial caesium beam frequency standards occasionally demonstrate small, but significant systematic frequency shifts.

The appearance of these shifts would indicate that the fluctuation phenomena of these standards cannot be fully described by the stability measure $\sigma_y(\tau)$ in accordance with Kolmogorov [1941], Malakhov [1966], and Allan [1966]. Some timing centres have found it useful during the software analysis to measure and remove these steps. Others have used $\sigma_y(\tau)$ to characterize these frequency shifts. This applies in particular to long time intervals (> 0.5 year). It is believed that this is due to the non-stationary behaviour of some clocks for time intervals which are an appreciable fraction of the clocks' lifetime. It has, however, been shown that the majority of these frequency steps can be modelled as a random walk frequency modulation process, and $\sigma_y(\tau)$ can be used to identify the $\tau^{1/2}$ process and its magnitude [Percival, 1976; Barnes *et al.*, 1982; Jones and Tryon, 1983].

2. Caesium beam frequency standards

In this section, performance reports on different standards are grouped by the method used for preparing and analyzing the caesium atom hyperfine state. Magnetic state selection is the established method, which has been supplemented by the continuing development of optical methods.

2.1 Magnetic state selection

Systematic effects in commercial caesium beam frequency standards have been investigated by several laboratories (PTB [Becker and Hetzel, 1973], BIH [Guinot, 1974], the USNO [Winkler *et al.*, 1970]). There is some evidence that commercial caesium standards exhibit frequency drift. Such drifts may range from a few parts in 10^{14} per year to a few parts in 10^{13} per year (BIPM Annual Reports).
Procedures have been developed [Becker and Hetzel, 1973] for periodically monitoring and adjusting the magnetic fields in these commercial standards. These procedures appear to produce improved stability performance, particularly during the first six months of a clock's life. A caesium beam tube accuracy evaluation technique has been developed that is applicable to both laboratory and commercial type standards [Hellwig *et al.*, 1973].

Laboratory-type primary caesium beam frequency standards are located at the PTB in the Federal Republic of Germany [Becker, 1976]; the NRC in Canada [Mungall *et al.*, 1976], the NIST in the United States of America [Wineland *et al.*, 1976]; VNIIFTRI, USSR [Iljin *et al.*, 1976] NRLM and CRL, Japan [Nakadan and Koga, 1985]; Nakagiri *et al.*, 1984]; NIM, the People's Republic of China. These standards have been evaluated with respect to most parameters affecting their output frequency; i.e., experiments and theoretical studies have been performed which yield knowledge about the biases which cause the output frequency to differ from the unperturbed atomic resonance frequency. The accuracy which then results from an analysis of the data yields agreement of about 1×10^{-13} for all these laboratory standards. International comparisons of these devices, using TAI as a common reference, show agreements to within 3×10^{-13} peak-to-peak variation. The measurements also indicated (1976) that the TAI frequency was too high with respect to the definition of the second by about 1×10^{-12}. A step adjustment in TAI of 1×10^{-12} corrected this offset on 1 January 1977. The offset was due to the fact that TAI was constructed by the BIH in such a way as to maximize its uniformity, thus reasonably maintaining the rate adopted for TAI on 1 January 1969 on the basis of a limited number of contributing clocks. Other studies were made of the long-term stability of the TAI scale, constructed from commercial caesium standards, using primary standards as the reference. Over a period from 1969 to 1973, the PTB measurements showed the TAI frequency to have decreased on the average by about 1×10^{-13} each year [Becker, 1973]. Later measurements indicate that this drift continued through 1977.

Three long beam primary caesium clocks are now in operation at NRC. CsV, the first long beam primary clock, started operation in May 1975. Accuracy evaluations performed at 6 to 12 month intervals, contribute negligible errors to the time scale, and have given consistent accuracy estimates of better than 1×10^{-13} [Mungall and Costain, 1977; Mungall, 1978]. Three —— smaller clocks; CsVI A, B and C, constructed during 1977 and 1978 were used as secondary clocks during 1979, and as primary clocks from 1979 to 1988. [Mungall *et al.*, 1980, 1981; Mungall and Costain, 1983]. In 1988 CsVI B was removed from the ensemble and used as an experimental clock. These clocks have an accuracy limit of about 1.5×10^{-13}, and require more frequent accuracy evaluations in order to maintain this limit. Systematic corrections for the magnetic field reversal effect and the cavity phase difference tend to be less stable than for CsV, but the re-evaluations, performed when necessary, have maintained agreement with CsV to better than 1×10^{-13}. The long-term frequency instability of all four clocks is approximately 1×10^{-14} for periods of about 24 hours and has attained values of several parts in 10^{15} over periods of several weeks or months. Routine reports to the BIH from these clocks commenced in January, 1980. Since 1985 a degradation of the stability of CsV has been found and is believed to be due to an aging of some electronic components. This has led to rebuilding parts of the electronic system to restore original stability and accuracy.

The difference between the time scales TA(NRC) and TA(PTB) has remained constant within ± 1.2 μs for the period 1977-1983. The frequencies of the primary standards NRC CsV and PTB Cs1, from which the respective time scales are directly derived, have agreed to 3×10^{-14} on a yearly average until 1985. Since that time comparison of time scales have been affected by the stability problems mentioned above.

The Millman effect in the caesium beam clock has been re-examined both theoretically and experimentally. It has been shown that the effect does not exist for $\Delta m_F = 0$ transitions. When such transitions are used to determine the static magnetic field intensity in the clock, the resulting uncertainty on the clock frequency is less than 2×10^{-14} [Vanier *et al.*, 1984].

A new method for the determination of the caesium atom velocity distribution, based on the variation of the Ramsey pattern height with the RF interrogation power, has been implemented. The method leads to the determination of the second order Doppler shift with an uncertainty less than 10^{-14} [Boulanger *et al.*, 1984].

The Physikalisch-Technische Bundesanstalt (PTB) has two primary caesium beam time and frequency standards (Cs1 and Cs2) at its disposal. Cs1 was put into service in 1968. At that time, it had only been switched on approximately every three months to monitor the frequency of PTB's group of atomic clocks consisting of industrial caesium clocks. Since 1978, Cs1 has been in continuous operation as a primary caesium atomic clock, the time scales of PTB have been derived since then directly from Cs1. In addition, the results of primary clock Cs1 contribute directly to the formation of the International Atomic Time scale TAI (Becker, 1979). After a 1-year test phase, Cs2 has now been in continuous operation since 1985. The physically relevant parameters and characteristics of Cs2 are similar to those of Cs1. In contrast to Cs1, however, Cs2 is a double beam apparatus. The uncertainty evaluation for Cs1 yields a 1-σ value of the fractional frequency of $3 \cdot 10^{-14}$ (Dorenwendt, 1986). The corresponding value for Cs2 is $1.5 \cdot 10^{-14}$ (Bauch, 1988). The fractional frequency difference between Cs2 and Cs1, determined from 700 daily values, was $2.5 \cdot 10^{-14}$; it lies in the uncertainty range of both clocks.

Figure 1 shows, for the first time, the two-sample standard deviation of PTB's two primary atomic clocks (Cs2 and Cs1) from data taken over a period of 1000 days.

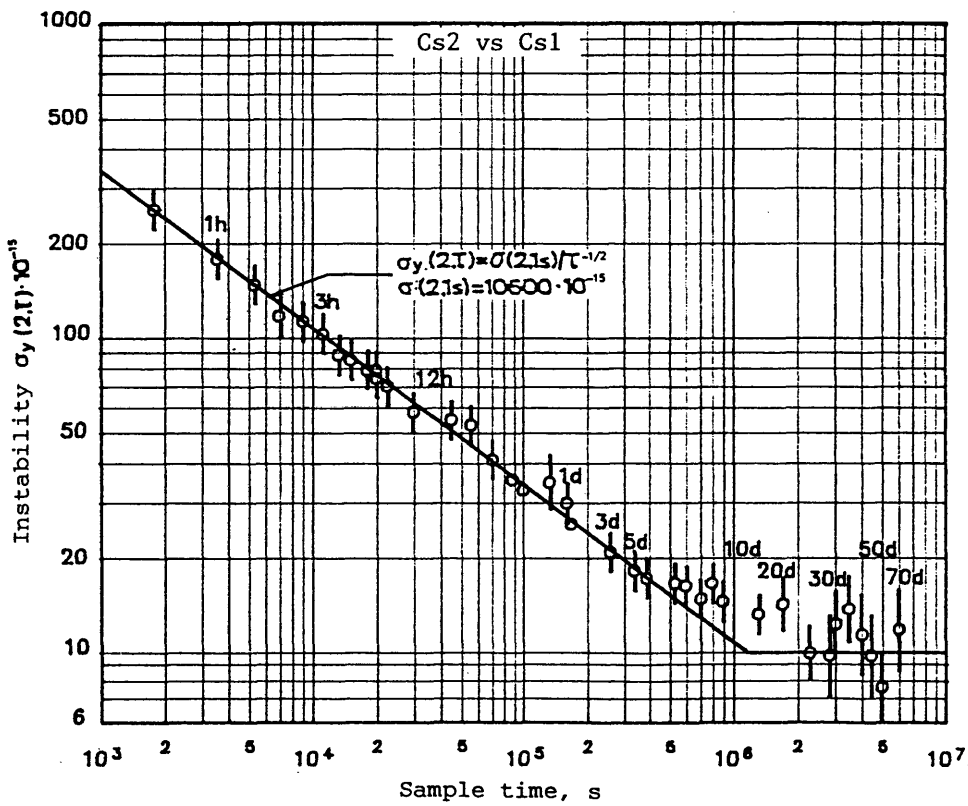

FIGURE 1 - Two sample standard deviation of PTBs Cs2 vs Cs1

The National Institute of Standards and Technology (NIST) (formerly the National Bureau of Standards) has used a series of laboratory-type primary caesium standards for its basic frequency reference since 1960. The current versions, designated NBS-6 and NBS-4, feature interaction regions of up to 3.7 m, reversible beams, and other characteristics designed to permit the thorough re-evaluation of accuracy limits on a regular basis. The yearly accuracy evaluations typically produce uncertainties of less than 1×10^{-13}. The most recent evaluation (July 1987) of NBS-6 gave an accuracy of 2×10^{-13}, which, when combined with the NIST accuracy algorithm, maintained the SI second at NIST with an accuracy of 1×10^{-13}.

At the National Institute of Metrology (NIM) of the People's Republic of China, two laboratory-type 3.8 m caesium primary standards with reversible beams, CsII and CsIII were evaluated and measured several times between 1977 and 1980. The total uncertainties (root mean square) are 4.1 and 4.5×10^{-13} but because of some limitations in operational conditions, it is preferred to claim an accuracy of 8×10^{-13} for CsII. Improvements have been made to the CsIII as a result of which the accuracy is now evaluated at 2.5×10^{-13}.

The USSR state time and frequency standard has two primary caesium standards (MTs-1 and MTs-2) of length 63 and 100 cm respectively. MTs-1 has been operational since 1975 [Iljin *et al.*, 1976] and MTs-2 has been operational since 1980 [Abashev *et al.*, 1980]. Recent improvements in these standards yield accuracies of 1×10^{-13} with frequencies uncertainty of 1.5×10^{-13} for MTs-1 and 1×10^{-13} for MTs-2. The agreement in frequency between the two is 1.5×10^{-13} [Elkin *et al.*, 1983].

The laboratory-type caesium beam standard of the NRLM in Japan has been in operation since 1976. Its accuracy was estimated as 2.2×10^{-13} [Nakadan and Koga, 1985]. During the experiments, an improved method of measuring the Zeeman shift was proposed utilizing a pair of sigma-transitions with the same absolute value of quantum number [Koga, 1984]. The CRL laboratory-type caesium beam standard Cs1 featured a hexapole magnet focusing system and a 55 cm Ramsey cavity using a coaxial line-to-waveguide transducer inside the magnetic shield [Kobayashi *et al.*, 1978]. The CRL has been reporting the data of the accuracy evaluation to the BIH. To improve the accuracy of the CRL Cs 1, the magnetic field effect [Nakagiri et al., 1987], the pulling by the neighbouring transitions [Nakagiri et al., 1988a], and the beam trajectory effect on frequency stability and microwave power-dependent frequency shift were examined [Nakagiri et al., 1988b]. The total uncertainty of CRL Cs 1 in April 1986 was [Nakagiri et al., 1988a] 0.7×10^{-13}.

Analysis has shown that the proper adjustment of commercial caesium beam standards to minimize the effects of RF power sensitivity can improve the performance of the standard to parts in 10^{14} [De Marchi, 1988].

The ASMW Primary Caesium Beam Standard was evaluated and has been operational since 1989. It will be used in continuous operation with an estimated accuracy better than 5.10^{-13} as the base of the national time scale of the German Democratic Republic [ASMW, 1989].

2.2 Optical methods

Optical pumping is being developed as a method for preparing the hyperfine state of the atoms in the beam of a caesium frequency standard. The most obvious attraction of this method is the prospect of more than an order of magnitude increase in beam flux for atoms in a clock transition state ($m_F = 0$), but there are other advantages as well.

The implementation of this has required development of reliable single-mode diode lasers, operating at 852 nm with highly stabilized outputs. A similar laser can also serve to excite optical fluorescence from only one of the hyperfine states to analyse the caesium beam after the microwave resonance region. Optical state preparation and detection are usually used together in an "optically pumped caesium beam frequency standard".

The initial experimental standard [Arditi and Picqué, 1980] used the same laser for optical pumping and detection. It produced an accuracy of a few parts in 10^{11}.

Theoretical work has been done on the shift in the microwave resonance caused by the light [Brillet, 1981; De Clercq and Cérez, 1983], and on the conditions for efficient use of all the hyperfine sub-levels by optical pumping [Avila et al., 1985]. Further theoretical work [Avila et al., 1987] on the optimum conditions has studied various methods for optical pumping and detection in systems with one, two and three lasers. For a two-laser system, very good line symmetry was found for the clock transition, while other microwave resonances had practically disappeared. The resulting reduction of frequency pulling by the neighbouring resonances of the clock transitions permits a useful reduction of the C field [Giordano, 1987].

Progress has been made in stabilizing the frequency of the laser diodes for optical pumping of the caesium beam. The method uses the semiconductor diode as the optical gain medium in an external optical cavity [de Labachelerie and Cérez, 1985]. A signal-to-noise ratio of 10^4 in a 1 Hz noise band was measured for the clock transition resonance at 9.2 GHz [Giordano et al., 1988]. The stability of experimental standard, with a 25 cm microwave cavity was measured for sampling times τ between 1 and 10^3s as $2 \times 10^{-12}/\sqrt{\tau}$ [Candelier et al., 1988].

At NRLM, a laboratory type optically pumped frequency standard was developed [Ohshima et al., 1988a], and some experiments were carried out using two lasers ($F = 4$ to $F' = 4$, σ, for optical pumping and $F = 4$ to $F' = 5$, π, for detection). Each laser line width was narrowed by optical feedback from an external Fabry-Perot cavity, and a signal-to-noise ratio of 6 500 in a 1 Hz noise band was measured. This is essentially beam shot noise limited performance, obtained with a signal-to-background ratio of unity. When this noise level is combined with the measured line Q of 1×10^8, the expected limit to the short-term stability of the standard is as good as $\sigma y\ (\tau) = 3 \times 10^{-13}/\sqrt{\tau}$ (τ in seconds), [Ohshima et al., 1988b]. Actual short-term stability realized by the present system was estimated to be $1.1 \times 10^{-12}/\sqrt{\tau}$ by comparing with a commercial atomic clock [Ohshima et al., 1989a]. The atomic beam velocity distribution of the optically pumped standard was measured by the pulse excitation method, and it was not sensitive to the laser power when it was more than a few milliwatts [Nakadan et al., 1988]. Microwave power dependent frequency shifts were also measured in both beam directions, which were in agreement with the theoretical predictions within the standard deviation of 6×10^{-14} [Ohshima et al., 1989b].

3. Hydrogen frequency standards

For the range of averaging times up to about 10^5 s, the performance of active masers is much better than that of caesium devices. A passive maser can produce better frequency stability performance than a caesium device for averaging times between 1000 and 100 000 s [Walls and Persson, 1984]. Hydrogen masers are not primary standards because of the uncontrolled wall shift [Vanier *et al.*, 1975; Vanier and Larouche, 1978].

Work on the reduction or measurement of the wall shift to improve the accuracy of the maser has been carried out at a number of laboratories. The frequency of the masers at NRC measured against TAI has decreased since 1971; the most accurate measurements, taken over the period 1975 to 1979, showed a change of about 4×10^{-13} per year, with the total change over this period of 1.7×10^{-12} [Morris, 1978]. However, this effect has not been confirmed by all laboratories. Use of a variable volume storage bulb [Brenner, 1969 and 1970; Debely 1970; Uzgiris and Ramsey, 1970; Reinhardt, 1973; Vanier *et al.*, 1975; Vessot *et al.*, 1971], selecting the operating temperature to be at the point where the wall shift is zero (approximately 100 °C) [Vessot *et al.*, 1971; Zitzewitz and Ramsey, 1971; Vessot and Levine, 1970] are possibilities that have been considered. Discovery of an anomalous spin exchange shift and a magnetic inhomogeneity shift [Crampton and Wang, 1974] and development of means to correct for these shifts [Crampton and Wang, 1974; Reinhardt and Peters, 1975] lend some support to a potential achievement of 1×10^{-14} accuracy. The metrological properties of two hydrogen masers were studied in detail [Petit *et al.*, 1974]. A relative frequency stability of 3×10^{-13} for $\tau \approx 10^3$ s and of 2×10^{-14} for $\tau = 5$ days was obtained [Petit *et al.*, 1975]. The elimination of the mean dephasing by collision on the FEP 120 lining in the neighbourhood of 90 °C was verified [Petit *et al.*, 1975]. The theoretical estimate of the spin exchange frequency shift was confirmed experimentally [Desaintfuscien *et al.*, 1975]. It is very useful for the accurate determination of the residual frequency shifts revealed by Crampton *et al.*, [1976]. An accuracy of 6×10^{-13} was achieved on a hydrogen maser equipped with a storage bulb having two teflon-lined compartments [Petit *et al.*, 1980].

Cavity pulling is probably the most important cause for long-term (1 day and longer) instabilities in hydrogen masers. Cavity tuning schemes have been developed and used in active masers [Peters *et al.*, 1968; Vessot and Levine, 1970] as well as passively operating masers [Hellwig and Bell, 1972; Walls and Hellwig, 1976]. Pairs of masers which are auto-tuned against one another can maintain stabilities of 1 to 2×10^{-14} for up to 7 days [Petit *et al.*, 1975; Morris and Nakagiri, 1976]. Long-term stability performance can be improved through servo control of cavity tuning: a value of 3×10^{-15} for times of 3×10^4 s has been obtained [Yahyabey et al., 1987] without degrading short-term stability, similar performance was reported earlier, [Peters, 1984].

The time-keeping performance of a prototype small passive hydrogen maser developed at the NBS [Walls and Hellwig, 1976] was evaluated against UTC (NBS). The measurement indicated a joint time-keeping stability of about 1.2 ns/day and a long-term stability versus NRC Cs-V of as good as 2×10^{-15} at $\tau = 8$ days [Walls, 1987; Weiss and Allan, 1987].

The frequency instability of the small passive maser was measured to be $\sigma_y(\tau) = 1.4 \times 10^{-12}\,\tau^{-1/2}$ for τ in seconds up to one day and $5 \times 10^{-15}\,\tau^{-1/2}$ for a τ of 16 days based on 64 consecutive days of data. The drift versus the NBS caesium ensemble was found to be zero within an uncertainty of $\pm 3 \times 10^{-16}$/day. There was also no evidence of flicker [Walls and Persson, 1984]. Preliminary stability measurements indicate great potential for the maser as a clock. A small passive hydrogen maser now contributes to the NIST time scale. This work demonstrated that the wall shift is constant to within an uncertainty of 3×10^{-16} per day, averaged over 64 days, and that the cavity drift can also be controlled to that level.

The amplitude noise of hydrogen and rubidium masers was analyzed experimentally [Lesage *et al.*, 1980]. The ultimate frequency stability of passively operated hydrogen masers, which depends chiefly on freedom from amplitude noise, was determined [Lesage *et al.*, 1979]. The effect on frequency stability of an electronic reaction enhancing the quality factor of a hydrogen maser cavity was studied both theoretically and experimentally [Tetu *et al.*, 1981]. It was shown that the frequency stability of actively operated compact hydrogen masers should be slightly better than for passively operated masers [Audoin *et al.*, 1981].

An evaluation programme [NASA, 1983] to determine the characteristics of masers of two different types was completed at the Jet Propulsion Laboratory, under the supervision of NASA. The magnetic sensitivity of the masers was measured as 8 to 30 $\times$ 10^{-10}/T, the temperature sensitivity as 7.5 to 15 $\times$ 10^{-15}/K and the pressure sensitivity as 1.5 to 3 $\times$ 10^{-15}/kPa. The frequency instability was 2.0 $\times$ 10^{-14} at 10 s, 9 to 21 $\times$ 10^{-16} at 4000 s and 7 to 8 $\times$ 10^{-15} at 10^6 s. The frequency drift of the masers was 5 to 10 $\times$ 10^{-15} per day. Later VLG-11 masers delivered to the USNO have used improved methods of optical lapping of the joints in the maser cavity and produce a drift of less than 2.5 $\times$ 10^{-15}/day [Vessot *et al.*, 1984].

Later tests of the NASA NR maser at the Johns Hopkins University, Applied Physics Laboratory, showed an instability of 4 $\times$ 10^{-15} at 10^5 s when the drift was removed. The drift rate was constant over one year to an uncertainty of $\pm$ 5 $\times$ 10^{-16}/day [Rueger, 1981].

Work on hydrogen masers in the USSR has been aimed at increasing the long-term frequency stability to 1 $\times$ 10^{-14} and improving their reliability. By inverting the population densities of Zeeman sub-states of the atoms entering the bulb [Zhestkova and Elkin, 1979], the shift due to the inhomogeneity of the permanent magnetic field in the area of the storage bulb was reduced by a factor of several tens to a value 1 to 3 $\times$ 10^{-14} [Elkin *et al.*, 1980]. A determination of the shift in the frequency of the tuned hydrogen maser by spin-exchange processes [Elkin and Zhestkova, 1979] showed that a further improvement in the long-term frequency stability of the hydrogen maser calls for strict control on the stability of the relaxation time of the atoms radiating in the bulb. A more serius obstacle to the further increase in frequency stability for long averaging times is the hydrogen maser frequency change due to the variation in wall shift. A frequency change of the continuously tuned hydrogen maser of 1 $\times$ 10^{-14} per month is fairly characteristic [Gaygerov *et al.*, 1982] and may be due to various reasons relating to changes of the bulb coating, including crystallization or contamination. Research into improved wall shift reproducibility is proceeding in two directions; the use of a flexible storage bulb with zero shift temperature selection, and the search for new bulb coating materials [Demidov *et al.*, 1978]. At present, hydrogen frequency standards are the main means of maintaining the State standard time scale and a number of secondary time and frequency standards in the USSR.

Work on hydrogen masers has been continued since 1966 at the Radio Research Laboratories (RRL, now Communications Research Laboratory (CRL)) of Japan [Saburi *et al.*, 1974; Ohta *et al.*, 1974]. The performance of hydrogen masers was improved by the single-state selection method (Majorana method). A reversible magnetic field and double focusing method were used in this state selection. About 90% of the undesirable atoms in the Zeeman subs-state were eliminated, and the magnetic inhomegeneity shift was reduced to about one-tenth of the shift observed in the conventional state selection [Urabe *et al.*, 1984]. Work on auto-tuned masers with the new state selector is now continuing so that they can be used as clocks. The RRL has also developed two hydrogen masers capable of operating in the field [Morikawa *et al.*, 1984] for use as the time and frequency standard of the K-3 VLBI system, which was developed for the joint VLBI experiment between the RRL and NASA [VLBI Research Development Group, RRL, 1984]. The measured frequency stability is 2.4 $\times$ 10^{-15} for a sample time of 830 s and 1.4 $\times$ 10^{-14} for 10^5 s. The sensitivy to the room temperature is 2.3 $\times$ 10^{-14}/K and the sensitivy to the external magnetic field is 2.5 $\times$ 10^{-9}/T, which is good enough for the usually encountered geomagnetic fields. At VLBI stations, however, the tracking of the antenna may produce large external magnetic field disturbances, which shows the necessity for careful control of the static magnetic field.

4. Superconducting-cavity oscillators

The superconducting cavity oscillator data perhaps merit special attention since this device is not yet as well known as other types of highly stable oscillator frequency standards. This oscillator concept has demonstrated stability performance that exceeds that of any other known oscillator [Jiménez and Septier, 1973; Turneaure and Stein, 1975]. Instabilities of 6 $\times$ 10^{-16} at averaging times of hundreds of seconds were observed under particularly favourable conditions [Stein, 1975]. The super-conducting cavity oscillator appears adaptable to commercial design given reliable low-temperature cryostats, and would be the best oscillator for short or medium-term stabilities (averaging times of up to thousands of seconds). It could be of interest for special uses such as very long baseline interferometry and for the production of high spectral purity microwave and higher frequencies. While the earlier designs showed excessive sensitivity to environmental conditions which would militate against wide usage in spite of their ruggedness and small size, newer designs promise to greatly reduce the environmental effects [Dicks and Strayer, 1984].

The Radio Research Laboratories of Japan (RRL) presently CRL (Communications Research Laboratory) have studied the 9.2 GHz superconducting cavity stabilized oscillator (SCO) since 1976. A stability of $1.1 \times 10^{-14} \tau^{-1/2}$ was calculated from the measured S/N of a SCO and from the cavity, Q of 2.9×10^8. However, the frequency fluctuation of the SCO due to mechanical deformation of the cavity, caused by the tilt and vibration of the dewar container, appears to be serious. The measured acceleration sensitivity of the superconducting cavity was 6.5×10^{-8}/g for vibration frequencies less than 80 Hz [Komiyama, 1985].

5. Ion storage devices

An $^{199}Hg^+$ trapped ion device demonstrated a frequency instability of $\sigma_y(\tau) = 3.6 \times 10^{-11} \tau^{-1/2}$ for $10 \text{ s} < \tau < 3500$ s [Jardino *et al.*, 1980, Jardino et al., 1984], Meis et al., 1988]. Several such devices have been built which show an instability of $\sigma_{y\tau} = 1.2 \times 10^{-12} \tau^{-1/2}$ [Cutler *et al.*, 1981, Cutler et al., 1987]. A $^9Be^+$ trapped ion standard using laser cooling and optical pumping, double resonance exhibited stability equal to that of a commercial caesium standard [Bollinger *et al.*, 1984]. Studies have shown that the main limitation of this technique is the uncertainty of the second order Doppler due to rotation of the ion cloud, which is not affected by the cooling.

A new concept for a frequency standard based on "sympathetic cooling" is being studied theoretically and experimentally. In sympathetic cooling, one ion species is cooled by Coulomb coupling with another ion species which is laser cooled. This was demonstrated by cooling Hg^+ ions via laser-cooled Be^+ ions and is now being considered for use in the mercury standard. The advantage is that the "clock" ions can be continuously cooled, as a.c. Stark shifts from the cooling radiation can be made negligibly small.

Optical frequency standards based on single, laser-cooled ions are being pursued in several laboratories. Cooling to the Lamb-Dicke limit at 281 nm has been demonstrated in Hg^+ ions [Bergquist, et al., 1987] and $Q > 3 \times 10^{10}$ (limited by laser linewidth) has been achieved.

6. Other devices

A frequency instability of 6×10^{-14} over 128 s was obtained with a quartz crystal, fitted with non-adhering electrodes, in the passive mode [Stein *et al.*, 1978; Besson and Peier, 1980].

At the IEN (Istituto Elettrotecnico Nazionale) research has been performed for several years on submillimetre beams using magnesium atoms [Strumia, 1972]. This work may result in a potential primary standard with an accuracy in the region of 10^{-13} [De Marchi *et al.*, 1983]. At IEN experimental and theoretical work has pursued aiming at assessing the characteristics of a Mg beam standard. A Ramsey technique interrogation has been realized [Godone et al., 1986; Bava et al., 1987] and after some improvements the Mg transition frequency has been measured with an uncertainty of 20 Hz, which corresponds to 3×10^{-11}, and the stability in the white frequency noise region turned out $\sigma y\ (2, \tau) = 8 \times 10^{-12} \tau^{-1/2}$ [Godone et al., 1987].

An analysis of the Mg and Ca beam operation was carried out evaluating the signal-to-background and the signal-to-noise ratios at the detector [Bava et al., 1986]. Some sources of uncertainty in the accuracy of the Mg standard were considered in detail: Zeeman corrections [Novero et al., 1988], velocity distribution of metastable atoms [Giusfredi et al., 1988], microwave source instability [Godone et al., 1989a], cavity phase-shift [Bava et al., 1989], black-body radiation shift [Bava et al., 1983]. An overall evaluation of bias and uncertainties is reported in [Godone et al., 1989b].

7. Performance of various devices

The particular type of frequency standard which is selected to serve as an optimum frequency reference in a given application depends, at least in part, on the measurement averaging time involved. Figure 2 presents some measured stability data as a function of measurement averaging time for several different types of frequency standards ranging from commercially available units to large primary standards. Frequency ageing has been removed from these plots. No attempt has been made to extend the stability plots to longer averaging times than shown because sufficiently documented long-term data do not exist for most of the devices.

In Figure 2 it is clear that the quartz oscillator has the best stability at averaging times less than approximately 0.1 s. The atomic standards generally use a quartz oscillator as a flywheel, so their performance is identical to that of the quartz oscillator at sufficiently short averaging times that the servo loop no longer controls the quartz oscillator. Similarly, in the medium-term (1 s to 10^5 s) the hydrogen maser has the best stability, and in the long-term the caesium standard has the best performance (if drift is not removed). Stability improves with increasing cost so, while the rubidium gas cell standard is not the best in any averaging range, it is a good compromise in terms of cost, size, and performance for many applications [Rovera, 1976; Rovera and Beverini, 1977].

Figure 3 uses the data from Figure 2 as well as measured performance to show the power spectral density of phase of various standards.

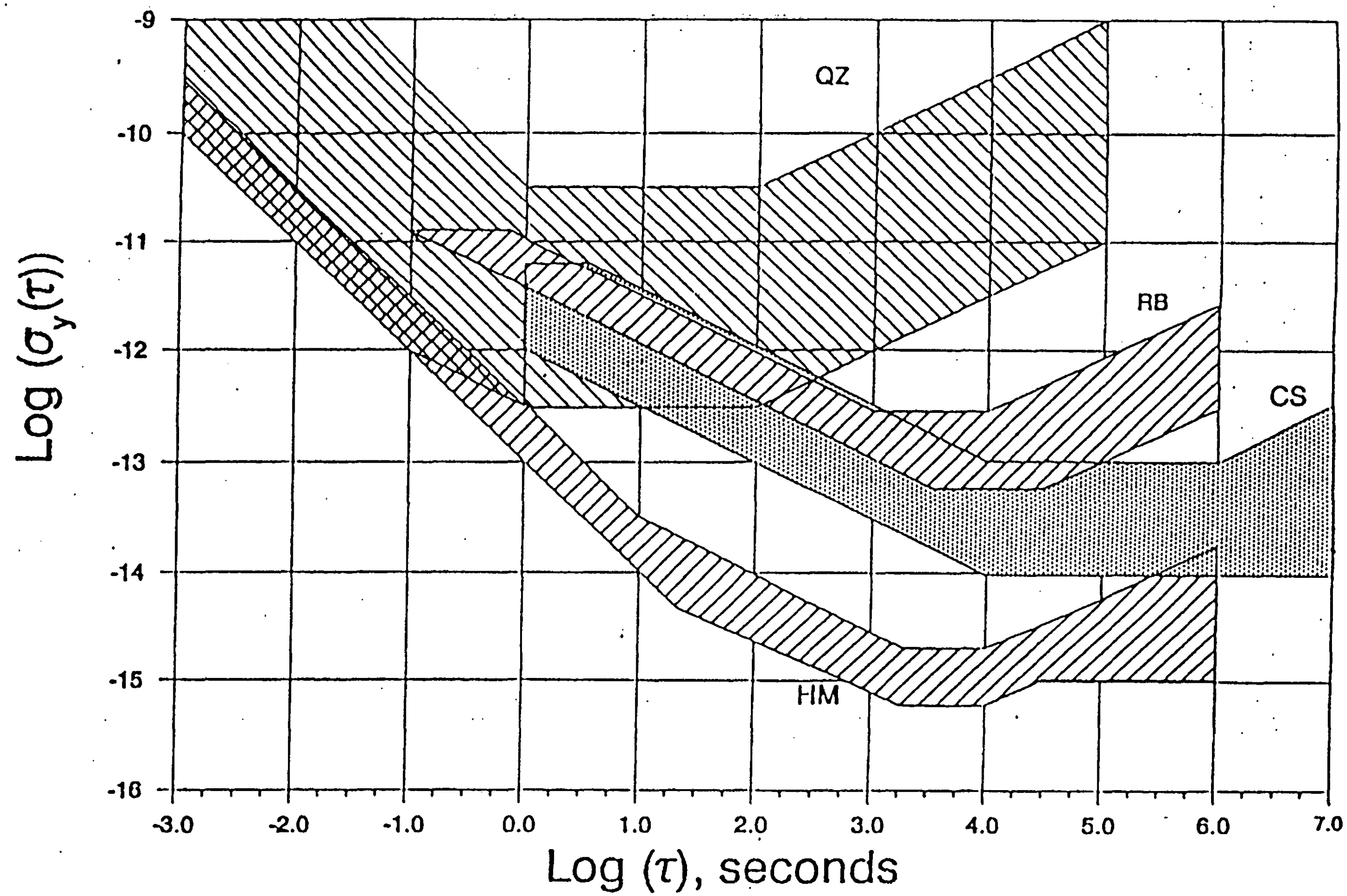

FIGURE 2

Stability Ranges of Various Frequency Standards

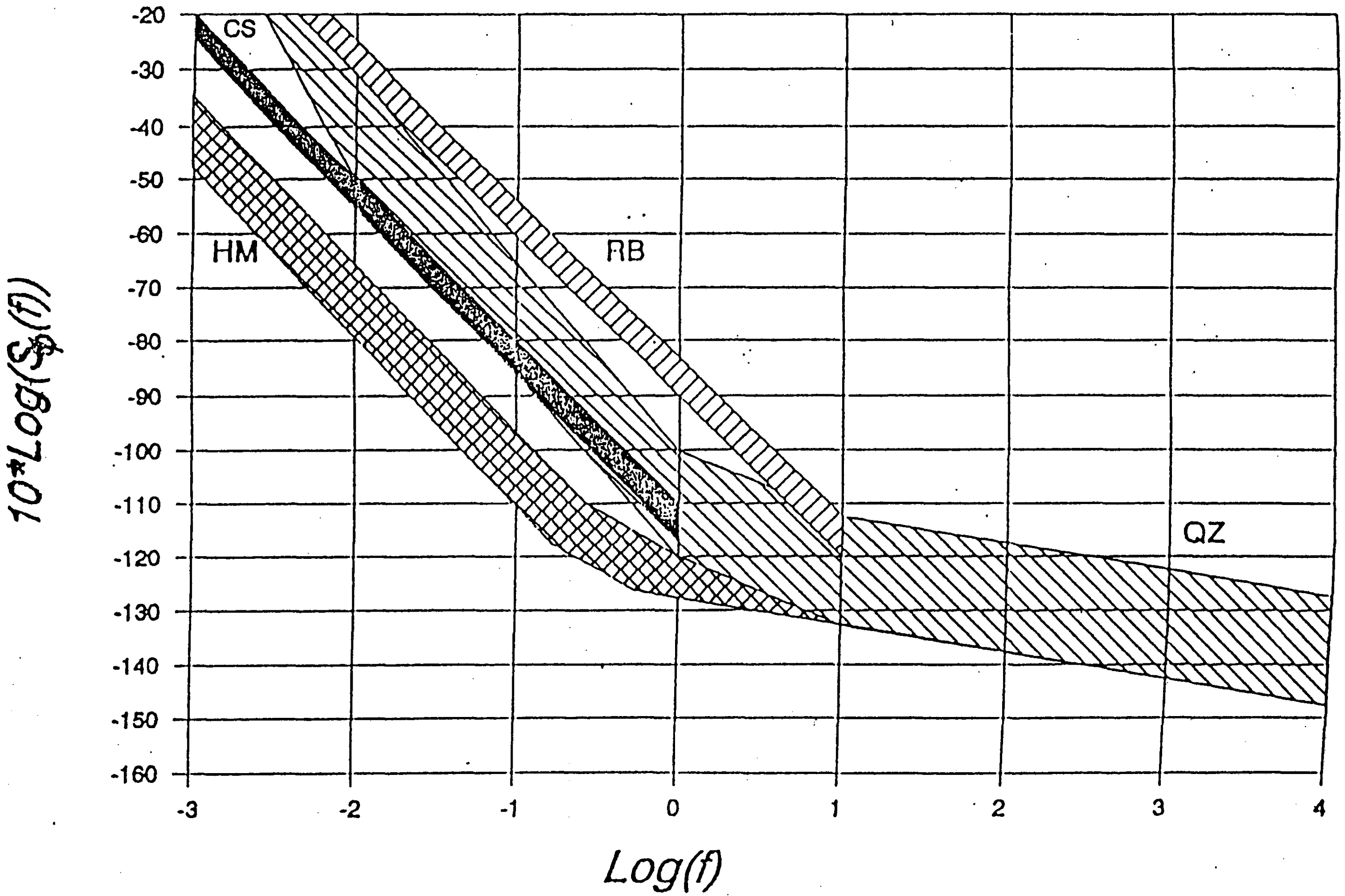

FIGURE 3

Nominal Power Spectral Density of Phase for Various Standards
Calculated at 5 MHz

8. System applications

Table I and Fig. 2 illustrate that the choice of atomic frequency standards should be a matter of careful consideration of the technical alternatives, cost, size, and performance requirements. For system applications using precision oscillators, it is important to first determine the required stability performance of the devices; secondly, to consider the environmental conditions under which the standard has to perform; and thirdly to determine the availability, size, weight, cost and other pertinent characteristics of the standard. Occasionally, a system designer will find that a standard with all the characteristics needed does not exist on the market. In this case, the designer has three alternatives: either to adjust his system parameters to accommodate one of the available standards, choose a combination of these standards to fulfil his need or to initiate a research programme to develop the required standard. It is important to realize that a combination of available standards may satisfy his requirements; suppose, for example, that a system requires very good long-term stability and clock performance, but at the same time high spectral purity; i.e., very good short-term stability. In addition, no cost, weight or size constraints are imposed. An optimum combination for this case could be a crystal oscillator paired with a caesium beam or hydrogen frequency standard. The use of this system's concept as a solution to a design problem, is a very powerful tool, as it can be realized technically without sacrificing the performance of the individual components of the system. The only actual restrictions may be physical size and cost. It may be that, since most frequency standards are already combinations of several technologies, i.e. the caesium standard incorporates a quartz crystal oscillator, as does the hydrogen maser, a minor modification of one of the devices by the substitution of a higher quality quartz crystal oscillator, for example, and a small change in the system time constants may satisfy the design requirements. It should also be noted that with atomic clocks now orbiting the earth in satellites, a satellite receiver can provide long stabilities approaching that of primary timing centers that control and measure them.

Table II gives typical sensitivities of various frequency standards to some environmental effects. Other environmental effects are also important. For example, the humidity effect was investigated at the Istituto Elettrotecnico Nazionale (IEN), Italy, where long-term frequency instabilities and seasonal variations have been detected on the caesium clock ensemble. A relationship between humidity and frequency variations has been evaluated by means of mathematical and statistical processes and coefficients of fractional frequency variations per absolute humidity ranging from $+24 \times 10^{-15}/g^{-1}m^3$ to $-48 \times 10^{-15}/g^{-1}m^3$, depending on the clock considered, have been found [Bava et al., 1987].

Note - For additional information on performance of various frequency standards with respect to reliability see Report 898.

TABLE I

Typical performance in a controlled environment

Frequency standard	Uncertainty	Stability			Volume (dm^3)	Instrument mass (Kg)	Power demand (W)	Commercial availability	Estimated cost 1987 (x 1000 $)
		Short term (100s)	Floor	Ageing per year					
Quartz frequency standard	(1)	10^{-10} to 10^{-13} (2)	10^{-10} to 10^{-13}	10^{-6} to 10^{-10}	1-10	0.1-10	0.1-20	Yes	0.1-10
H maser (large)	10^{-12}	$2x10^{-15}$	$8-20x10^{-16}$	10^{-12} to 10^{-13}	1000	250	100	Yes	350-450
H maser (small unit)	10^{-12}	$1x10^{-14}$	$5x10^{-15}$		100	45	30	Yes	200
Cs beam laboratory	$1x10^{-13}$	$1x10^{-13}$	10^{-14}	(1)	2000	500	100	No	(3)
Cs beam(4) (commercial unit)	$2x10^{-12}$	$1x10^{-12}$	$2-5x10^{-14}$	$<3 \times 10^{-13}$	45	30	30	Yes	40
Rb cell (high performance)	(1)	$7x10^{-13}$	1×10^{-13}	10^{-10}	26	15	35	Yes	20
$^{127}I_2$ stabilized laser (small)	$2x10^{-10}$	$5x10^{-13}$	10^{-12}	(3)	30	40	50	No	40
CH_4 stabilized laser (small)	$4x10^{-11}$	$5x10^{-15}$	$5x10^{-15}$	(3)	30	40	50	No	150
CO_2 stabilized laser	10^{-10}	$1x10^{-12}$	10^{-13}	(3)	60	100	200	No	150

(1) The specification does not apply.

(2) Stability at 1 s

(3) Not available

(4) "High performance unit".

TABLE II

Environmental sensitivities of major frequency standards

Frequency Standard Type	Temperature, per K	Acceleration, per m/s^2*	Magnetic Field, per Tesla	Barometric Pressure, per Pascal	Ageing, per Year
Precision Quartz, Oven Controlled	10^{-12}	10^{-11}	10^{-11}	10^{-12}	10^{-8}
H Maser	10^{-14}	10^{-14}	10^{-11}	10^{-12}	10^{-12}
Cs Beam	10^{-14}	10^{-14}	10^{-10}	10^{-13}	10^{-12}
Rb Cell	10^{-12}	10^{-13}	10^{-14}	10^{-15}	10^{-10}

* For frequencies inside the servo bandwidth. Outside the bandwidth this sensitivity is that of the quartz oscillator.

Other parameters of interest but not tabulated here are: ionizing radiation, acoustical noise, humidity, thermal hysteresis, load isolation and supply voltage.

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REPORT 439-5

RELATIVISTIC EFFECTS IN A TERRESTRIAL COORDINATE TIME SYSTEM

(Study Programme 3C/7)

(1970-1974-1978-1982-1986-1990)

1. Introduction

Advances in the accuracy of time comparisons require the adoption of a set of conventions and a coordinate reference frame in order to account for relativistic effects in a self-consistent manner. Use of transponders or atomic clocks in satellites and jet aircraft will soon result in a network of time standards which are spread over the entire globe; the large distances involved also contribute to the need for well-defined procedures in accounting for relativistic effects in time comparisons. This Report proposes the adoption of local, geocentric reference frames to be used in these time comparisons.

The Consultative Committee for the Definition of the Second (CCDS) at its 9th session (23-25 September, 1980) recognized this need and proposed to the International Committee of Weights and Measures (CIPM):

- that TAI is a coordinate time scale defined at a geocentric datum line and having as its unit one SI second as obtained on the geoid in rotation and
- that, in consequence, in the present state of the art it may be extended with sufficient accuracy to any fixed or mobile point near the geoid by applying the corrections of the first order of general relativity, i.e. the corrections for differences in gravitational potential and velocity and for the rotation of the Earth.

The present Report is consistent with the CCDS proposal, but extends the proposed procedures to heights which include geostationary-satellite orbits. The following equations are accurate in representing clock rates to better than 1 part in 10^{14}.

When transferring time from point P to point Q, the process can be viewed either from a geocentric, earth-fixed, rotating reference frame, case R or from a geocentric, non-rotating, local inertia frame, case N.

2. Clock transport

2.1 *Case R*

When transferring time from point P to point Q by means of a portable clock, the coordinate time accumulated during transport is:

$$\Delta t = \int_P^Q \mathrm{d}s \left[1 - \frac{\Delta U(\vec{r})}{c^2} + \frac{v^2}{2c^2} \right] + \frac{2\omega}{c^2} A_E \tag{1}$$

where c is the speed of light; ω is the angular velocity of rotation of the Earth; v is the velocity of the clock with respect to the ground; $\vec{r}$ is a vector whose origin is at the centre of the Earth and whose terminus moves with the clock from P to Q; A_E is the equatorial projection of the area swept out during the time transfer by the vector $\vec{r}$ as its terminus moves from P to Q; $\Delta U(\vec{r})$ is the potential difference between the location of the clock at $\vec{r}$ and the geoid as viewed from an earth-fixed coordinate system, with the convention that $\Delta U(\vec{r})$ is positive when the clock is above the geoid; and ds is the increment of proper time accumulated on the portable clock. The increment of proper time is the time accumulated on the portable standard clock as measured in the "rest frame" of the clock; that is, in the reference frame travelling with the clock. A_E is measured in an earth-fixed coordinate system. As the area A_E is swept, it is taken as positive when the projection of the path of the clock on the equatorial plane is eastward. When the height h of the clock is less than 24 km above the geoid, $\Delta U(\vec{r})$ may be approximated by gh, where g is the total acceleration due to gravity (including the rotational acceleration of the Earth) evaluated at the geoid. This approximation applies to all aerodynamic and earthbound transfers. When h is greater than 24 km, the potential difference $\Delta U(\vec{r})$ must be calculated to greater accuracy as follows:

$$\Delta U(\vec{r}) = -GM_e\left(\frac{1}{r} - \frac{1}{a_1}\right) - \frac{1}{2}\,\omega^2(r^2 \sin^2\theta - a_1{}^2) + \frac{J_2 GM_e}{2a_1}\left[1 + \left(\frac{a_1}{r}\right)^3 (3\cos^2\theta - 1)\right] \tag{2}$$

where a_1 is the equatorial radius of the Earth; r is the magnitude of the vector $\vec{r}$; θ is the colatitude; GM_e is the product of the Earth's mass and the gravitational constant; and J_2 is the quadrupole moment coefficient of the Earth, $J_2 = +1.083 \times 10^{-3}$.

2.2 *Case N*

When transferring time from point P to point Q by means of a clock the coordinate time elapsed during the motion of the clock is:

$$\Delta t = \int_P^Q \mathrm{d}s \left[1 - \frac{U(\vec{r}) - U_g}{c^2} + \frac{v^2}{2c^2}\right] \tag{3}$$

where $U(\vec{r})$ is the potential at the location of the clock and v is the velocity of the clock, both as viewed (in contrast to equation (1)) from a geocentric non-rotating reference frame, and U_g is the potential at the geoid, including the effect on the potential of the Earth's rotational motion. Note that $\Delta U(\vec{r}) \neq U(\vec{r}) - U_g$, since $U(\vec{r})$ does not include the effect of the Earth's rotation. This equation also applies to clocks in geostationary orbits but should not be used beyond a distance of about 50 000 km from the centre of the Earth.

3. Electromagnetic signals

3.1 *Case R*

From the viewpoint of a geocentric, earth-fixed, rotating frame, the coordinate time elapsed between emission and reception of an electromagnetic signal is:

$$\Delta t = \frac{1}{c}\int_P^Q \mathrm{d}\sigma \left[1 - \frac{\Delta U(\vec{r})}{c^2}\right] + \frac{2\omega}{c^2} A_E \tag{4}$$

where $\mathrm{d}\sigma$ is the increment of standard length, or proper length, along the transmission path; $\Delta U(\vec{r})$ is the potential at the point, $\vec{r}$, on the transmission path less the potential at the geoid (see equation (3)), as viewed from an earth-fixed coordinate system, and A_E is the area circumscribed by the equatorial projection of the triangle whose vertices are:

- at the centre of the Earth;
- at the point, P, of transmission of the signal;
- at the point, Q, of reception of the signal.

The area, A_E, is positive when the signal path has an eastward component. The second term amounts to about a nanosecond for an Earth-to-geostationary satellite-to-Earth trajectory. In the third term, $2\omega/c^2 = 1.6227 \times 10^{-6}$ ns/km^2; this term can contribute hundreds of nanoseconds for practical values of A_E. The increment of proper length, $\mathrm{d}\sigma$, can be taken as the length measured using standard rigid rods at rest in the rotating system; this is equivalent to measurement of length by taking $c/2$ times the time (normalized to vacuum) of a two-way electromagnetic signal sent from P to Q and back along the transmission path.

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3.2 *Case N*

From the viewpoint of a geocentric non-rotating (local inertial) frame, the coordinate time elapsed between emission and reception of an electromagnetic signal is:

$$\Delta t = \frac{1}{c} \int_P^Q d\sigma \left[1 - \frac{U(\vec{r}) - U_g}{c^2} \right] \tag{5}$$

where $U(\vec{r})$ and U_g are defined as in equation (3), and $d\sigma$ is the increment of standard length, or proper length, along the transmission path. The quantities of $d\sigma$ appearing in equation (4) and (5) differ slightly because the reference frames in which they are measured are rotating with respect to each other.

4. Examples

Due to relativistic effects, a clock at an elevated location will appear to be higher in frequency and will differ in normalized rate from TAI by:

$$\frac{\Delta U_T}{c^2}$$

where ΔU_T is the difference in the total potential (gravitational and the centrifugal potentials), and where c is the velocity of light. Near sea level this is given by:

$$\frac{g(\varphi)h}{c^2} \tag{6}$$

where $g(\varphi) = (9.780 + 0.052 \sin^2 \varphi)$ m/s^2, φ is the geographical latitude, and $g(\varphi)$ is the total acceleration at sea level (gravitational and centrifugal) and where h is distance above sea level. Equation (6) must be used in comparing primary sources of the SI second with TAI and with each other. For example, at latitude 40°, the rate of a clock will change by $+1.091 \times 10^{-13}$ for each kilometre above sea level.

If a clock is moving relative to the Earth's surface with the speed v which may have the component v_E in the direction to the East, the normalized difference of the frequency of the moving clock from that of a clock at rest at sea level is:

$$-\frac{1}{2}\frac{v^2}{c^2} + \frac{g(\varphi)h}{c^2} - \frac{1}{c^2} \cdot \omega \cdot r \cdot \cos\varphi \cdot v_E \tag{7}$$

ω is the angular rotational velocity of the Earth ($\omega = 7.992 \times 10^{-5}$ rad/s), r the distance of the clock from the centre of the Earth (Earth radius = 6378.140 km), c is the velocity of light ($c = 2.99792458 \times 10^5$ km/s) and φ the geographical latitude.

For example, if a clock is moving 270 m/s East at 40° latitude at an altitude of 9 km, the normalized difference of frequency of the moving clock relative to that of a clock at rest at sea level due to this effect is:

$$-4.06 \times 10^{-13} + 9.82 \times 10^{-13} - 1.072 \times 10^{-12} = -4.96 \times 10^{-13}$$

The choice of a coordinate frame is purely a discretionary one, but to define coordinate time, a specific choice must be made. It is recommended that for terrestial use a topocentric frame be chosen. In this frame, when a clock B is synchronized with a clock A (both clocks being stationary on the Earth) by a radio signal travelling from A to B, these two clocks differ in coordinate time by:

$$B - A = -\frac{\omega}{c^2} \int_P r^2 \cos^2\varphi \, d\lambda \tag{8}$$

where φ is the latitude, λ the longitude (the positive sense being toward East), and P is the path over which the radio signal travels from A to B. If the two clocks are synchronized by a portable clock, they will differ in coordinate time by:

$$B - A = \int_P \mathrm{d}t \left(\frac{\Delta U_T}{c^2} - \frac{v^2}{2c^2}\right) - \frac{\omega}{c^2} \int_P r^2 \cos^2 \varphi \, \mathrm{d}\lambda \qquad (9)$$

where v is the portable clock's ground speed, and P is the portable clock's path from A to B.

This difference can also be as much as several tenths of a microsecond. It is recommended that equations (8) or (9) be used as correction equations for long-distance clock synchronization. Since equations (8) and (9) are path dependent, they must be taken into account in any self-consistent coordinate time system.

If a clock is transported from a point A to a point B and brought back to A on a different path at infinitely low speed at $h = 0$, its time will differ from that of a clock remaining in A by:

$$\Delta t = -\frac{2\omega A_E}{c^2} \qquad (10)$$

where A_E is the area defined by the projection of the round trip path on to the plane of the Earth's equator. A_E is considered positive if the path is traversed in the clockwise sense viewed from the South Pole.

For example since:

$$2\omega/c^2 = 1.6227 \times 10^{-6} \text{ ns/km}^2$$

the time of a clock carried eastward around the Earth at infinitely low speed at $h = 0$ at the equator will differ from a clock remaining at rest by -207.4 ns.

Additional definitions and conventions are under consideration by the International Astronomical Union (IAU) [Guinot and Seidelmann, 1988].

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REPORT 579-4

TIME SCALE ALGORITHM AND ASSOCIATED AVERAGING PROBLEMS

(Study Programme 10B/7)

(1974-1978-1982-1986-1990)

1. Uniformity

In most laboratories the local independent time scale is obtained from an ensemble of commercial caesium standards and is maintained uniform without reference to the calibrations by laboratory primary standards. To achieve a high uniformity, predicted rate corrections and weighting factors are applied to individual standards.

Rate prediction is essential for maintaining stability during modifications to the clock ensemble and to changes in weighting. It usually plays no part in forming the scale in the case of invariable ensembles having a fixed weighting [Guinot, 1987].

The simplest and most widespread rate prediction is the mean observed rate during a past time interval (linear prediction) relative to the clock ensemble. However, it is not justified by theoretical considerations. A near-optimum recursive prediction for a realistic model of frequency fluctuations was developed by the National Bureau of Standards [Allan and Gray, 1971; Allan et al., 1973]. This method of prediction features both a short-term and a long-term pair of weighting factors for each member clock. In addition, an adaptative filter (estimating the performance of each clock) is used to respond to degraded performance as well as gradual changes in the stochastic behavior [Allan et al., 1974; Allan and Weiss, 1988].

In some cases, a simpler weighting procedure is satisfactory: a clock is either considered with full "weight 1" or, in case of unsatisfactory performance, with "weight 0".

Clock averaging procedures which make use of different assumptions concerning clock behaviour and the concept of a uniform time scale are also used [Winkler *et al.*, 1970; Percival, 1978]. These methods employ iterative procedures with corrections applied which compensate for the contributions of those clocks which have excessively deviated from expected behaviour.

Research at the Physikalisch-Technische Bundesanstalt (PTB) and other laboratories has shown that the random model may not be sufficient to characterize fully long-term performance. Systematic frequency drifts and frequency jumps may occur. Effort has been devoted to the recognition of these non-random effects [Ganter, 1973]. They emphasize the need for precise calibrations of the clocks.

In the United Kingdom, an attempt is proposed to bring into operation a time scale combining the capabilities of several establishments, initially the National Physical Laboratory (NPL) and the Royal Greenwich Observatory (RGO). Such a system would be of a character intermediate between the two extreme cases of a central and a distributed system and would achieve the advantages of both with respect to availability and reliability. Centralization of the time scale computations, along with the appropriate improvements in the necessary links, would satisfy the accuracy requirements [Gibbs, 1980].

An improved method of time scale computation with weighted clock contributions [Imae, 1979; RRL, 1978] has been introduced by the Radio Research Laboratories (RRL ,presently Communication Research Laboratories (CRL)) of Japan. By using a weighting factor ~~~~ for each clock which is derived from long term ($\tau \geqslant 10$ days) as well as short term ($\tau \leqslant 1$ day) variances, it is possible to improve the time scale stability in both areas, long term and short term. It has been demonstrated in a computer simulation that the time scale computation can be considerably improved if the bias of the clock variances is compensated before these variances are used for the determination of individual weighting factors [Yoshimura, 1980].

Stability of a time scale using the compensated weighting factors for the bias of the clock variances which correspond to the long-term and short-term stability proved to be about 2×10^{-13} for the averaging times of 10 to 300 days, with reference to TAI via Loran-C (9970-M) of four commercial caesium standards (Cs 2 and Cs 3).

Using an ensemble of rubidium clocks, the Shanghai Observatory atomic time scale and the Shaanxi Observatory atomic time scale were established respectively in 1978 and 1979. The calibration references for the Shanghai Observatory atomic time scale are a caesium beam standard and three hydrogen masers and for the Shaanxi Observatory atomic time scale are two hydrogen masers. All atomic clocks used in these two observatories were developed and constructed in the People's Republic of China [Chuang and Jair, 1980 and 1981; Shaanxi Observatory, 1979].

The atomic time scales of Shanghai and Shaanxi Observatories were compared with each other and with other atomic time scales in China via television links and portable clock and with UTC time scales abroad via satellite and LF (Loran-C) and VLF transmissions. The long-term instability over 30-day sampling time of the Shanghai Observatory atomic time scale is (3 to 4) $\times 10^{-13}$ relative to UTC(USNO) for a period of two years from 1978. The Shaanxi Observatory atomic time scale has a comparable long-term stability to that of the Shanghai Observatory.

The atomic time scale of the National Institute of Metrology of China was established in 1980. This atomic time scale is based on an ensemble of four commercial caesium standards (HP-5061A) and is calibrated against two primary laboratory caesium beam standards (Cs 2 and Cs 3). During more than one year of continuous operation the accuracy of TA(NIM) was determined as $1 \times 10^{-12}(1\sigma)$. The uniformity of TA(NIM) is $\sigma_y(\tau = 10 \text{ days}) \leqslant 1.0 \times 10^{-13}$ (this value was obtained by internal comparisons).

In France, a method of comparison by television, which has been applied since 1968, uses data from a dozen caesium clocks placed in different laboratories to calculate the French atomic time-scale TA(F). A statistical weighting method, using as a criterion the long-term stability of each of the standards, is employed to form the average scale; each weight may vary from 0-1. The average weight improved from 0.4-0.5 in 1972-73 to 0.8-0.98 in 1981-82. The stability of the TA(F) time scale in relation to the TAI has been of the order of $\pm 3 \times 10^{-13}$, since 1972. On 1 January, 1977, the frequency of the TA(F) was reduced by 15×10^{-13}, so as to make it agree as closely as possible with the SI second. In 1983, it varied between -3 and -5×10^{-13}. Since it is not derived from a primary laboratory standard, the TA(F) has an accuracy given by the mean frequency of the commercial clocks used.

During June 1982, the National Bureau of Standards and the BIH co-sponsored the 2nd International Symposium on Atomic Time Scale Algorithms at NBS/Boulder. Some of the topics discussed included:

- timekeeping processes;
- an automated high-accuracy phase measurement system [Stein *et al.*, 1982];
- the history and structure of ALGOS;
- a maximum likelihood method for estimating clock parameters and the development of a Kalman filter algorithm based on these parameters for minimum time dispersion in an ensemble [Jones and Tryon, 1983];
- the use of robust statistics in forming time scales;
- international clock comparisons at the 10 ns accuracy level using common view of GPS satellites [Davies *et al.*, 1981];
- a real-time ensemble clock system at NBS; and
- reports on timekeeping at various international laboratories.

During 1987 and 1988 some additional important results were reported regarding the effects on time scale accuracy and uniformity. Changes to humidity were found to correlate with frequency changes in several commercial cesium beam frequency standards [Bava et al, 1987; Gray et al, 1988]. The outstanding long-term stability of millisecond pulsars has created a need for improving the frequency stability of time scales and for better utilization of resources on an international basis [Rawley, 1987; Allan, 1987]. The importance of post analysis, that is, generating time scales in retrospect, and of considering systematic and environmental perturbations as well as stochastic perturbations has become more apparent [Allan et al, 1989; Guinot, 1988]. Specifically, Guinot has generated a time scale, TTBIPM88 (Terrestrial Time from the BIPM in 1988), in retrospect because of the more exacting demands coming from millisecond pulsar astrometry. The increased interest in long-term time scale stability resulted in the Third International Atomic Time Scale Algorithm Symposium; proceedings are available from NIST. A modified Kalman time-scale algorithm has been developed as the station clock for GPS and is now being tested [Stein, 1988; Gifford et Varnum, 1988].

2. Accuracy

The above-mentioned methods may give rise to important frequency departure in the long term. Frequency corrections must be applied in order to maintain the agreement of the time scale unit with the second.

One of the problems is to evaluate the frequency correction, when several calibrations of the time scale frequency with respect to the primary standards are available. Yoshimura [1972], Azoubib *et al.* [1977] derived formulae giving the weights of the calibrations for usual models of random noise in the time scales.

At the National Research Council of Canada, commercial caesium clocks were calibrated twice a week with CsIII [Mungall, 1971] until 28 December 1975. Since that date TA(NRC) has been derived, with a 0.97 ns/day gravitational correction, directly from the output of the primary standard of time and frequency, CsV. For most of the twelve years the annual evaluation has shown that the clock has maintained its estimated accuracy of 5×10^{-14}. Occasionally (1985, 1987) aging components affected severely the frequency of the clock (offset of the order of $1\text{-}2 \times 10^{-13}$). In 1979 three smaller primary standards, CsVIA, B and C were put into continuous operation as clocks. On evaluation, the CsVI clocks have usually been within 5×10^{-14} of CsV, with the outside limit of 1×10^{-13}. However, their magnetic fields and cavity phase differences tend to be less stable than in CsV, and evaluations at about 6 months intervals have been necessary to maintain their accuracy limit of 1.5×10^{-13} [Mungall and Costain, 1983]. Routine reports are made to the BIPM on the individual clocks. NBS performs a complete evaluation of its primary standard approximately annually, and the results are used in a steering algorithm to control TA(NBS) [Allan *et al.*, 1975]. This steering algorithm has the advantage of incorporating the short-term (days-to-weeks) stability of the NBS clock ensemble but also of having the long-term stability determined by the accuracy of the primary standard. Thus, the rate of TA(NBS) is always steered toward the SI second.

Until July 1978, the atomic time scale TA(PTB) of the Physikalisch-Technische Bundesanstalt at Braunschweig was derived from the weighted average of an ensemble of commercial clocks [Hübner, 1979]. With the aid of the primary standard Cs1, a frequency calibration of the TA(PTB) was performed four times a year on an average. Since the continuous operation of Cs1, which started at that time, TA(PTB) has been directly derived from the primary standard. The most important operational parameters of Cs1 are measured at regular intervals. A beam reversal is executed every five to six weeks [Becker, 1979]. For the period 1977-1983, the relative frequency difference of the atomic time scale TA(NRC) of the National Research Council in Canada and the atomic time scale TA(PTB), both directly derived from primary standards, has remained smaller than 7×10^{-14} on an 80-day average.

3. International Atomic Time (TAI)

Until August, 1973, TAI was a mean of 7 local independent atomic times. The weighting of these scales was discussed by Becker and Hubner [1973]; several weighting procedures were tested by these authors and also at the Bureau international de l'heure (BIH) [Granveaud and Guinot, 1972]. As a consequence of the difficulties in assigning weights to the time scales, the BIH began in June, 1973 to use directly data from individual clocks with a prediction and weighting procedure described in the BIH Annual Report for 1973. Since 1 January, 1977 a steering procedure has been applied in order to maintain the TAI time scale unit in conformity with the realizations of the SI second at the geoid level (see BIH Annual Report for 1977).

Improvements in atomic clocks and time comparisons have twice led to revision of the rules for weighting clocks participating in TAI, once in 1981 and again in 1988. Under the weighting rule in force since 1 January 1988, the maximum assignable weight corresponds to a clock having:

$$\sigma_y\ (N = 6,\ \tau = 2\ \text{months}) = 3.7 \times 10^{-14}.$$

The BIH has studied the response to random and non-random variations for the TAI type of algorithm [Granveaud, 1982]. Detailed information on the calculation of TAI from 1973 to 1984 is set out in "Echelles de temps atomique" [Granveaud, 1986].

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REPORT 580-3

CHARACTERIZATION OF FREQUENCY AND PHASE NOISE

(Study Programme 3B/7)

(1974-1978-1986-1990)

1. Introduction

Techniques to characterize and to measure the frequency and phase instabilities in frequency generators and received radio signals are of fundamental importance to users of frequency and time standards.

In 1964 a subcommittee on frequency stability was formed, within the Institute of Electrical and Electronic Engineers (IEEE) Standards Committee 14 and later (in 1966) in the Technical Committee on Frequency and Time within the Society of Instrumentation and Measurement (SIM), to prepare an IEEE standard on frequency stability. In 1969, this subcommittee completed a document proposing definitions for measures on frequency and phase stabilities. These recommended measures of stabilities in frequency generators have gained general acceptance among frequency and time users throughout the world. Some of the major manufacturers now specify stability characteristics of their standards in terms of these recommended measures.

Models of the instabilities may include both stationary and non-stationary random processes as well as systematic processes. Concerning the apparently random processes, considerable progress has been made [IEEE-NASA, 1964; IEEE, 1972] in characterizing these processes with reasonable statistical models. In contrast, the presence of systematic changes of frequencies such as drifts should not be modelled statistically, but should be described in some reasonable analytic way as measured with respect to an adequate reference standard, e.g., linear regression to determine a model for linear frequency drift. The separation between systematic and random parts however is not always easy or obvious [Barnes, 1983]. The systematic effects generally become predominant in the long term, and thus it is extremely important to specify them in order to give a full characterization of a signal's stability [Allan, 1987]. This Report presents some methods of characterizing the random processes and some important types of systematic processes.

Since then, additional significant work has been accomplished. For example, Baugh [1971] illustrated the properties of the Hadamard variance – a time-domain method of estimating discrete frequency modulation sidebands – particularly appropriate for Fourier frequencies less than about 10 Hz; a mathematical analysis of this technique has been made by Sauvage and Rutman [1973]; Rutman [1972] has suggested some alternative time-domain measures while still giving general support to the subcommittee's recommendations; De Prins *et al.* [1969] and De Prins and Cornelissen, [1971] have proposed alternatives for the measure of frequency stability in the frequency domain with specific emphasis on sample averages of discrete spectra. A National Bureau of Standards Monograph devotes Chapter 8 to the "Statistics of time and frequency data analysis" [Blair, 1974]. This chapter contains some measurement methods, and applications of both frequency-domain and time-domain measures of frequency/phase instabilities. It also describes methods of conversion among various time-domain measures of frequency stability, as well as conversion relationships from frequency-domain measures to time-domain measures and vice versa. The effect of a finite number of measurements on the accuracy with which the two-sample variance is determined has been specified [Lesage and Audoin, 1973, 1974 and 1976; Yoshimura, 1978 ; Howe *et al.*, 1981]. Box-Jenkins-type models have been applied for the interpretation of frequency stability measurements [Barnes, 1976; Percival, 1976] and reviewed by Winkler [1976].

Lindsey and Chie [1976] have generalized the r.m.s. fractional frequency deviation and the two-sample variance in the sense of providing a larger class of time-domain oscillator stability measures. They have developed measures which characterize the random time-domain phase stability and the frequency stability of an oscillator's signal by the use of Kolmogorov structure functions. These measures are connected to the frequency-domain stability measure $S_y(f)$ via the Mellin transform. In this theory, polynominal type drifts are included and some theoretical convergence problems due to power-law type spectra are alleviated. They also show the close relationship of these measures to the r.m.s. fractional deviation [Cutler and Searle, 1966] and to the two-sample variance [Allan, 1966]. And finally, they show that other members from the set of stability measures developed are important in specifying performance and writing system specifications for applications such as radar, communications, and tracking system engineering work.

Other forms of limited sample variances have been discussed [Baugh, 1971; Lesage and Audoin, 1975; Boileau and Picinbono, 1976] and a review of the classical and new approaches has been published [Rutman, 1978].

Frequency and phase instabilities may be characterized by random processes that can be represented statistically in either the Fourier frequency domain or in the time domain [Blackman and Tukey, 1959]. The instantaneous, normalized frequency departure $y(t)$ from the nominal frequency ν_0 is related to the instantaneous-phase fluctuation $\varphi(t)$ about the nominal phase $2\pi\nu_0 t$ by:

$$y(t) = \frac{1}{2\pi\nu_0}\frac{d\varphi(t)}{dt} = \frac{\dot{\varphi}(t)}{2\pi\nu_0} \tag{1}$$

$$x(t) = \frac{\varphi(t)}{2\pi\nu_0}$$

where $x(t)$ is the phase variation expressed in units of time.

2. Fourier frequency domain

In the Fourier frequency domain, frequency stability may be defined by several one-sided (the Fourier frequency ranges from 0 to ∞) spectral densities such as:

$S_y(f)$ of $y(t)$, $S_\varphi(f)$ of $\varphi(t)$, $S_{\dot{\varphi}}(f)$ of $\dot{\varphi}(t)$, $S_x(f)$ of $x(t)$, etc.

These spectral densities are related by the equations:

$$S_y(f) = \frac{f^2}{\nu_0^2} S_\varphi(f) \tag{2}$$

$$S_{\dot{\varphi}}(f) = 4\pi^2 f^2 S_\varphi(f) \tag{3}$$

$$S_x(f) = \frac{1}{(2\pi\nu_0)^2} S_\varphi(f) \tag{4}$$

Power-law spectral densities are often employed as reasonable models of the random fluctuations in precision oscillators. In practice, it has been recognized that for many oscillators these random fluctuations are the sum of five independent noise processes and, with few limitations, the following equation is representative:

$$S_y(f) = \begin{cases} \sum_{\alpha=-2}^{+2} h_\alpha f^\alpha & \text{for } 0 < f < f_h \\ 0 & \text{for } f > f_h \end{cases} \tag{5}$$

where h_α's are constants, α's are integers, and f_h is the high frequency cut-off of a low pass filter. Equations (2), (3) and (4) are correct and consistent for stationary noises including phase noise. High frequency divergence is eliminated by the restrictions on f in equation (5). The identification and characterization of the five noise processes are given in Table I, and shown in Fig. 1. In practice, only two or three noise processes are usually sufficient to describe the random frequency fluctuations in a specific oscillator; the others may be neglected.

3. Time-domain

Random frequency instability in the time-domain may be defined by several sample variances. The recommended measure is the two-sample standard deviation which is the square root of the two-sample zero dead-time variance $\sigma_y{}^2(\tau)$ [von Neumann *et al.*, 1941; Allan, 1966; Barnes *et al.*, 1971] defined as:

$$\sigma_y{}^2(\tau) = \left\langle \frac{(\bar{y}_{k+1} - \bar{y}_k)^2}{2} \right\rangle \tag{6}$$

where

$$\bar{y}_k = \frac{1}{\tau} \int_{t_k}^{t_k + \tau} y(t)\, \mathrm{d}t = \frac{x_{k+1} - x_k}{\tau} \quad \text{and} \quad t_{k+1} = t_k + \tau \quad \text{(adjacent samples)}$$

$< >$ denotes an infinite time average. The measure written in equation (6) is often called the Allan variance. The x_k and x_{k+1} are time residual measurements made at t_k and $t_{k+1} = t_k + \tau$, $k = 1, 2, \ldots$, and $1/\tau$ is the fixed sampling rate which gives zero dead time between frequency measurements. By "residual" it is understood that the known systematic effects have been removed.

If the initial sampling rate is specified as $1/\tau_0$, then it has been shown [Howe *et al.*, 1981] that in general one may obtain a more efficient estimate of $\sigma_y(\tau)$ using what is called "overlapping estimates". This estimate is obtained by computing equation (7).

$$\sigma_y^2(\tau) = \frac{1}{2(N - 2n)\tau^2} \sum_{i=1}^{N-2n} (x_{i+2n} - 2x_{i+n} + x_i)^2 \tag{7}$$

where N is the number of original time departure measurements spaced by τ_0, ($N = M + 1$, where M is the number of original frequency measurements of sample time, τ_0) and $\tau = n\tau_0$.

If dead time exists between the frequency departure measurements and this is ignored in computing equation (6), it has been shown that the resulting stability values (which are no longer the Allan variances), will be biased (except for the white frequency noise) as the frequency measurements are regrouped to estimate the stability for $n\tau_0$ ($n > 1$). This bias has been studied and some tables for its correction published [Barnes and Allan, 1988; Lesage, 1983].

If there is no dead time, then the original $\bar{y}_i$'s can be combined to create a set of $\bar{y}_k$'s:

$$\bar{y}_k = \frac{1}{n} \sum_{i=k}^{k+n-1} \bar{y}_i .$$

An "overlapping estimate" of $\sigma_y(\tau)$ can then be obtained:

$$\sigma_y(\tau) \approx \left| \frac{1}{2(M-2n+1)} \sum_{k=1}^{M-2n+1} [\bar{y}_{k+n} - \bar{y}_k]^2 \right|^{\frac{1}{2}} \tag{8}$$

Thus, one can ascertain the dependence of $\sigma_y(\tau)$ as a function of τ from a single data set in a very simple way.

A plot of $\sigma_y(\tau)$ versus τ for a frequency standard typically shows a behaviour consisting of elements as shown in Fig. 1. The first part, with $\sigma_y(\tau) \sim \tau^{-1/2}$ (white frequency noise) and/or $\sigma_y(\tau) \sim \tau^{-1}$ (white or flicker phase noise) reflects the fundamental noise properties of the standard. In the case where $\sigma_y(\tau) \sim \tau^{-1}$, it is not practical to decide whether the oscillator is perturbed by white phase noise or by flicker phase noise. Alternative techniques are suggested below. This is a limitation of the usefulness of $\sigma_y(\tau)$ when one wishes to study the nature of the existing noise sources in the oscillator. A frequency-domain analysis is typically more adequate for Fourier frequencies greater than about 1 Hz. This τ^{-1} and/or $\tau^{-1/2}$ law continues with increasing averaging time until the so-called flicker "floor" is reached, where $\sigma_y(\tau)$ is independent of the averaging time τ. This behaviour is found in almost all frequency standards; it depends on the particular frequency standard and is not fully understood in its physical basis. Examples of probable causes for the flicker "floor" are power supply voltage fluctuations, magnetic field fluctuations, changes in components of the standard, and microwave power changes. Finally the curve shows a deterioration of the stability with increasing averaging time. This occurs typically at times ranging from hours to days, depending on the particular kind of standard.

A "modified Allan variance", $MOD\ \sigma_y^2(\tau)$, has been developed [Allan and Barnes, 1981] which has the property of yielding different dependences on τ for white phase noise and flicker phase noise. The dependences for $MOD\ \sigma_y(\tau)$ are $\tau^{-3/2}$ and τ^{-1} respectively. The relationships between $\sigma_y(\tau)$ and $MOD\ \sigma_y(\tau)$ are also explained in [Allan and Barnes, 1981; IEEE 1983; Lesage and Ayi, 1984]. $MOD\ \sigma_y(\tau)$ is estimated using the following equation:

$$MOD\ \sigma_y^2(\tau) = \frac{1}{2\tau^2 n^2 (N - 3n + 1)} \sum_{j=1}^{N-3n+1} \left[\sum_{i=j}^{n+j-1} (x_{i+2n} - 2x_{i+n} + x_i) \right]^2 \tag{9}$$

where N is the original number of time variation measurements spaced by τ_0, and $\tau = n\tau_0$ the sample time of choice.

Properties and confidence of the estimate are discussed in Lesage and Ayi[1984]. Jones and Tryon [1983] and Barnes et al. [1982] have developed maximum liklihood methods of estimating $\sigma_y(\tau)$ for the specific models of white frequency noise and random walk frequency noise. These two models have been shown to be useful for sample times longer than a few seconds for caesium beam standards.

4. Conversion between frequency and time domains

In general, if the spectral density of the normalized frequency fluctuations $S_y(f)$ is known, the two-sample variance can be computed [Barnes *et al.*, 1971; Rutman, 1972]:

$$\sigma_y{}^2(\tau) = 2 \int_0^{f_h} S_y(f) \frac{\sin^4 \pi\tau f}{(\pi\tau f)^2} \, df \tag{10}$$

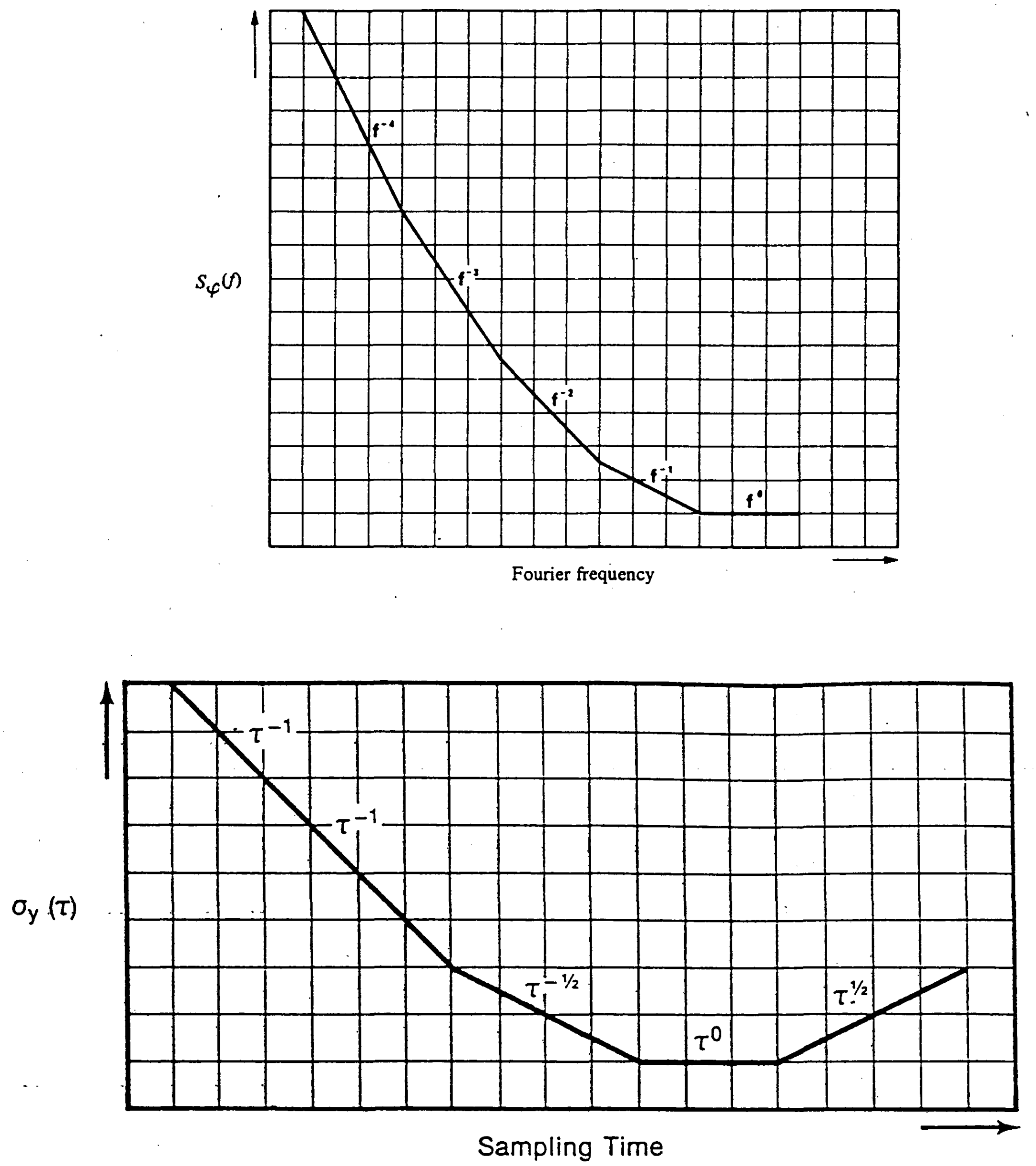

FIGURE 1 – *Slope characteristics of the five independent noise processes* (log scale)

Specifically, for the power law model given by equation (5), the time-domain measure also follows the power law as derived by Cutler from equations (5) and (10).

$$\sigma_y^2(\tau) = h_{-2}\,\frac{(2\pi)^2}{6}\,\tau + h_{-1}\,2\log_e 2 + h_0\,\frac{1}{2\tau} + h_1\,\frac{1.038 + 3\log_e(2\pi f_h\,\tau)}{(2\pi)^2\,\tau^2} + h_2\,\frac{3f_h}{(2\pi)^2\,\tau^2} \qquad (11)$$

Note – The factor 1.038 in the fourth term of equation (11) is a correction to values given in most previous publications.

The values of h_α are characteristics of oscillator frequency noise. One may note for integer values (as often seems to be the case) that $\mu = -\alpha - 1$, for $-3 \lesssim \alpha \lesssim 1$, and $\mu \simeq -2$ for $\alpha \gtrsim 1$ where $\sigma_y^2(\tau) \sim \tau^{\mu}$.

These conversions have been verified experimentally [Brandenberger *et al.*, 1971] and by computation [Chi, 1977]. Table II gives the coefficients of the translation among the frequency stability measures from time domain to frequency domain and from frequency domain to time domain.

The slope characteristics of the five independent noise processes are plotted in the frequency and time domains in Fig. 1 (log log scale).

5. Measurement techniques

The spectral density of phase fluctuations $S_\varphi(f)$ may be approximately measured using a phase-locked loop and a low frequency wave analyzer [Meyer, 1970; Walls *et al.*, 1976]. A double-balanced mixer is used as the phase detector in a lightly coupled phase lock loop. The measuring system uses available state-of-the-art electronic components; also a very high quality oscillator is used as the reference. For very low Fourier frequencies (well below 1 Hz), digital techniques have been used [Atkinson *et al.*, 1963; De Prins *et al.*, 1969; Babitch and Oliverio, 1974]. New methods of measuring time (phase) and frequency stabilities have been introduced with picosecond time precision [Allan and Daams, 1975], and of measuring the Fourier frequencies of phase noise with 30 dB more sensitivity than the previous state of the art [Walls *et al.*, 1976].

Several measurement systems using frequency counters have been used to determine time-domain stability with or without measurement dead time [Allan, 1974; Allan and Daams, 1975]. A system without any counter has also been developed [Rutman, 1974; Rutman and Sauvage, 1974]. Frequency measurements without dead time can be made by sampling time intervals instead of measuring frequency directly. Problems encountered when dead time exists between adjacent frequency measurements have also been discussed and solutions recommended [Blair, 1974; Allan and Daams, 1975; Ricci and Peregrino, 1976]. Discrete spectra have been measured by Groslambert *et al.* [1974].

6. Confidence limits of time domain measurements

To estimate the confidence interval or error bar for a Gaussian type of noise of a particular value $\sigma_y(\tau)$ obtained from a finite number of samples [Lesage and Audoin, 1973] have shown that:

$$\text{Confidence Interval } I_\alpha \simeq \sigma_y(\tau)\cdot\kappa_\alpha\cdot M^{-1/2} \text{ for } M > 10 \qquad (12)$$

where:

M: total number of data points used in the estimate,

α: as defined in the previous section,

$\kappa_2 = \kappa_1 = 0.99$,

$\kappa_0 = 0.87$,

$\kappa_{-1} = 0.77$,

$\kappa_{-2} = 0.75$.

As an example of the Gaussian model with $M = 100$, $\alpha = -1$ (flicker frequency noise) and $\sigma_y(\tau = 1 \text{ second}) = 10^{-12}$, one may write:

$$I_\alpha \simeq \sigma_y(\tau) \cdot \kappa_\alpha \cdot M^{-1/2} \doteq \sigma_y(\tau) \cdot (0.77) \cdot (100)^{-1/2} = \sigma_y(\tau) \cdot (0.077), \tag{13}$$

which gives:

$$\sigma_y(\tau = 1 \text{ second}) = (1 \pm 0.08) \times 10^{-12} \tag{14}$$

A modified estimation procedure including dead-time between pairs of measurements has also been developed [Yoshimura, 1978], showing the influence of auto-correlation of frequency fluctuations.

The above confidence intervals apply to "non-overlapping estimates". In the case of "overlapping estimates" the confidence interval is smaller and can be calculated in particular from Howe et al., [1981].

The bias resulting from the application of two-sample variance to time intervals obtained by linking several successive measures with dead time has been determined as a function of noise type. This bias may be significant [Lesage, 1984; Barnes and Allan, 1988].

The effect of the nature of the analogue filtering which limits the noise power of the signal in question about its nominal frequency has been determined [Lesage, 1987], particularly for the use of a low pass filter instead of a band-pass filter centred on the nominal frequency.

The above confidence intervals are in particular from Howe et al., [1981]. Yoshimura [1989] has calculated the degrees of freedom (d.f.) for 'overlapping estimates'. They are theoretically derived and plotted for power-law spectra for estimation of the confidence interval of the two-sample standard deviation. The confidence interval for the two-sample standard deviation $\sigma_y(\tau)$ is

$$\frac{\sqrt{(\text{d.f.})\ \hat{\sigma}_y^2(\tau)}}{x_{P_1}} < \sigma_y(\tau) < \frac{\sqrt{(\text{d.f.})\ \hat{\sigma}_y^2(\tau)}}{x_{P_2}}, \tag{15}$$

where x_{P_1} and x_{P_2} are percentile values for the chi-square distribution, and where the hat '^' denotes the estimate or the measured two-sample variance from finite set.

For $\alpha = +2$ the improvement of the d.f. is nearly n times better than with respect to the non-overlapping estimate case. Significant improvement is also gained for $\alpha = +1$. For $\alpha = 0$ the ratio of the degrees of freedom is 2; for $\alpha = -1$ it is 1.3; and for $\alpha = -2$ it is 1.04.

7. Conclusion

The statistical methods for describing frequency and phase instability and the corresponding power law spectral density model described are sufficient for describing oscillator instability on the short term. Equation (9) shows that the spectral density can be unambiguously transformed into the time-domain measure. The converse is not true in all cases but is true for the power law spectra often used to model precision oscillators.

Non-random variations are not covered by the model described. These can be either periodic or monotonic. Periodic variations are to be analyzed by means of known methods of harmonic analysis. Monotonic variations are described by linear or higher order drift terms.

TABLE I – *The functional characteristics of five independent noise processes for frequency instability of oscillators*

Description of noise process	Slope characteristics of log log plot			
	Frequency-domaine		Time-domaine	
	$S_y(f)$	$S_\varphi(f)$ or $S_x(f)$	$\sigma^2(\tau)$	$\sigma(\tau)$
	α	$\beta \equiv \alpha - 2$	μ	$\mu/2$
Random walk frequency	−2	−4	1	½
Flicker frequency	−1	−3	0	0
White frequency	0	−2	−1	−½
Flicker phase	1	−1	−2	−1
White phase	2	0	−2	−1

$$S_y(f) = h_\alpha f^\alpha$$

$$S_\varphi(f) = \nu_0^2 h_\alpha f^{\alpha-2} = \nu_0^2 h_\alpha f^\beta \quad (\beta \equiv \alpha - 2)$$

$$S_x(f) = \frac{1}{4\pi^2} h_\alpha f^{\alpha-2} = \frac{1}{4\pi^2} h_\alpha f^\beta$$

$$\sigma^2(\tau) \sim |\tau|^\mu$$

$$\sigma(\tau) \sim |\tau|^{\mu/2}$$

TABLE II – *Translation of frequency stability measures from spectral densities in frequency domain to variance in time domain and vice versa (for $2\pi f_h \tau \gg 1$)*

Description of noise process	$\sigma_y^2(\tau) =$	$S_y(f) =$	$S_\varphi(f) =$
Random walk frequency	$A\left[f^2 S_y(f)\right]\tau^1$	$\frac{1}{A}\left[\tau^{-1}\sigma_y^2(\tau)\right]f^{-2}$	$\frac{\nu_0^2}{A}\left[\tau^{-1}\sigma_y^2(\tau)\right]f^{-4}$
Flicker frequency	$B\left[f S_y(f)\right]\tau^0$	$\frac{1}{B}\left[\tau^0\sigma_y^2(\tau)\right]f^{-1}$	$\frac{\nu_0^2}{B}\left[\tau^0\sigma_y^2(\tau)\right]f^{-3}$
White frequency	$C\left[f^0 S_y(f)\right]\tau^{-1}$	$\frac{1}{C}\left[\tau^1\sigma_y^2(\tau)\right]f^0$	$\frac{\nu_0^2}{C}\left[\tau^1\sigma_y^2(\tau)\right]f^{-2}$
Flicker phase	$D\left[f^{-1} S_y(f)\right]\tau^{-2}$	$\frac{1}{D}\left[\tau^2\sigma_y^2(\tau)\right]f^1$	$\frac{\nu_0^2}{D}\left[\tau^2\sigma_y^2(\tau)\right]f^{-1}$
White phase	$E\left[f^{-2} S_y(f)\right]\tau^{-2}$	$\frac{1}{E}\left[\tau^2\sigma_y^2(\tau)\right]f^2$	$\frac{\nu_0^2}{E}\left[\tau^2\sigma_y^2(\tau)\right]f^0$

$$A = \frac{4\pi^2}{6} \qquad D = \frac{1.038 + 3\log_e(2\pi f_h \tau)}{4\pi^2}$$

$$B = 2\log_e 2 \qquad E = \frac{3 f_h}{4\pi^2}$$

$$C = 1/2$$

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REPORT 738-3

FREQUENCY GENERATORS IN THE FAR INFRA-RED, INFRA-RED AND VISIBLE LIGHT REGIONS OF THE SPECTRUM

(Question 5/7)

(1978-1982-1986-1990)

1. Introduction

The past 20 years have witnessed major advances in the optical frequency domain (frequencies above 300 GHz). Particularly striking has been the progress made in the generation and measurement of such frequencies, which have fostered many applications: in telecommunications (high bit rate links, spacelinks, etc.), geodesy and basic research (relativity, Rydberg constant,astronomy). They have already led to a revolution in length metrology. The17th General Conference on Weights and Measures (October 1983) set the speed of light at c = 299 792 458 m/s, defining the unit of length as follows [CIPM, 1983]: "The metre is the length of the path travelled by light in vacuum during a time interval of $\frac{1}{299\,792\,458}$ of a second".

That definition can be worked out by measuring the length of a time interval or measuring a frequency using the relation $\lambda = c/f$ between the wavelength and frequency of a radiation. A list of recommended values for laser frequencies (Table I) has been established by the International Committee on Weights and Measures [CIPM, 1983].

This report discusses the techniques used in optical frequency metrology and the performance of frequency generators in the optical domain. It sets out to present the state of the art as represented by reviews available in 1989 [Guelachvili, Narahari Rao, 1986; Jennings et al., 1986; Knight, 1986; Vanier and Audoin, 1989]. Selected, new, important developments in this rapidly changing field of metrology are also included. This report supplements Report 364 which deals with standard-frequency generators in the radio and microwave domains. Details of the aspects of optical frequencies specially related to telecommunications are given in Reports 680 and 681-1 of CCIR Study Group 2.

2. Technical aspects

Measurements of frequencies up to the visible cannot presently be carried out in one step with reference to the caesium frequency standard. However, considerable work is focused towards directly connecting the regions of a few hundred GHz to a few hundred THz (visible domain). Moreover, lasers as such are not frequency standards; their frequency depends on the geometry of the optical cavity. Both these problems have been solved by developing frequency stabilization techniques chiefly using saturated absorption and by extending heterodyne techniques into the optical domain.

2.1 Frequency stabilization of lasers

High frequency stability (better than 10^{-10}) can be obtained only by locking the laser emission frequency to a highly stable reference consisting of a molecular or atomic line. To obtain a narrow frequency reference(10^{-8} to 10^{-10} relative width), line widening due to the Doppler effect and pressure must be overcome. Various techniques may be envisaged: atomic or molecular beam (whether or not combined with Ramsey fringes), saturated absorption or two-photon transition. Saturated absorption has been used widely. It was demonstrated for the first time in 1967 [Lee and Skolnick, 1967] with a neon cell placed in the laser cavity. The technique has been extended to other lasers and considerably refined. Inter alia, it has been used with SF_6, OsO_4, CH_4, I_2 molecules and many others.

Frequency stabilization techniques using saturated fluorescence have also been developed and used (CO_2, N_2O lasers).

2.2 Non-linear elements

The direct counting of cycles per unit of time can be effected up to a few GHz; the measurement of higher frequencies requires the use of heterodyne techniques in which several oscillators, one of them at an unknown frequency, are mixed in an appropriate element in such a way that a directly measurable beat frequency is obtained.

Frequencies of up to 4 THz can be synthesized by the direct generation of harmonics of frequencies lower than 100 GHz using small Schottky diodes (multiplication factor of the order of 50) [Weiss and Sakurai, 1987] Josephson junctions (multiplication factor of the order of 80) [Miki and Sakuma, 1987].

Above 4 THz, only the metal-insulator-metal (MIM) point contact diode, first used at MIT [Hocker et al., 1968], permits the generation of harmonics as high as 12 in the infra-red [Evenson et al., 1970] and mixing up to the visible [Jennings et al., 1986]. Harmonic generation can be achieved up to 150 THz and frequency additions up to roughly 200 THz. It is interesting to note that frequency differences of a few THz between lasers operating in the visible regions have been obtained using W-Ni diodes. The operation of this diode probably relies on the tunnel effect through an oxide layer; several materials such as W-Ni, W-Co, W-Nb etc. have proven effective [Riccius, Siemsen, 1984]. Long-term stability of MIM diodes has been studied [Sakurai, 1986].

Above 200 THz, non-linear crystals (e.g. lithium niobate) are used for frequency multiplication. In the case of CW lasers, only twofold multiplications can be used for reaching visible frequencies.

2.3 Frequency multiplication chains

Since the multiplication factors of non-linear elements are limited, several intermediate oscillators are needed for synthesizing optical frequencies from microwave frequencies. Together, all the devices, lasers, non-linear elements and supplementary oscillators constitute a frequency multiplication chain. Oscillator phase-locking techniques considerably improve the accuracy of frequency measurements made with such chains.

3. Optical frequency generators

Many laboratories are working on optical frequency metrology with a view to improving the stability, the reproducibility and the accuracy of locked lasers, developing devices for measuring ever higher frequencies and simplifying frequency synthesis.

Of the different lasers studied, those achieving the values recommended by the CIPM in 1983 are of special metrological importance, and the CO_2 laser is of particular interest. A comprehensive list of lasers has been compiled [Weber, 1982].

3.1 Far-IR frequency generators

For high frequency synthesis, one necessarily has to pass through the far-IR region which is a continuation of the microwave domain. The associated laser and other frequency generators are particularly important in spectroscopy and astronomy applications [Godone et al., 1987; Inguscio et al., 1986; Nolt et al., 1987]. All known CW laser emissions are given by Douglas [Douglas, 1989].

3.2 CO_2 lasers

Because of its multiple qualities (power, stability, numerous lines), the CO_2 laser is a basic tool in almost every frequency synthesis experiment in the infra-red and visible regions. Stabilized by saturated absorption in OsO_4, it offers a stability of some 10^{-14} over 100 s and an accuracy of about 1.5×10^{-12} [Clairon et al., 1985]. Besides the regular lines of $^{12}C^{16}O_2$ lasers, [Petersen et al., 1983] many other lines can be obtained by using higher energy levels [Siemsen and Whitford, 1977] or other isotopes [Bradley et al., 1986]. A frequency multiplication chain using only CO_2 lasers has been phase-locked to a caesium standard for periods of up to 20 minutes [Whitford, 1984].

3.3 HeNe(CH_4) lasers

This was the first high-performance stabilized laser [Barger and Hall, 1969] displaying a stability of 3×10^{-13} over 1 s and a reproducibility of about 10^{-11}; it has been used for determining the speed of light [Evenson et al., 1973]. In addition, being the only laser whose frequency has been measured by several laboratories working on optical frequency synthesis, it may be used for the purposes of international comparisons [Akimoto, 1987; Akimoto and Felder, 1989; Basov et al., 1987; Bagaev et al., 1987; Clairon et al., 1988; Weiss et al., 1988]. The reproducibility of compact lasers of different constructions appears to be limited to a few kHz. However, more efficient arrangements devised in the USSR and using the methane E line afford an accuracy close to 10^{-12} [Malyshev et al., 1980]. HeNe(CH_4) lasers have afforded short-term stability of a few times 10^{-15} for one to ten seconds' integration [Bagaev et al., 1981]. An experimental clock working from a methane stabilized laser has been demonstrated [Bagaev et al., 1983].

3.4 Other lasers

HeNe and Argon lasers stabilized by saturated absorption in iodine have been developed at many laboratories and are used both in length metrology and high-resolution spectroscopy. Devices using an absorbant cell give a reproducibility close to 10^{-12} and 10^{-10} with cells outside or inside the laser cavity, respectively. An important contribution to the CIPM recommended frequencies (Table I) was the direct frequency measurement of a $^{127}I_2$ stabilized laser at 520 THz with a one-sigma uncertainty of 1.6×10^{-10} [Pollock et al., 1983].

4. Conclusion

Over the past twenty years, significant advances have been made in the development of optical frequency generators and in the measurement of frequencies generated. Figure 1 illustrates the state of the art with regard to the stability of a number of lasers.

The techniques of atom and ion storage and cooling offer promise of accurate frequency standards in the visible and higher frequency bands [Wineland, 1986]. Major improvements may be expected, particularly with the development of laser diodes and related techniques.

TABLE I – *Values of laser frequencies recommended by the CIPM in 1983 for the realization of the metre*

Laser	Frequency (THz)	Relative uncertainty (3σ)
He-Ne laser, stabilized by saturated absorption in CH_4 (transition ν_3, P (7), component F_2^2)	88.376 181 608	$\pm 1.3 \times 10^{-10}$
Dye laser (or He-Ne laser with doubling of frequency), stabilized by saturated absorption in $^{127}I_2$ (transition 17-1, P (62), component o)	520.206 808 51	$\pm 6 \times 10^{-10}$
He-Ne laser, stabilized by saturated absorption in $^{127}I_2$ (transition 11-5, R (127), component i)	473.612 214 8	$\pm 10 \times 10^{-10}$
He-Ne laser, stabilized by saturated absorption in $^{127}I_2$ (transition 9-2, R (47), component o)	489.880 355 1	$\pm 11 \times 10^{-10}$
Ar^+ laser, stabilized by saturated absorption in $^{127}I_2$ (transition 43-0, P (13), component a_3)	582.490 603 6	$\pm 13 \times 10^{-10}$

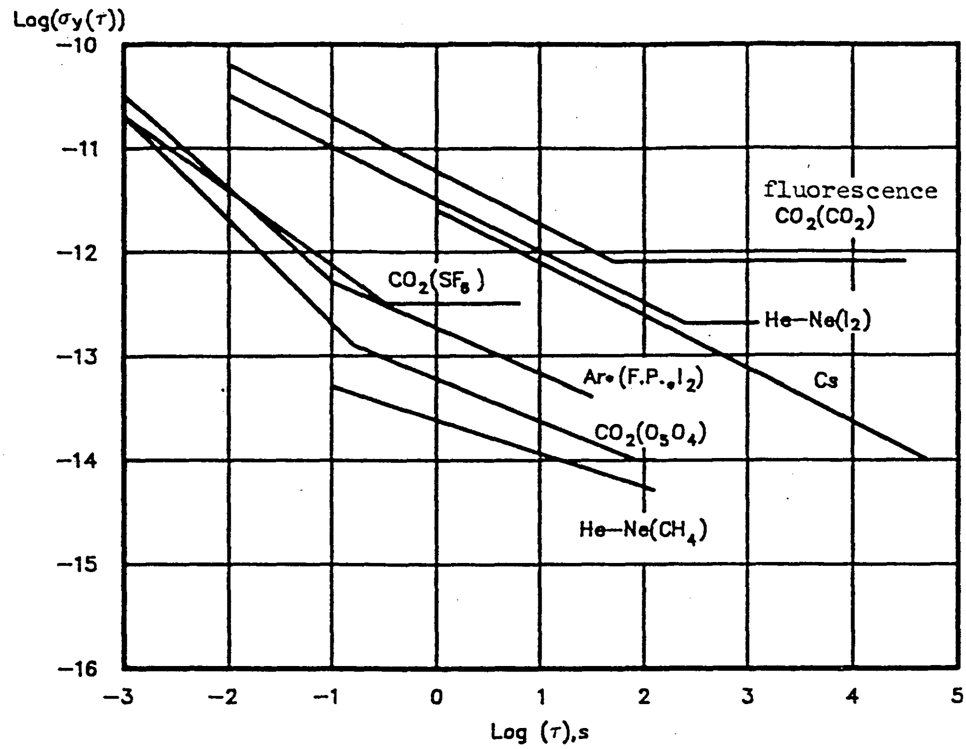

FIGURE 1

Frequency instability of different locked oscillators

Frequency instability is characterized by the two-sample variance.

Report 364 gives corresponding information for microwave oscillators.

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REPORT 898-2

OPERATIONAL EXPERIENCE WITH REFERENCE CLOCKS IN TIME SYSTEMS

(Question 8/7)

(1982-1986-1990)

1. Introduction

This Report is an answer to the questions asked by CCITT Study Group XVIII to CCIR Study Group 7 concerning the performance and reliability of reference clocks to be used in digital communications systems. It also offers some comments on CCITT Recommendation G.811.

Section 2 of this Report intends to ensure that the questions have been understood and answered correctly and develop as far as possible a common language in the field of timing and synchronization.

Section 3 contains the currently available data on the reliability of some types of clocks operating in services such as standard time and frequency, navigation and communications.

Section 4 refers to the Reports of the CCIR concerning the available measurement techniques required to relate a clock to the common reference time scale UTC.

2. Terms and definitions concerning the characterization of clock performance

In order to facilitate the understanding of its texts, CCIR Study Group 7 has compiled a glossary in its Report 730 listing, defining and explaining most terms currently used in frequency and time measurements.

The long-term frequency departure of $\pm$ 1 part in 10^{11} allowed in Recommendation G.811 is about two orders of magnitude larger than the uncertainty of UTC, as determined by the Bureau international des poids et mesures. In the present context UTC is therefore a satisfactory approximation to an ideal clock.

For reasons of the non-stationary nature of the time interval errors (TIE) of actual clocks over long periods of observation ($T >$ 10 days), Study Group 7 has based most of its work on the concepts of frequency instability as the basic phenomenon.

The TIE as mentioned in Recommendation G.811 may be interpreted as the integral of the normalized frequency departure computed over the time interval S. If t_0 is the starting time of the interval S, one has:

$$TIE = x(t_0 + S) - x(t_0) = \int_{t_0}^{t_0 + S} y(t)\mathrm{d}t \tag{1}$$

using the notation of Report 580. The slope indicated as a dashed line in Fig. 1/G.811 thus represents the average frequency departure:

$$\bar{y}_0(t_0, S) = \frac{1}{S} \int_{t_0}^{t_0 + S} y(t)\mathrm{d}t \tag{2}$$

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* The Director, CCIR, is requested to bring this Report to the attention of the CCITT.

Obviously, this departure is due to the *frequency instability* of the clock, whereas the long term average slope is due to the *error in initial frequency setting* of the clock relative to the nominal value. The error in initial frequency setting depends on the measurement techniques used to relate the clock to an external reference such as Loran-C or the national time and frequency services. The characteristics describing the performance of clocks and other properties such as size, weight, power, consumption, etc., are contained in Report 364. The random instabilities are described using the statistical measures recommended in Recommendation 538 and described in Report 580. In these texts, the sampling time, equivalent to the observation period (of S seconds) is designated by the lower case Greek letter τ.

The following estimate of the standard deviation of the TIE, based on computer simulations [Kartaschoff, 1979] of the statistical clock model, can be used to predict a probable time interval error of a clock adjusted and synchronized at $t = 0$ and left free running thereafter:

$$(TIE)_{est} = \frac{a}{2} t^2 + t \cdot (\sigma_{y_0}{}^2 + \sigma_y^2(\tau = t))^{1/2} \tag{3}$$

where:

a : normalized linear frequency drift per unit of time (ageing);

σ_{y_0} : two sample standard deviation of the initial frequency setting; and

$\sigma_y(\tau)$: two sample standard deviation describing the random frequency instability of the clock.

It is assumed that the parameters characterizing the clock do not change with time and that the initial setting error and the subsequent random frequency fluctuations are statistically independent. As can be seen from the formula above, it is the initial frequency setting error which will be predominant in most cases.

3. Clock reliability

3.1 *General*

The reliability of a device is the mathematical probability that it will function within certain specifications until some time t. The traditional measure of reliability for electronic devices has been the "mean time before (or between) failure" (MTBF) statistic.

The MTBF estimate requires many clock-years of data to develop a useful statistic. These data can be obtained from the large number of clocks in operational use as reported in § 3.3. However, the MTBF statistic ignores the time-dependent characteristic of atomic clock reliability. Section 3.2 shows that those caesium clocks of a carefully managed clock ensemble that have been in operation for more than one year appear to be more reliable than new units. This may be due to ageing or end-of-life of some parts, such as the beam tube or optical package. Section 3.3 discusses why this characteristic was not found in the large set of clocks in general operation.

Two characterizations of atomic clock reliability are the mean-life (ML) and the half-life (HL) [Percival and Winkler, 1975]. The mean-life statistic requires for its determination that all units of a test-set fail, and thus is very limited in usefulness for characterizing atomic clock reliability. However, if a failure-rate function can be hypothesized from available data, then the mean-life statistic may be estimated. The half-life statistic is more useful for characterizing atomic clock reliability. This statistic has a simple probability interpretation: the probability that a clock will survive to a half-life time is 50%. An estimate of this time is available after one-half of a test set of clocks have failed.

The best statistic for calculating reliability factors is the probability that a clock, having survived a time t, will fail by time $t + \Delta t$. If clocks are removed from further reliability evaluation following their first failure, the conditional failure rate function may be defined as:

$$Z(t)\,\Delta t = -\left[\frac{N(t + \Delta t) - N(t)}{N(t)}\right]. \tag{4}$$

where $N(t)$ represents the number of clocks expected to be operating at a time t and $N(0)$ represents the number of clocks initially in a given ensemble.

Under the same conditions, $Z(t)$ may be estimated to be:

$$Z(t) = -\left[\frac{\Delta N'(t)}{N'(t)\,\Delta t}\right] \tag{5}$$

where $N'(t)$ represents the number of clocks which were operating at time t and either failed in the interval t to $t + \Delta t$ or were still operating at time $t + \Delta t$, and $\Delta N' = N'(t + \Delta t) - N'(t)$.

If clocks that fail are repaired and put back into operation, then $Z(t)$ can be estimated to be:

$$Z(t) = \frac{F}{U} \tag{6}$$

where:

F: number of failures during a given time interval; and

U: number of units in operation during the same time interval.

The slight conceptual difference between the two $Z(t)$ defined above are considered as unimportant.

$Z(t)$ may be modelled with rather simple functions for restricted regions of t.

$Z(t) = c$, where c is a constant, corresponds to the exponential probability law. It is used to describe such phenomena as electronic tube life, etc. It assumes purely random accidents as the causes for failures, which are thus independent of age. In this case, the MTBF can be estimated to be equal to the half-life t_{HL}.

$Z(t) = kt$, where k is a constant, assumes the conditional failure rate increases with time. This model seems to characterize the failure rate of commercial caesium beam clocks after they have been in operation for several years, but not over their entire life span.

3.2 *Observations of a carefully managed caesium clock ensemble*

The conditional failure rate (in January, 1970) of a clock ensemble at the United States Naval Observatory was approximately described by $Z(t) = kt$ where $k = 0.1$. Most of these clocks were production units already operating for more than one or two years. Table I shows the mean life and half-life for various models of $Z(t)$.

Table II gives an estimate for $Z(t)$ for a US Navel Observatory clock ensemble composed of two different commercial models, some of which were early production units.

TABLE I *Mean-life and half-life for various models of Z (t)*

(for *Z (t)* per year)

	$Z(t) = c$		$Z(t) = kt$
	$c = 0.1$	$c = 0.3$	$k = 0.1$
t_{HL} (years)	6.93	2.31	3.72
t_{ML} (years)	10.00	3.33	3.96

TABLE II – *Estimate of $Z(t)$ based on a USNO clock ensemble*

(Probability, $Z(t)\Delta t$ for $\Delta t = 1$ year, that a clock will fail in the next year, given that it has already lasted t years)

t	$Z(t)\Delta t$ for $\Delta t = 1$ year
0.0	0.31 ± 0.03
0.5	0.24 ± 0.04
1.0	0.19 ± 0.04
1.5	0.20 ± 0.04
2.0	0.21 ± 0.05
2.5	0.20 ± 0.05
3.0	0.36 ± 0.07
3.5	0.46 ± 0.08
4.0	0.47 ± 0.11

3.3 *Operational clock reliability*

Data on the operational reliability are presented for the following devices:

- caesium clocks,
- rubidium clocks,
- quartz crystal oscillators.

Other devices also listed in Report 364 are left aside for various reasons such as continuing research, very small population, lack of reliability data, etc., which at present limit their suitability for systems applications on a wide scale.

Based on the performance limits specified in CCITT Recommendation G.811, the failure criteria to be applied fall into two classes.

Crystal and rubidium clocks require initial frequency setting and subsequent frequency control from an external reference to compensate for the inherent frequency drift. Misadjustment and absence of control leading to the violation of the specification cannot be regarded as being failures of these devices.

Caesium clocks have a systematic uncertainty which is lower than the ± 1 part in 10^{11} limit specified by CCITT Recommendation G.811 and in general show negligible frequency drift. A violation of the limit can therefore be regarded as being a failure.

Except for this distinction other failures such as degradation or loss of output signal are common to all devices.

A reliability survey by means of questionnaires sent to users and manufacturers in the participating countries via the delegates of the respective administrations was started in January 1981. The delegates also collected the completed questionnaires, checked and corrected them where necessary and forwarded them to the Chairman of Interim Working Party 7/5 for further processing. The results presented in this Report are based on data received until October, 1983. Up to this date, Reports have been received from the following countries: the People's Republic of China, Federal Republic of Germany, United States of America, France, Italy, Japan, the Netherlands, Sweden, Switzerland and the United Kingdom. The total number of units reported on was 4125 which included 1230 caesium clocks, 225 rubidium clocks and 2670 crystal oscillators.

Most of the data covered the 11-year period from 1970 to 1980.

In the processing of the data, the following general procedure was used:

The sheets were grouped for each model using the manufacturers designation, for example: HP 5061A (Cs); R&S XSRM (Rb); B 5400 (Xtal), etc.

Manufacturers' reports were kept separately from the users' reports.

The following figures were defined and computed for each model:

ΣU: the sum over all units of the number of years of operation for each unit.

ΣF: total of failures observed for these units.

Then, the ratio $\Sigma U/\Sigma F = MTBF$ in years as an estimate assuming constant failure rate during the 11-year period of observation was computed.

There are several reasons why conditional failure rate functions as defined in § 3.1 cannot be estimated with less "uncertainty" than that of the MTBF estimate mentioned above. A large variation exists in the age and model design; moreover, in order to obtain a large statistical sample, data were taken from all available sources in the 11-year period, including clocks which failed, were repaired and subsequently may have failed again one or more times.

There is also a wide variance in the MTTR (mean time to repair a failed unit including shipping time) figures reported. Since the individual averages vary between 80 and 140 days and there is a strong influence due to the geographical location of the unit, the general average for Cs and Rb clocks of about 90 days MTTR is at best indicative. No MTTR figures are given for crystal clocks.

Tables III, IV and V show the resulting MTBF estimates based on the available data.

TABLE III – *Caesium clocks*

Model (year)	ΣU	ΣF	MTBF (years)	MTTR (days)	No. of units in survey
Users' report					
HP5061A (1968)	3347	823	$4.07^{+0.69}_{-0.52}$	90	492
OSA 3200 (1975/76)	96	32	$3.0^{+0.6}_{-0.4}$	90	25
HP5061A-004 (1973)	118	44	$2.68^{+0.41}_{-0.31}$	90	24
HP5060A (1) (1965)	133	42	3.17	90	21
OSA 3000 (1976)	29	10	$2.9^{+0.9}_{-0.6}$	90	14
HP5062 (1) (1973)	1648	319 (2)	$5.2^{+1.0}_{-0.7}$	-	408
Manufacturers' report (see comment § 3.3)					
OSA 3000 (1976)	285	30	9.6	35	97
OSA 3200 (1975)	679	161	4.22	50	149

(1) Old model, no longer in production.

(2) Only caesium beam tube failures and other failures associated with beam tube failures are included for this particular type of clock.

TABLE IV – *Rubidium clocks*

Model (year)	ΣU	ΣF	MTBF (years)	MTTR (days)	No. of units in survey
HP5065A (1970)	159	21	7.6	120	31
FRT/FRK (1973)	584	52	11.2	90	159
XSRM (1972)	71	13	5.5	90	15
P01 (1976)	44	41	1.08	–	20

TABLE V – *Crystal clocks*

Model	1st year	ΣU	ΣF	MTBF (years)	No. of units in survey	Notes
Users' report						
B5400	1974	48	1	48	11	
B1250	1973	8	1	8	1	(1)
B1010	1965	926	25	37	132	(1)
HP104/105	1970	46	4	11.5	5	(2)
R&S XSC/D/S	1970	136	13	10.5	15	(2)
C60MCS	1972	223	1	200	52	
CP12MCS	1970	6316	33	191	1288	
MT	1975	834	13	64	139	
K	1975	1353	2	200	235	
Manufacturers' report						
OSA B5400	1974	1352	27	50	318	
OSA B1250	1970	214	3	71	20	(1)
HCD HCD50	1970	4383	104	42	587	

(1) Obsolete, no longer manufactured.

(2) Units combined in single survey because of high similarity of design and no apparent bias.

- In Table III, 1σ confidence margins are given for the MTBF estimates. These margins have been computed in the following way:

The data on the largest population (HP5061A, 492 units in the survey) were used. Adding the columns for each year, sequences of numbers of units in operation (ΣU_i) and of failures (ΣF_i) were obtained. Then a sequence of ratios:

$$Z_i = \frac{\Sigma F_i}{\Sigma U_i}$$

was computed for each year (1970 to 1980), as shown in Table VI below. Z_i is an estimate of the yearly failure rate in the mixed population of devices of various ages, this population growing as more new devices are put into service than old ones retired. A test has shown that these Z_i values are normally distributed. The median value is $Z_m = 0.22$ with a standard deviation of $\sigma_z = \pm 0.094$. The probable relative error of the median is thus about $\pm$ 6%. The inverse of the median value, $Z_m^{-1} = 4$ years is very close to the MTBF estimate of 4.07 years shown in Table III in which the confidence margins have been computed using the above 12.5% probable relative error estimate on the average failure rates of $1/4.07 = 0.246$.

The confidence margins of the other models have been computed in a similar way. Data on the HP5060A are of historical interest only. No such estimates have been done on the data summarized in Tables IV and V. For Table IV, the populations are too small and the units in Table V are quite diverse and some units have consistently high MTBF.

Table VII shows the distributions of failures among the various sub-assemblies of caesium clocks based on user and manufacturer reports. The data on the HP units are taken from [Johnson *et al.*, 1980].

A comment is in order on the bias appearing between user and manufacturers reports, especially in Table III. One can be sure that the manufacturer has done his best in order to report real and correct figures. However, there are always some users who repair some minor faults in their own facilities without reporting these actions to the manufacturer. Thus, some bias is practically inevitable. Improvement of the feedback loop on failures and repairs would serve the interests of both manufacturers and users.

The data collected until now cover only a fraction of the world population of precision clocks. No peak has been observed in the first year of operation of caesium clocks, i.e. the "early failures" seem to have been eliminated by the burn-in process performed by the manufacturers.

TABLE VI

Year	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
ΣU_i	51	70	104	162	204	255	291	328	349	370	386
ΣF_i	7	24	19	16	32	36	48	54	67	95	118
Z_i	0.137	0.343	0.183	0.099	0.157	0.141	0.165	0.165	0.192	0.257	0.306

TABLE VII – *Caesium beam clocks*

Model: HP5061A – OSA B3200 – HP5061A-004 – HP5062A – OSA 3000

Model	Atomic Resonator	Crystal Oscillator	Frequency conditioning circuits	Servo circuits	Output circuits	Internal power conditioning	Other parts	ΣU (ΣF) (1)
Users' report								
HP5061A								
F_i	175	72	97	50	12	68	28	3347
%	35	14	19	10	2	14	6	(502)
OSA B3200								
F_i	38	4	0	0	8	40	15	96
%	36	4	0	0	8	38	14	(105)
HP5061A-004								
F_i	16	9	4	4	1	2	4	118
%	40	23	10	10	3	5	10	(40)
HP5062A								
F_i	213	46	41	88	69	228	102	1648
%	27	6	5	11	9	29	13	(787)
Manufacturers' report								
HP5061 (2)								
5061-004 F_i	62	17	44	21	40	6	4	(194)
5062C %	32	9	23	11	20	3	2	
OSA 3200 F_i	20	21	15	15	9	83	1	679
%	12	13	9	9	5	51	1	(164)
OSA 3000 F_i	8	8	1	3	1	3	6	289
%	27	27	3	10	3	10	20	(30)

(1) Usually larger than the ΣF reported in Table III due to multiple simultaneous defects.

(2) Number of units not available.

3.4 *Qualifications and acceptance tests*

There should be a specified ***design qualification*** test for each Clock/Standard Type that establishes performance margins in environmental conditions equal to the extremes to be encountered in service. Also, the performance margin should be determined for the situation in which all limits are simultaneously encountered. The environmental tests should include, but not be limited to:

Temperature
Vibration
Shock
Alternating Magnetic Fields
Static Magnetic Fields
Conducted RFI
Radiated RFI
Atmospheric Pressure
Humidity

A measurement of the effect of environmental conditions on the rate of a commercial high performance caesium clock was carried out using a vacuum chamber designed for this purpose. The rate changes due to changes of temperature (per °C between 24 and 31 °C), absolute humidity (per gm^{-3} between 7 and 18 gm^{-3}), atmospheric pressure (per 100 mbar between 673 and 1007 mbar (100 mbar = 10^4 Pa)) and geomagnetic field (per 100 mOe between −135 and 135 mOe (100 mOe = $8Am^{-1}$)) were less than $\pm 2 \times 10^{-14}$ with the estimated mean uncertainty of the order of 10^{-15}. These results for one caesium clock indicate that the effects of the above environmental influences are not negligibly small and that the environmental conditions should be carefully controlled in order to keep the operation of atomic clocks as uniform as possible [Iijima *et al.*, 1978]. Further measurements of the effects of humidity have been made [Bava et al., 1987] which showed a dependance of $\pm 5 \times 10^{-14}\, gm^{-3}$ for caesium standards.

It should be noted, however, that the specific values could not be generalized in the form of sensitivity coefficients. They are not the same from clock to clock and are not even fixed for a particular clock since they depend on the range and speed of parameter changes.

Once these limitations are established for a given design, *acceptance test levels* should be set, and it should be specified that each delivered unit has to be measured within these performance margins.

Prior to delivery to remove *workmanship* faults, each unit should be exposed to three axis random vibrations of at least two minutes duration on each axis. Following this, the unit should be exposed to five cycles of temperature extremes, dwelling at each extreme for at least four hours, and examined for one week's operation to establish that performance margins have not been degraded.

3.5 *Continuity of operation*

In most applications of time and frequency standards, particularly in the field of communications, stringent requirements are placed on continuity of operation which requires the provision of multiple sources to guard against operational failures. A frequency averager which has been developed at the National Physical Laboratory is based on an extension of earlier work [McLeod and Wise, 1975]. This equipment produces an output frequency which is the weighted average of up to five input frequencies, the weighting factor for each source frequency being variable from 0 to 5 in unit steps. There is automatic compensation for any variation in the weighting factors and for the addition or removal of input frequencies. It thus constitutes a highly redundant system and in consequence would be an extremely reliable source for a communications channel. Moreover, the improvement in frequency stability of the averaged output as compared with any one input could be of significant benefit in some applications.

Other possibilities of securing continuity of operation exist such as using synchronized slave oscillators having a memory in the control system.

3.6 *Conclusions*

The survey on the reliability of precision clocks presented in § 3.3 has yielded some interesting results. The MTBF estimates for caesium, rubidium and crystal clocks confirm the old rule that MTBF is inversely proportional to the complexity of the device. However, the most complex device also shows the highest frequency stability and might thus require less supervision and maintenance work (such as frequency adjustments) in the operation of a system. It should also be realized that any statistic based on widely different sources and conditions of operation has limitations and is subject to possible biases.

Tables III and IV also show the importance of production experience for obtaining improved reliability. Parts screening and burn-in have been successful measures for minimizing the so-called early failures. Some insidious hidden weaknesses may appear only after a few years of production in the field. In view of this, the level of reliability attained with caesium beam standards is remarkable.

4. Measurement techniques

Measurements are the only means to assure conformity to the specifications. The current comparison methods for the transfer and dissemination of time signals and standard frequencies are reviewed in Reports 363 and 518.

Crystal, rubidium and caesium clocks all require checks to assure proper operation. Crystal and rubidium clocks require periodic calibration and readjustment of the frequency, but caesium clocks do not require such readjustments to meet the frequency tolerances of CCITT Recommendation G.811. Long-term comparison with another reference however constitutes a significant safety factor for detection of failure.

The main problem in the measurement of clock time over a distance is the uncertainty of transmission path delay which usually determines the choice of the comparison method. Although synchronism in an extended network is feasible and desirable, the fact that transmission delays are not perfectly stable raises the question of the level of precision which should be provided. The effect of variations in transmission delay can be largely eliminated by two-way time comparisons. Such comparisons can be achieved relatively easily by using the normal synchronization pulses of duplex digital communications links, i.e., those providing simultaneous communication in both directions. This makes it practicable to provide very precise measurements of timing errors for use in the operation of digital communication networks.

The digital communications system designer is faced with several choices. The clocks in the system may be referred to a single master clock which in turn is referred to UTC. An extended system may be subdivided into regions each having their master clock individually referred to UTC. These two varieties have been examined in Canada with good success. In the first case, the network master was compared to the national frequency standard at the National Research Centre (NRC). In the second case, several master clocks were phase-locked to the signals of the Loran-C navigation system.

A most important design choice is the degree of reliance on the clocks, i.e. the time constant in the frequency control loop versus the quality of the clocks [Kartaschoff, 1980].

Comparison methods via satellite show great potential, especially for areas where other high stability time signals are not available (Report 518).

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DECISIONS

DECISION 65

HANDBOOK ON THE USE OF SATELLITE TIME AND FREQUENCY DISSEMINATION

(1985)

CCIR Study Group 7,

CONSIDERING

(a) the extent and depth of the studies carried out by Interim Working Party (IWP) 7/4 over two study periods on the technical possibilities for time transfer and dissemination by means of satellites;

(b) that the utility and economy of satellite methods of time dissemination may find application in a number of developing countries desirous of establishing a national time and frequency reference;

(c) that satellite methods of dissemination may increasingly supplement and replace some of the existing ground-based services of standard-frequency and time-signal dissemination;

(d) that operational experience has been accumulated over many years with a time and frequency service allied to the GOES meteorological satellites;

(e) that the use of the geostationary-satellite orbit for regional telecommunication systems, e.g. ARABSAT, BRAZILSAT, INSAT, PALAPA, etc., offers technical possibilities for adding a time and frequency channel of modest bandwidth;

(f) that the advent of direct satellite TV broadcasting will similarly extend the possibilities for inserting a time reference in an already time-disciplined system;

(g) that Resolution 33 on technical cooperation encourages the prepartion of handbooks,

DECIDES

1. that an ad hoc Working Group should be formed with the task of preparing the text of a handbook on satellite-based services of time and frequency dissemination;

2. that this handbook should draw initially on the texts of Study Group 7 and should also include any relevant documentation from the text of IWP 7/4 and also of Study Groups 2, 4, 8, 10 and 11 and from the extensive literature associated with the systems of navigation and position determination by satellite;

3. that administrations should be encouraged to provide specific contributions to the text of the handbook in those areas in which they have developed special knowledge or expertise;

4. that a coordinator be appointed to supervise the overall compilation and integration of the contributions;

5. that the aim of the coordinator and the contributors should be to complete the text of the handbook before the XVIIth Plenary Assembly.

ANNEX I

At the end of the XVIth Plenary Assembly, 1986, the following Administrations and International Organizations have indicated their participation in the ad hoc Working Group:

Administrations:

Austria
Canada
United States of America
France
India
Japan
United Kingdom
Yugoslavia (Socialist Federal Republic of)
Bureau international des poids et mesures (BIPM)

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