13

Frequency and Time Coordination, Comparison, and Dissemination

David W. Allan

Time and Frequency Division
National Bureau of Standards
Boulder, Colorado

LIST OF ACRONYMS

BIH	Bureau International de l'Heure
ESA	European Space Agency
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System

PRECISION FREQUENCY CONTROL
Volume 2
Oscillators and Standards
ISBN 0-12-280602-6

LASSO	Laser synchronization from stationary orbit
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NOAA	National Oceanic and Atmospheric Administration
OTS-2	Orbital Test Satellite No. 2 by ESA
TAI	International Atomic Time
TDRS	Tracking and data-relay satellites
USNO	United States Naval Observatory
UT1	Universal time scale obtained by correcting UT0 for polar motion, where UT0 is the mean solar time at the Greenwich meridian plus 12 hr.
UT2	Universal time scale obtained by correcting UT1 for secular variations (e.g., annual and semiannual) in the rate of rotation of the earth
UTC	Universal Coordinate Time
VLBI	Very-long-baseline interferometry

13.1 INTRODUCTION

The purpose of this chapter is to review both the current and some anticipated metrology techniques useful in comparing or calibrating remotely located time and frequency (T/F) standards. Typically, the interest in this regard is to make available to a remote user some primary frequency or time standard reference. The techniques usually employed to accomplish this either involve the transport of a secondary standard or the propagation of time and frequency information carried on an electromagnetic signal. The accuracy, reasonable coverage areas, convenience to the user, and, in some cases, nominal cost of some of these techniques of comparison and dissemination will be reviewed (Beehler, 1981; Sperry Gyroscope Co. Staff, 1967; Jespersen *et al.*, 1972; Kamas and Howe, 1979).

Time and frequency coordination is the process of combining primary standards to generate coordinated T/F standards for the world or for a particular country. Coordination is important in the generation of International Atomic Time (TAI) and Universal Coordinate Time (UTC) (Smith, 1972). State-of-the-art comparison methods are usually employed to accomplish this coordination. T/F dissemination, on the other hand, occurs at a wide variety of accuracy levels and is typically provided as a service to a largely unknown receiving audience (Allan *et al.*, 1972c). The more useful methods of T/F coordination, comparison, and dissemination will be discussed in this chapter.

13.1.1 Historical Perspectives and Methods of Comparison

We see four basic eras as we review methods of measuring oscillators and clocks at remote locations. The first era employed astronomical observations. The second, which is perhaps highlighted in its early years by the Harrison chronometer, involved the transport of the best chronometer possible to do accurate navigation. The third era is associated with the advent of time and frequency information on electromagnetic signals that could be transmitted from a known fixed site to any general receiver location to measure clocks and oscillators at that location. The fourth era is just now dawning and is a marriage of the concepts from the second and third eras in which we have very good clocks whose signals can be transported or transponded via satellite. This opens up new opportunities and possibilities because of the different parts of the electromagnetic spectrum that can be utilized. Greater bandwidths are now available. In contrast to earth-fixed transmitters, line-of-sight paths are natural from the earth to a satellite, which can be used to give worldwide coverage with extremely accurate time and frequency signals.

13.1.2 Time and Frequency Standards

The time and frequency standard for the world is generally accepted as International Atomic Time (TAI), generated and maintained at the International Time Bureau, Bureau Internationale de l'Heure (BIH) (Guinot and Granveaud, 1972). The rate of TAI is periodically adjusted to be within one part of 10^{13} or better of the rates as given by primary frequency standards at key laboratories in the world (Granveaud and Guinot, 1978). Currently these laboratories are the National Bureau of Standards (NBS) in Boulder, Colorado, the National Research Council (NRC) in Ottawa, Canada, and the Physikalisch-Technische Bundesanstaldt (PTB) in Braunschweig, Federal Republic of Germany. The current accuracies of these three standards are eight parts in 10^{14}, four parts in 10^{14}, and two parts in 10^{14}, respectively. The TAI is generated by a computer algorithm (called ALGOS) that combines the time readings of about 100 remote clocks from various laboratories and observatories in North America and Europe (Guinot, 1974; Bureau International de l'Heure, 1981). The remote time readings of these clocks are transferred to the BIH mostly via Loran-C, as outlined above. Satellite techniques are coming more into use (Costain *et al.*, 1979b; Allan *et al.*, 1985). Loran-C limits the locations and the accuracies that can be achieved (Allan *et al.*, 1972a). The new era will greatly improve the accuracy with which T/F data can be transferred from remote areas of the earth. The rates of the clocks participating are determined from historical data so that the rate of TAI (ALGOS output) is in agreement with the primary standards. The second, as generated by the primary standards, is "the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom." The time origin of TAI is 00 hours, 1 January 1958, at which time it was made synchronous with the earth time scale UT2. Since that date TAI has been independent of earth time and astronomical data. However, the time scale UTC (Universal Coordinate Time), as generated by the BIH, is constrained to within 0.9 sec of the earth time scale UT1 by adding *leap seconds* as needed. UT1 is dependent on the spin of the earth and is the most useful time scale for most navigators. By keeping UTC nominally synchronous with UT1, UTC has utility for both the navigator and the precision T/F metrologist who wishes to base his measurements on the definition of the second. As of 1 July 1983 the time difference TAI − UTC = 22 sec. Most countries have adopted UTC as civil time and generate within their country a near-synchronous equivalent to UTC, usually denoted UTC(i), where i denotes the laboratory or observatory where the time scale is generated.

In the following sections we shall discuss some of the ways in which one can calibrate the time or frequency of a local clock, oscillator, or resonator with respect to the UTC(i)'s and frequency standards available. The most popular method of receiving the UTC T/F signals is via the standard T/F transmitters located around the earth. The relative merits and accuracies of different techniques will be indicated as well as some other techniques that hold promise in the foreseeable future.

A useful variation on the above is for two sites, A and B, to receive time and/or frequency signals T from a transmitter in common view to both sites. A time difference can be simultaneously measured at the two sites: $A - T + D_A$ and $B - T + D_B$, where D_A and D_B are the delays in propagating the signal to A and B, respectively. Differencing these two measures yields $A - B + \Delta D$, where ΔD is the differential delay. The transmitter acts as a transfer standard (i.e., a standard to transfer T/F from A to B or vice versa) and its errors do not contribute to measurements of the difference between the standards, $A - B$. Furthermore, if there are delay variations that are the same for both paths, these errors cancel. This simultaneous common-view technique is very useful (Allan, 1972; Allan *et al*., 1972b; Allan and Weiss, 1980; Inouye and Nara, 1975). For example, it is used in the construction of International Atomic Time (TAI), with the transmitter being the Loran-C navigation chain (Shapiro, 1968; Doherty *et al*., 1961). This particular technique is utilized in several other systems that we will discuss in this chapter, for example, TV line 10, OTS-2 satellite (Hoffman, 1982), GPS satellites in common view, and very-long-baseline interferometry (VLBI).

The frequency-standard field is fairly unique in that the cesium atom provides an intrinsic frequency standard. That is, if one has access to either a commercial or laboratory cesium resonator, then one has access to the standard, and it is not necessary to relate the frequency standard back to some standards laboratory (within some accuracy limits). The accuracy of commercial cesium devices is typically only one order of magnitude worse than that available in laboratory devices. Current commercial cesium accuracies are as good as 7 parts in 10^{12}. Time, on the other hand, is not generated intrinsically with respect to anything but is based on definitions and procedures.

13.2 TERRESTRIAL TIME AND FREQUENCY COMPARISON OR DISSEMINATION METHODS

We shall define terrestrial methods as those confined to the surface of the earth or within its atmosphere. In several of these methods the ionosphere plays a key role, either acting as a reflective layer or one surface of a waveguide to propagate the electromagnetic signal that carries the time and frequency information. Because the ionosphere has significant diurnal variations, changing in its electron density with the day–night solar exposure, significant propagation-delay variation results on these terrestrial-bound signals (Winkler, 1972; Joyner and Butcher, 1977; Fleer and Vorob'eu, 1976). As a result of these diurnal variations, it is very often the case that one can average the signal at a quiet time each day, reducing the fluctuations due to the diurnal term by very significant amounts (Allan *et al.*, 1970a).

13.2.1 High and Medium Frequency

The transmissions listed in Table 13-1 are from 27 high-frequency (HF) transmitters located throughout the world. The accuracy of the signals as transmitted is typically on the order of one part in 10^{10} or better, and the time that is transmitted may be synchronous with UTC to within 10 or 20 μsec (Milton, 1974). However, the received accuracy will be greatly degraded due to the propagation fluctuations. Time synchronizations can be achieved on the order of 1 msec and frequency accuracies range between one part in 10^9 and a few parts in 10^7 depending on the distance from the transmitter, the propagation conditions, and the averaging times involved (Kobayashi *et al.*, 1968). For HF and medium-frequency (MF) transmissions, making measurements at the same time each day will reduce the effect of some of the diurnal fluctuations (Sen, 1977).

Transmissions can be received at most locations at any time even though HF and MF propagation is often adversely affected by ionospheric disturbances. See Fig. 13-1 for frequency-stability comparisons (Allan *et al.*, 1974).

13.2.2 Low- and Very-Low-Frequency Transmissions

Table 13-2 lists 17 low-frequency (LF) broadcast stations throughout the world. The accuracies of the frequencies generated at each location are also listed because the long-term phase stability of a propagation signal measured

TABLE 13-1

Standard Frequency- and Time-Signal Broadcasts in the High and Very High Frequency Bands

				Standard frequencies used		
Station	Latitude and longitude	Power (kW)	Antenna	Carrier (MHz)	Modulation (Hz)	Times of UT transmissions
ATA	New Delhi, India 28°34′ N 77°19′ E	8	Horizontal Folded dipole	5.0 10.0 15.0	1; 1000	Continuous
BPM	Pucheng, China 35°0′ N 109°31′ E	10–20	Omni-directional	5.0 10.0 15.0	1; 1000	15/30 (UTC) 9/30 (UT1)
BSF	Taiwan, Peoples Republic of China 24°57′ N 121°9′ E	2		5.0 15.0		Continuous except interruption between minutes 35 and 40
CHU	Ottawa, Canada 45°18′ N 75°45′ W	3 10 3	Omni-directional	3.330 7.335 14.670	1	Continuous
DAM	Elmshorn, Federal Republic of Germany 53°46′ N 9°40′ E	10 15 5		8.6385 16.9804		1155–1206
		10 5		4.2650 8.6385		2355–2406 from 21 Oct. to 26 March
		15		6.4755 12.7635		2355–2406 from 27 March to 20 Oct.

FFH	Paris, France 48°33′ N 2°34′ E	5	Vertical dipole	2.5	1	Continuous
IAM	Rome, Italy 41°47′ N 12°27′ E	1	Vertical dipole λ/4	5.0	1	Continuous
IBF	Torino, Italy 45°2′ N 7°46′ E	5	Vertical dipole λ/4	5.0	1	Continuous
JJY	Sanwa, Sashima, Ibaraki, Japan 36°11′ N 139°51′ E	2	Vertical dipole λ/4	2.5 5.0 10.0 15.0	1; 1000	Continuous
LOL	Buenos Aires, Argentina 34°37′ S 58°21′ W	2	Horizontal 3-wire folded dipole	5.0 10.0 15.0	1; 440; 1000	Continuous
MSF	Rugby, United Kingdom 52°22′ N 1°11′ W	5	Horizontal quadrant dipoles (vertical monopole, 2.5 MHz)	2.5 5.0 10.0	1	5 in each 10
OMA	Praha, Czechoslovakia 50°7′ N 14°35′ E	1	T	2.5	1; 1000	15 in each 30
PPR	Rio de Janeiro, Brazil 22°54′ S 43°11′ W			4.244 4.350 8.634 13.105 17.1944 22.603		During 5 min preceding 0130, 1430, 2130

Table continues

TABLE 13-1 (continued)

Station	Latitude and longitude	Power (kW)	Antenna	Standard frequencies used		Times of UT transmissions
				Carrier (MHz)	Modulation (Hz)	
RCH	Tashkent, USSR 41°19′ N 69°15′ E	1	Horizontal dipole	2.5	1; 10	39 in each 60
RID	Irkutsk, USSR 52°46′ N 103°39′ E	1	Horizontal dipole	5.004 10.004 15.004	1; 10	41 in each 60
RIM	Tashkent, USSR 41°19′ N 69°15′ E	1	Horizontal dipole	5.0 10.0	1; 10	39 in each 60
RTA	Novosibirsk, USSR 55°04′ N 82°58′ E	5	Horizontal dipole	10.0 15.0	1; 10	41 in each 60
RWM	Moscow, USSR 55°19′ N 38°41′ E	5 5 8	Horizontal dipole	4.996 9.996 14.996	1; 10	39 in each 60
SAJ	Stockholm, Sweden 59°15′ N 18°6′ E	0.02	Omni-directional	150.0	—	10(20)
VNG	Lyndhurst, Victoria, Australia 38°3′ S 145°16′ E	10	Omni-directional	4.5 7.5 12.0	1; 1000	Continuous

Y3S	Nauen, German Democratic Republic 52°39′ N 12°55′ E	5	Omni-directional	4.525	—	Continuous
YVTO	Caracas, Venezuela 10°30′ N 66°56′ W			6.1		Continuous
WWV	Ft. Collins, Colorado 40°41′ N 105°2′ W	2.5 10.0 10.0 10.0 2.5	Vertical $\lambda/2$ dipole arrays	2.5 5.0 10.0 15.0 20.0	1; 440; 500; 600	Continuous
WWVH	Kekaha, Kauai, Hawaii 21°59′ N 159°46′ W	5.0 10.0 10.0 10.0	Phased vertical half-wave dipole arrays	2.5 5.0 10.0 15.0	1; 440; 500; 600	Continuous
ZLFS	Lower Hutt, New Zealand 41°14′ S 174°55′ E	0.3		2.5	—	—
ZUO(′)	Olifantsfontein, Republic of South Africa 24°58′ S 28°14′ E	4	Vertical monopole	2.5 5.0	1	Continuous
ZUO(″)	Olifantsfontein, Republic of South Africa 24°58′ S 28°14′ E	0.06	Omni-directional	100	1	Continuous

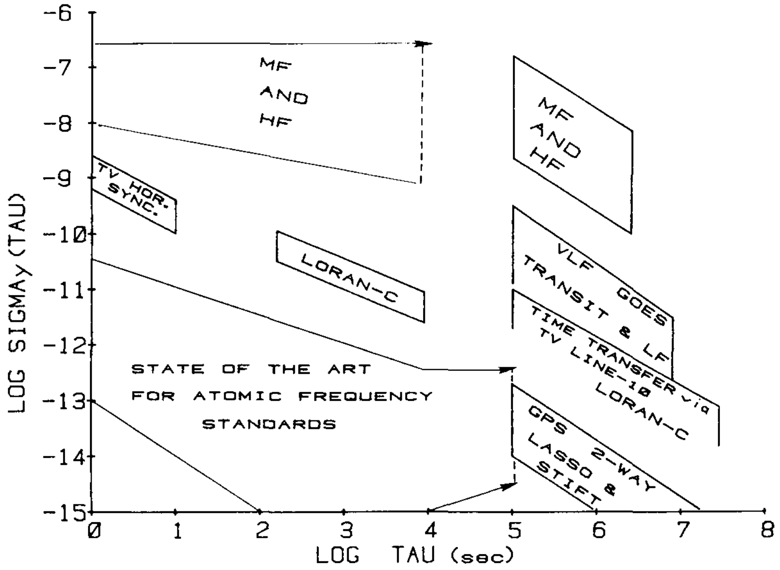

FIG. 13-1 Fractional-frequency stability as a function of averaging time for various T/F dissemination and coordination techniques.

during the same time each day is good enough to transfer frequency to high accuracies (see Fig. 13-1) (Allan and Barnes, 1967). In this case the ionosphere is acting like a waveguide that is quite stable and reproducible from day to day at the same time each day, for example, at noon on the path between the transmitter and the receiver. The coverage of the LF broadcast services, however, is not nearly so great as the very-low-frequency (VLF) and HF services (Weiss, 1976a,b,c; Feichtinger, 1977; Pierce, 1957; Guétrot *et al.*, 1969; Becker and Kramer, 1969; Fey and Looney, 1966). Typical coverage for LF may be a few thousand kilometers from the transmitter. For example, the radio broadcast services of the NBS radio station WWVB are nominally limited to North America.

In general, the user of LF signals wants both frequency and time information. Typical users include industrial, military, and civilian standards labs, electric power companies, calibrators of electronic-counter time bases, and a variety of other moderate-accuracy oscillators (and certifiers of communication-system frequencies as required by law). Typical uses of LF signals, where the emphasis is on time information, include the synchronization of communication systems (Kartaschoff, 1977), time coordination within electric power networks, event dating in electric power networks as an aid in fault analysis, and provision of a general time base in the simultaneous recording of geophysical data at many remote locations. A variety of

TABLE 13-2

Standard Frequency- and Time-Signal Broadcasts in the Low and Very Low Frequency

Station	Latitude and longitude	Power (kW)	Antenna	Standard frequencies used: Carrier (kHz)	Standard frequencies used: Modulation (Hz)	Times of UT transmissions	Accuracy
DCF77	Mainflingen, Federal Republic of Germany 50°1′ N 9°0′ E	20	Omni-directional	77.5	1	Continuous	5×10^{-13}
EBC	San Fernando, Cadiz, Spain 36°28′ N 6°12′ W	1	Omni-directional	12.008 6.840	50	10	1×10^{-10}
GBR	Rugby, United Kindom 52°22′ N 1°11′ W	60 750	Omni-directional	15.95 16.00	1	4×5^{10} per day	2×10^{-12}
HBG	Prangins, Switzerland 46°24′ N 6°15′ E	20	Omni-directional	75	1	Continuous	1×10^{-12}
JG2AS JJF-2	Sanwa, Sashima, Ibaraki, Japan 36°11′ N 139°51′ E	10	Omni-directional	40	1	Continuous	1×10^{-11}
MSF	Rugby, United Kingdom 52°22′ N 1°11′ W	25	Omni-directional	60	1	Continuous	2×10^{-12}

Table continues

TABLE 13-2 (continued)

Station	Latitude and longitude	Power (kW)	Antenna	Standard frequencies used		Times of UT transmissions	Accuracy
				Carrier (kHz)	Modulation (Hz)		
NAA	Cutler, Maine 44°39′ N 67°17′ W	1000	Omni-directional	17.8	—	—	1×10^{-11}
NDT	Yosami, Japan 34°58′ N 137°1′ E	50	Omni-directional	17.4	—	—	1×10^{-11}
NLK	Jim Creek, Washington 48°12′ N 121°55′ W	125	Omni-directional	18.6	—	—	1×10^{-11}
NPM	Cualualei, Hawaii 21°25′ N 158°9′ W	600	Omni-directional	18.6	—	—	1×10^{-11}
NSS	Annapolis, Maryland 38°59′ N 76°27′ W	400	Omni-directional	21.4	—	—	1×10^{-11}
NWC	Northwest Cape, Australia 21°49′ S 114°10′ E	1000	Omni-directional	22.3	—	—	1×10^{-11}
OMA	Podebrady, Czechoslovakia 50°8′ N 15°8′ E	5	T	50	1	23 hr per day	1×10^{-9}

RBU	Moscow, USSR 55°19′ N 38°41′ E	10	Omni-directional	66 2/3	1; 10	6 in each 60	1 × 10^{-11}
RTZ	Irkutsk, USSR 52°18′ N 104°18′ E	10	Omni-directional	50	1; 10	6 in each 60	1 × 10^{-11}
RW166	Irkutsk, USSR 52°18′ N 104°18′ E	40	Omni-directional	200	—	—	1 × 10^{-11}
UQC3	Khabarovsk, USSR 48°30′ N 134°51′ E	300	Omni-directional	25.6 25.1 25.5 23.0 20.5	1; 10; 40	40 min 4 times/day	
UTR3	Gorky, USSR 56°11′ N 43°58′ E	300	Omni-directional	25.0 25.1 25.5 23.0 20.5	1; 10; 40	40 min 4 times/day	
WWVB	Ft. Collins, Colorado 40°40′ N 105°3′ W	13	Top-loaded vertical	60	1	Continuous	1 × 10^{-11}

TABLE 13-3

Loran-C Chains

Chain name	Station name	Location: Latitude	Location: Longitude	Station identification	Peak power (kW)
Great Lakes	Dana, IN	39°51′8″ N	87°29′12″ W	8970 M[a]	400
Great Lakes	Malone, FL	30°59′39″ N	85°10′9″ W	8970 W[a]	800
Great Lakes	Seneca, NY	42°42′51″ N	76°49′34″ W	8970 X[a]	800
Great Lakes	Baudette, MN	48°36′50″ N	94°33′18″ W	8970 Y	
U. S. West Coast	Fallon, NV	39°33′6″ N	118°49′56″ W	9940 M	400
U. S. West Coast	George, WA	47°3′48″ N	119°44′40″ W	9940 W[a]	1600
U. S. West Coast	Middletown, CA	38°46′57″ N	122°29′45″ W	9940 X	400
U. S. West Coast	Searchlight, NV	35°19′18″ N	114°48′17″ W	9940 Y	540
Northeast U. S.	Seneca, NY	42°42′51″ N	76°49′34″ W	9960 M[a]	800
Northeast U. S.	Caribou, ME	46°48′27″ N	67°55′38″ W	9960 W[a]	350
Northeast U. S.	Nantucket, MA	41°15′12″ N	69°58′39″ W	9960 X[a]	275
Northeast U. S.	Carolina Beach, NC	34°3′46″ N	77°54′47″ W	9960 Y[a]	550
Northeast U. S.	Dana, IN	39°51′8″ N	87°29′13″ W	9960 Z[a]	400
Southeast U. S.	Malone, FL	30°59′39″ N	85°10′9″ W	7980 M[a]	800
Southeast U. S.	Grangeville, FL	30°43′33″ N	90°49′44″ W	7980 W	800
Southeast U. S.	Raymondville, TX	26°31′55″ N	97°50′0″ W	7980 X	400
Southeast U. S.	Jupiter, FL	27°1′58″ N	80°6′54″ W	7980 Y	275
Southeast U. S.	Carolina Beach, NC	34°3′46″ N	77°54′47″ W	7980 Z[a]	550
West Coast of Canada	Williams Lake, BC	51°57′59″ N	122°22′2″ W	5990 M	400
West Coast of Canada	Shoal Cove, AK	55°26′21″ N	131°15′20″ W	5990 X[a]	540
West Coast of Canada	George, WA	47°3′48″ N	119°44′40″ W	5990 Y[a]	1600
West Coast of Canada	Port Hardy, BC	50°36.5′ N	127°21.5′ W	5990 Z	400
Central Pacific	Johnston Island	16°44′44″ N	169°30′31″ W	4990 M	275
Central Pacific	Upolo Point, HI	20°14′49″ N	155°53′10″ W	4990 X	275
Central Pacific	Kure, Midway Island	28°23′42″ N	178°17′30″ W	4990 Y	275

North Pacific	St. Paul, Pribiloff Is., AK	57°9′10″ N	170°14′60″ W	9990 M	275
North Pacific	Attu, AK	52°49′45″ N	173°10′52″ W	9990 X	275
North Pacific	Point Clarence, AK	65°14′40″ N	166°53′14″ W	9990 Y	1000
North Pacific	Narrow Cape, Kodiak Is., AK	57°26′20″ N	152°22′11″ W	9990 Z[a]	400
Northwest Pacific	Iwo Jima, Bonin Is.	24°48′4″ N	141°19′29″ E	9970 M	1800
Northwest Pacific	Marcus Island	24°17′8″ N	153°58′52″ E	9970 X	1000
Northwest Pacific	Hokkaido, Japan	42°44′37″ N	143°43′09″ E	9970 X	1000
Northwest Pacific	Gesashi, Okinawa	26°36′25″ N	128°8′56″ E	9970 Y	1000
Northwest Pacific	Yap, Carolina Is.	9°32′46″ N	138°9′55″ E	9970 Z	1000
Gulf of Alaska	Tok, AK	63°19′43″ N	142°48′32″ W	7960 M	540
Gulf of Alaska	Narrow Cape, Kodiak Is., AK	57°26′20″ N	152°22′11″ W	7960 X[a]	400
Gulf of Alaska	Shoal Cove, AK	55°26′21″ N	131°15′20″ W	7960 Y[a]	540
North Atlantic	Angissoq, Greenland	59°59′17″ N	45°10′27″ W	7930 M	760
North Atlantic	Sandur, Iceland	64°54′27″ N	23°55′22″ W	7930 W[a]	1500
North Atlantic	Ejde, Faroe Island	62°17′60″ N	7°4′27″ W	7930 X[a]	400
North Atlantic	Cape Race, Newfoundland	46°46′32″ N	53°10′28″ W	7930 Z[a]	1500
Norwegian Sea	Ejde, Faroe Island	62°17′60″ N	7°4′27″ W	7970 M[a]	400
Norwegian Sea	Boe, Norway	68°38′7″ N	14°27′47″ E	7970 X	165
Norwegian Sea	Sylt, F. R. Germany	54°48′30″ N	8°17′36″ E	7970 W	275
Norwegian Sea	Sandur, Iceland	64°54′27″ N	23°55′22″ W	7970 Y[a]	1500
Norwegian Sea	Jan Mayen, Norway	70°54′53″ N	8°43′59″ E	7970 Z	250
Mediterranean Sea	Sellia Marina, Italy	38°52′21″ N	16°43′6″ E	7990 M	165
Mediterranean Sea	Lampedusa, Italy	35°31′21″ N	12°31′30″ E	7990 X	325
Mediterranean Sea	Karga Barun, Turkey	40°58′21″ N	27°52′2″ E	7990 Y	165
Mediterranean Sea	Estartit, Spain	42°3′36″ N	3°12′16″ E	7990 Z	165

---

[a] These stations are members of two or more chains and are therefore dual or triple rated. They transmit on two (or three) rates with two (or three) pulse repetition periods.

commercial receiving equipment is available for either or both types of application.

The Loran-C navigation chain has found a lot of use in the time and frequency community (Hefley, 1972; Fujiwara *et al.*, 1972; Akatsuka *et al.*, 1977; Mazur, 1973; Potts and Wieder, 1972). As mentioned above, it is the current operational method of communicating the times of most clocks contributing to the generation of TAI and UTC. Although the coverage is presently limited, the long-term plan is to continue to increase this coverage. Most of the northern hemisphere is currently covered by ground-wave propagation from Loran-C transmitters, with the exception of parts of Asia (see Table 13-3) (Allan *et al.*, 1972a). Using the ground-wave-propagated signal, adequate Loran-C signal is receivable up to about 2500 km over land and 3200 km over ocean from the transmitter (Wieder, 1971). Using the sky-wave-propagated signal, reception up to and even beyond 8000 km is possible. The ground-wave accuracy, once the path is calibrated, is typically better than 1 μsec. The sky-wave accuracy is at least an order of magnitude worse than the ground-wave accuracy. Within ground-wave coverage of a Loran-C transmitter, frequency accuracies on the order of one part in 10^{13} can be achieved over long-term averages on the order of two months (see Fig. 13-1).

Although some very good time and frequency accuracies are available with Loran-C, it has not proven as useful to the average user because of the fairly high level of sophistication needed to use the receiver equipment (Kamas and Howe, 1979). A variety of commercial receiver equipment is available.

The Omega Navigation System (Pierce, 1965; Fey, 1971; Swanson and Kugel, 1972) has nominal worldwide coverage because of the frequencies that have been selected and the use of eight different transmitting stations. The Omega Navigation System is composed of a group of VLF radio stations operating in the 10–15-kHz range. Each station time-shares common frequencies used for navigation. In addition, each station may transmit some frequencies unique to that particular station. Table 13-4 lists the specifics of each transmitter.

If one wishes to use an Omega station for frequency calibration, a phase-tracking receiver is highly recommended (Palmer, 1970). If one of the navigation frequencies is to be used, then an Omega commutator must also be used. This is a device that turns the phase-tracking receiver on and off at the proper time to receive only the desired Omega station.

The frequencies and the format segments of the Omega stations are derived from cesium-beam oscillators. The U.S. Naval Observatory (USNO) monitors and reports the Omega stations' phase values. These stations radiate a nominal power of 10 kW. This power level should be sufficient to allow users to receive at least three stations no matter where they are located.

TABLE 13-4

Characteristics of the Omega Navigation System Stations[a]

Station	Location	Latitude, longitude	Power (kW)	Carrier frequencies	Accuracy
OMEGA Ω/A[b]	Alda, Norway	66°25′ N 13°09′ E	10	12.1[c] 10.2 A 11 1/3 C 13.6 B	5×10^{-12}
OMEGA Ω/B	Monrovia, Liberia	06°18′ N 10°40′ W	10	12.0[c] 10.2 B 11 1/3 D 13.6 C	1×10^{-12}
OMEGA Ω/C	Haiku, Oahu, Hawaii	21°24′ N 157°50′ W	10	11.8[c] 10.2 C 11 1/3 E 13.6 D	1×10^{-12}
OMEGA Ω/D	La Moure, North Dakota	46°22′ N 98°20′ W	10	13.1[c] 10.2 D 11 1/3 F 13.6 E	1×10^{-12}
OMEGA Ω/E	La Reunion	20°58′ S 55°17′ E	10	12.3[c] 10.2 E 11 1/3 G 13.6 F	1×10^{-12}
OMEGA Ω/F	Golfo Nuevo, Argentina	43°03′ S 65°11′ W	10	12.9[c] 10.2 F 11 1/3 H 13.6 G	1×10^{-12}
OMEGA Ω/G	Australia	38°29′ S 146°56′ E	10	13.0[c] 10.2 B 11 1/3 D 13.6 C	1×10^{-12}
OMEGA Ω/H	Tsushima Is., Japan	34°37′ N 129°27′ E	10	12.8[c] 10.2 H 11 1/3 B 13.6 A	1×10^{-12}

[a] All stations use omnidirectional antenna.

[b] A through H designate the eight time slots formatted over 10 seconds. The letter by the frequency designates the time slot in which that frequency is broadcast.

[c] Unique station frequency broadcast in the remaining five of the eight time slots.

All Omega transmitting stations are synchronized by means of very stable cesium-beam frequency standards to within a few microseconds. These standards or clocks are referenced to an atomic time scale that is TAI − 10 sec, which was the same as UTC time on 1 January 1972. Choosing not to insert the UTC leap seconds causes the Omega 10-sec format to move nearly 1 sec with respect to UTC with each leap second.

The propagation characteristics that permit the use of Omega at great range also introduce certain limitations (Kirby, 1970). Two areas that require special attention are normal time variations and modal interference. Since signals are propagated within the waveguide formed by the earth and ionosphere, changes in propagation parameters such as velocity may be expected as a result of changes in the ionosphere–ground waveguide (Burgess and Walker, 1970). These changes may be as much as one complete cycle at the carrier frequency. Sometimes, with stable reference clocks, one can predict across these apparent cycle jumps since these variations are often repeatable.

13.2.3 Other Methods

Television signals are probably one of the most cost-effective, precise T/F comparison methods available.[§] There are basically three schemes for using TV signals: two are associated with fixed transmitters and one with satellite transmission. For fixed transmitters one can use TV as a timing device, assuming fixed delays from transmitter to receiver, by extracting one of the horizontal synchronization lines such as line 10. One can also use it as a frequency calibration device. Since many of the transmitters have atomic oscillators for frequency control, TV techniques have been demonstrated to be very feasible for remote frequency calibration.

Using a horizontal synchronization pulse, after calibrating and removing systematic time delays, one can achieve stabilities and accuracies on the order of a few microseconds. Hence, long-term multiday frequency averages can be as good as a few parts in 10^{13} if averaged over a long enough period (see Fig. 13-1) (Allan *et al.*, 1972a; Allan *et al.*, 1970a). If the frequencies of the transmissions of the main-network TV stations are known with respect to some primary standard, then the TV methods can be used as common-view transfer standards, yielding accuracies potentially as good as a few parts in 10^{13}. The use of TV frame synchronizers has rendered the above two schemes nonviable except where common view of the same transmitter is utilized between the two sites being compared.

[§] Tolman *et al.* (1967), Saxena and Mathur (1977), Hundertmark *et al.* (1976), Palii *et al.* (1972), Gabry *et al.* (1977), Becker and Enslin (1972), Rovera (1972), Parcelier (1970), Fujiwara *et al.* (1975), Davis *et al.* (1970), Miller (1970), and Fedorov *et al.* (1977).

The third scheme is being developed extremely well by the Yugoslavians and is mentioned here in the context of TV methods (Kovacevic *et al.*, 1979). They locate the position of the satellite that is transmitting the TV signal and then use the encoding on the TV signal to perform the time transfer between two fixed points on the surface of the earth. They believe accuracies of a few nanoseconds can be achieved between two sites within the beam width of their satellite signal. This particular system is fairly exclusive to Yugoslavia. However, other countries are pursuing similar techniques (Takashashi, 1976b).

Microwave techniques have been utilized to perform submicrosecond time transfer (Phillips *et al.*, 1970, 1971; Curtwright, 1969). A line-of-sight path is chosen between two clocks and the signal is sent in both directions. Assuming reciprocity of the two directions allows calculation of the absolute delay between the two sights. The limiting accuracy is usually in the calibration of delays in the transmitters and receivers at each site and not in the assumption of reciprocity. When microwave repeaters are required for overland transmissions, the stability degrades due to the longer path through the atmosphere as well as the instabilities in the repeaters. If a repeater is changed along a given path, then it is extremely difficult to reproduce the total transmission delay to a few nanoseconds (Leschiutta, 1973; Souček, 1969). In the case of the television microwave system in the U. S., the delay may change several microseconds when components are changed in the microwave transmission system (Allan *et al.*, 1972a). With current technology it appears that one can calibrate the equipment delays to better than 10 nsec (Imae *et al.*, 1982). The errors in the assumption of reciprocity for line-of-sight paths are less than 1 nsec. Time stabilities for sampling intervals from 1 sec to several thousand seconds have been measured at the 100-psec level and below (Costain *et al.*, 1979b; Janes, 1970). If, in addition to the benefits of reciprocal transmissions, one can also calibrate the atmospheric effects, then stabilities as good as 1–10 psec can be achieved (Vessot and Levine, 1974; Levine, 1977; Allan, 1981).

Portable clocks have been used for centuries in one form or another to transfer time and frequency between remote locations. Currently, one of the better ways to communicate time between two remote sites is by portable clock. However, with the advent of extraterrestrial dissemination methods, described in the following sections, that may very well change.

The current most popular clocks are based on cesium resonators (Bodily and Hyatt, 1967). Rubidium has been tried with some success (Hellwig and Wainwright, 1975), but apparently most people feel that, considering the time and expense involved in making a trip, it is better to carry a cesium clock since cesium will outperform rubidium under transport. Portable clocks are usually carried to transport time, not frequency. Most people experience

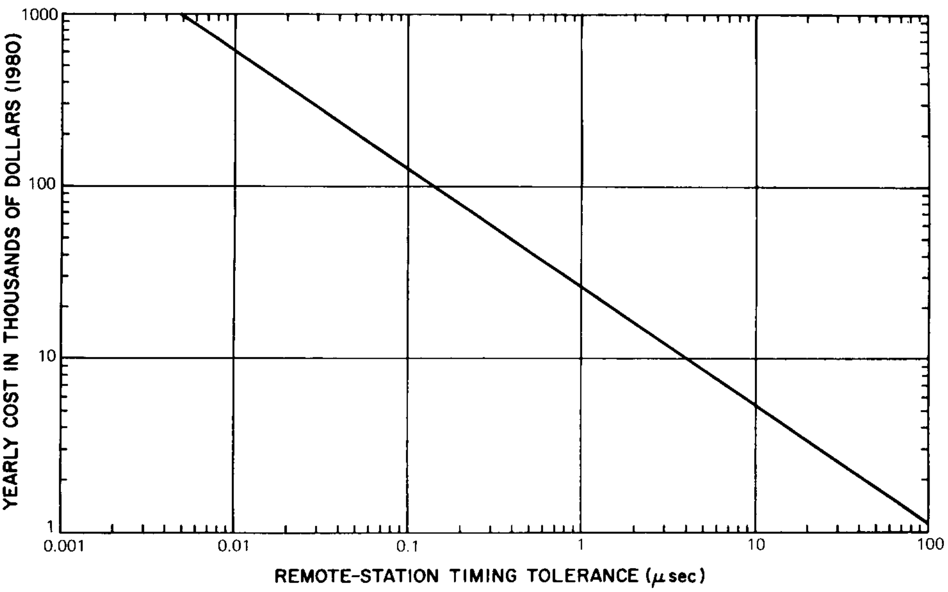

FIG. 13-2 An approximate estimate of yearly cost per station for time synchronization by portable clock as a function of remote-station timing tolerance.

fairly large inaccuracies when they try to transport frequency. However, this need not be the case, as will be discussed later.

Figure 13-2 gives an indication of the cost-effectiveness of portable clock transports. The accuracy of this method is as good as a few nanoseconds between points on the surface of the earth that are reasonably accessible to airports. Outlined in the references (Hafele and Keating, 1972b; Ashby and Allan, 1979; Hellwig and Wainwright, 1975) are some ways to achieve high accuracy using portable clocks.

Typically, portable clocks do not work well for frequency transfer between two locations, because of transport effects and environmentally induced instabilities. Some of the problems can be overcome. Some recovery time is required for the clock to reach thermal equilibrium. Also, a different magnetic field environment is usually encountered at each location. Often the frequency dividers that generate the one pulse per second (pps) from 5-MHz signals, for example, can have significant delay variations as a function of temperature (on the order of several nanoseconds in some cases). If one wishes to use a device for frequency transport, then there are two important steps. First, the delay between the 1-pps tick and the next zero-volt crossing of the 5- or 10-MHz sine-wave output should be measured. If the divider is perfect, then the delay should remain constant for the clock. The zero crossing will usually be a much better reflection of the cesium resonator than will the 1-pps tick if it is properly terminated when measured and cable delays are taken into account. The 1-pps tick can be used to remove the 200- or 100-nsec ambiguity in the timing of the 5- or 10-MHz zero crossings, respectively. Second, the clock should be allowed to reach equilibrium (which usually takes a few hours), and then the magnetic field should be measured. This can be done on most commercial cesium clocks without opening the servo loop if it is done with care. The effect of the magnetic field can be measured to a few parts in 10^{14}. These measurements allow one to account for different magnetic field environments at the two locations. The clock should be measured for a few day's time at the secondary site before being carried back to the original site to give a total round-trip frequency and an average frequency for the trip. If these procedures are followed, then accuracies of a few parts in 10^{14} can be achieved for transferring frequency to remote sites (Endsley, 1982).

Coaxial techniques for communicating time and frequency to remote locations have been fairly well documented (Powers, 1974). One particularly new and promising area, however, is optical fibers. Time stabilities on the order of about 30 psec have been demonstrated over a three kilometer path (Moreau, 1977b; Lutes, 1981).

One of the most popular time-dissemination services offered in some countries is *telephone time of day*. These services can be accurate to better than 0.1 sec with time stabilities of a few milliseconds, which allows one to obtain frequency accuracies of about one part in 10^5 (Koide, 1966).

13.3 EXTRATERRESTRIAL TIME AND FREQUENCY COMPARISON OR DISSEMINATION METHODS

The word "extraterrestrial," is used here to refer to signals or clocks that are above the atmosphere of the earth. Such methods certainly include satellites and may also include deep-space radio sources. Over the last several years there has been a lot of interest in this area, and several interesting ideas have emerged.[§]

13.3.1 Operational-Satellite Techniques

As a complement to its other time and frequency services, the National Bureau of Standards (NBS) sponsors a satellite-disseminated time code using the Geostationary Operational Environmental Satellite (GOES) satellites of

---

[§] Cooper and Chi (1979), Taylor (1974), Hanson and Hamilton (1971a,b, 1973), Chi (1975), Fisher *et al.* (1976), Buisson (1973), Gatterer *et al.* (1968), and Nottarp *et al.* (1979), Allan *et al.* (1985).

the National Oceanic and Atmospheric Administration (NOAA) (Hanson *et al.*, 1979; Beehler *et al.*, 1979). This system is an example of how a meteorological satellite can be used for time dissemination. The time code is referenced to the UTC(NBS) time scale. Although the time code was designed to provide a means of dating environmental data collected by the GOES satellites, it can also be used as a general-purpose time reference for many other applications. The time code is operationally available nearly full time to the entire Western hemisphere from two satellites.

There are always at least three GOES satellites in orbit, two in operational status with a third serving as an in-orbit spare. The western satellite operates at 468.825 MHz and is located at 135° West longitude. The eastern satellite is received on 468.8375 MHz and is positioned at 75° West longitude. The spare is at 105° West longitude. Coverages of the two operational satellites are shown in Fig. 13-3.

The GOES satellites collect environmental data from remote sensors. The time code is part of the interrogation channel that is used to communicate with these sensors. The interrogation messages and time code are prepared and sent to the GOES satellites from Wallops Island, Virginia. The National Bureau of Standards maintains atomic clocks referenced to the UTC (NBS) time scale at this site to generate the time code. The time code includes a sync word, a time-of-year message (including day of year, hour, minute, and second), UT1 correction, and satellite position. A description of the time code and receiver is given in Cateora *et al.* (1978).

The GOES time code can be used at three levels of performance: uncorrected for path delay, corrected for mean path delay only, and fully corrected.

(1) *Uncorrected*: The path delay from the point of origin (Wallops Island, Virginia) to the earth via the satellite is approximately 260,000 μsec. Since the signals are advanced in time by this amount before transmission from Wallops Island, they arrive at the earth's surface on time to within 16 msec.

(2) *Corrected for mean path delay*: Accounting for the mean path delay to any point on the earth's surface but ignoring the cyclic (24-hr) delay variation generally guarantees the signal arrival time to within ±0.5 msec.

(3) *Fully corrected*: The cyclic delay variation is a result of the satellite orbit not being perfectly circular and not in the plane of the equator. The orbit is actually an ellipse and has a small inclination, usually less than 1°. To compensate for these and other effects, the satellite position is included with the time message for correction of path delay either by the user or automatically within the receiving equipment. This correction, in principle, provides path delays accurate to ±10 μsec, assuming the availability of good quality satellite tracking data. The ultimate accuracy of the recovered time,

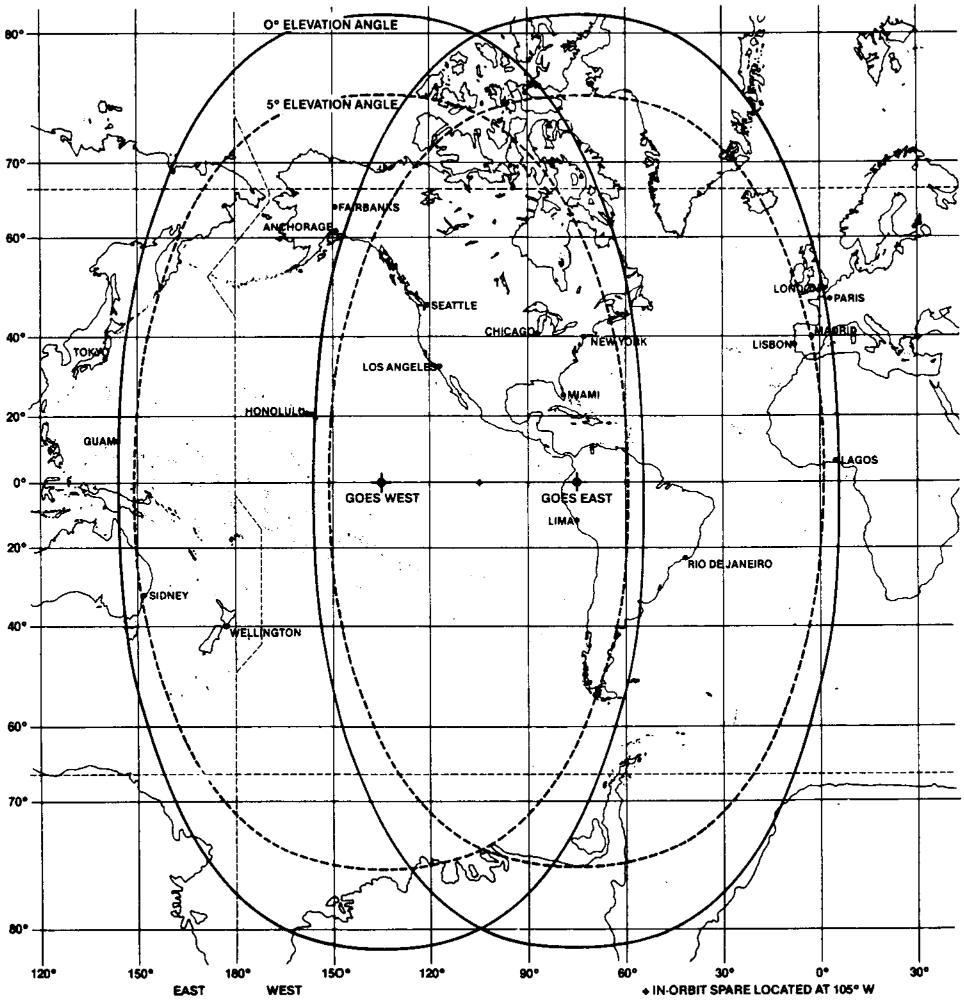

FIG. 13-3 Area covered on the surface of the earth by the two operational GOES satellite timing-signal transmissions.

however, depends on knowledge of the satellite's ephemeris, signal path delay, and user equipment delays and noise levels. Approximately five years of experience with this system has shown that much larger errors occasionally occur. These errors result from such sources as unusually poor-quality orbit elements for the satellites being supplied to NBS by the tracking organizations, unannounced shifts from one satellite to another, and satellite maneuvers. Occasional temporary time-code shifts due to such causes have

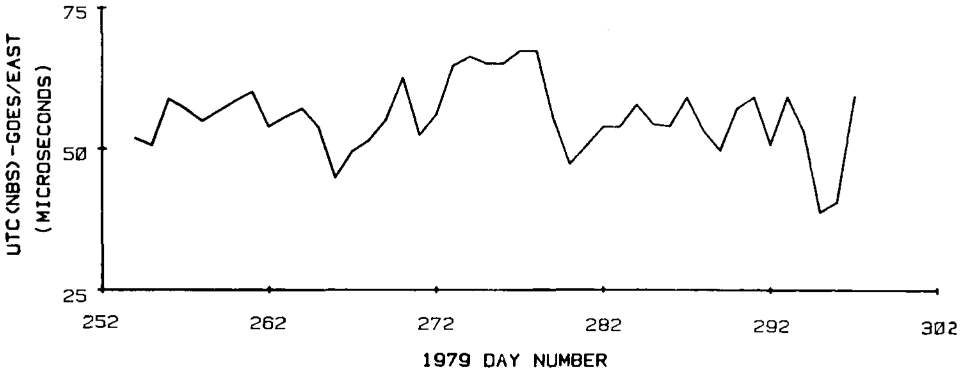

FIG. 13-4 Time-stability plot of filtered daily averages of GOES/EAST timing signal referenced to UTC (NBS), Boulder, Colorado.

been observed at the several hundred microsecond level. However, the timing signal can usually be relied on to remain within ±50 μsec of UTC (NBS) over long periods of time, that is, months (Hanson *et al.*, 1979).

Figure 13-4 shows the variation of path-delay-corrected daily averages of UTC (NBS) − GOES (East) over a typical 45-day period. Figure 13-5 shows the performance of GOES (East) over a longer period of 258 days but based only on a single measurement made at 0000 UT each day. For comparison, Fig. 13-6 shows how the received time code varied over a period of about 6

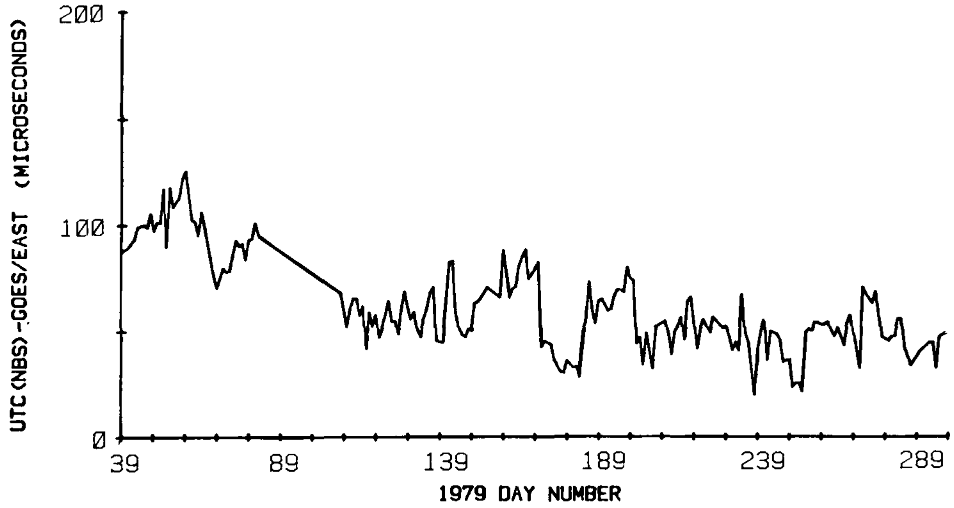

FIG. 13-5 Time stability of single daily measurements taken at 0000 UT of GOES/EAST timing signal referenced to UTC (NBS), Boulder, Colorado.

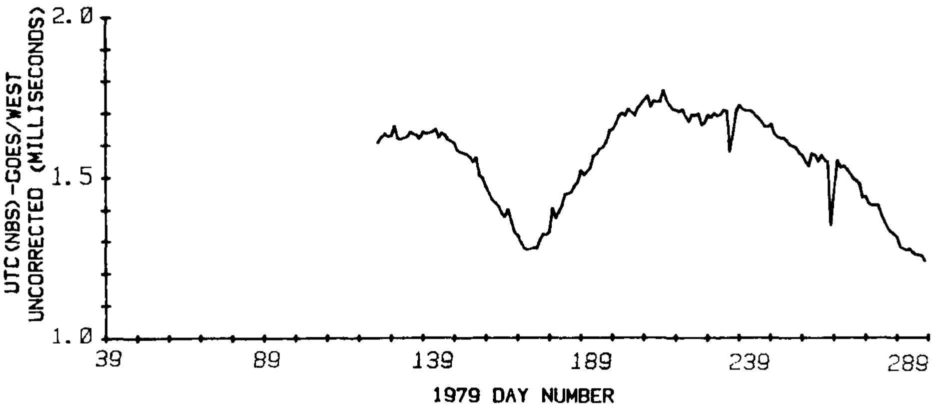

FIG. 13-6 Time stability of single daily measurements taken at 0000 UT uncorrected for path delay for the GOES/WEST timing signal referenced to UTC (NBS), Boulder, Colorado.

months for GOES (West) when no corrections were made to the data for path delay.

Commercial receivers are available at different levels of complexity and performance. Based on estimates of commercial receiver sales, there are currently more than 400 users of the GOES satellite time code. Applications vary widely, with special emphasis on those situations where multiple receiving sites are involved that must be synchronized over large geographical areas and where remote geographical areas are involved that are not well served by terrestrial-based T/F services. Examples include time coordination throughout large electric-power networks in South America, Central America, and Canada; provision of a widely accessible standard for comparing phase-angle measurements throughout electric-power networks; synchronization of communication-system sites, both on the ground and in aircraft; and correlation of extensive data collected from geophysical monitoring networks.

The worldwide meteorological satellite system, of which the GOES satellites are a part, also includes operational satellites for the European and Japanese regions; these are known as Meteosat and GMS, respectively. A number of new and upgraded satellites designed to replace those currently in operation are in the planning, design, and construction stages, thus assuring continued operation of the overall system well into the 1990s.

Although the time code is presently available only from the U.S. components of the international system, the appropriate bits in the data format needed for the time code are available on the other satellites. Some discussions have been held with European and Japanese T/F organizations and the European Space Agency concerning an international expansion of the time-code capability, but firm decisions have not yet been made. Also, there is some possibility that an Indian Ocean satellite component of this overall system will be added at some later time, giving considerable improvement in the coverage of that region.

Also, in the future the operational GOES time-code system may be improved by arranging direct access by NBS to a NOAA computer in order to access satellite position information on a more current basis. The system would then be capable of about 10-μsec accuracy.

The TRANSIT, or NOVA, satellite system is the first to provide an operation worldwide timing system (Laidet, 1972; Stansell, 1971; Rueger, 1970, 1971; Beehler *et al.*, 1979). The system is also known as the Navy Navigational Satellite System (NNSS). It currently consists of a constellation of five satellites in polar orbits at altitudes of about 1000 km. This altitude gives a $1\frac{3}{4}$-hr orbit period, and the satellite longitudes are chosen so that any point on the surface of the earth can be covered by any of the satellites as the earth spins under their orbits. Two-minute intervals on the satellite transmissions are measured at Navy tracking stations, which in turn are coordinated with UTC (USNO). The corrections are uploaded for each satellite, so that the satellite signal can be traceable to UTC (USNO). By averaging over several of the satellites and a large number of passes, one can obtain the root-mean-square (rms) time errors with respect to UTC (USNO), which are less than 10 μsec (Beehler *et al.*, 1979). Figure 13-7 illustrates the improvement gained by averaging sequential passes, and Fig. 13-8 illustrates the stability obtained by averaging 30 passes over an 8-month period with UTC (NBS) as the reference. At any given single measurement the time difference with respect to UTC (USNO) should be less than 50 μsec. The transmission frequency for transit is 400 MHz, and commercial receivers are available in the $12,000 price range. One-day averages would allow a frequency calibration of better than one part in 10^{10}. The accuracy of calibration would nominally improve as the inverse of the averaging time.

13.3.2 Experimental-Satellite Techniques

There are several very interesting experiments that have been done comparing T/F at remote locations, and there are several experiments that are either in process or being planned. We shall look briefly at some of the experiments that show future potential.

Although T/F services such as those described earlier will continue to serve the needs of a great majority of users for many years to come, they are already proving to be deficient for applications demanding state-of-the-art accuracies. As more sophisticated technology continues to be introduced throughout most societies, T/F dissemination and coordination capabilities,

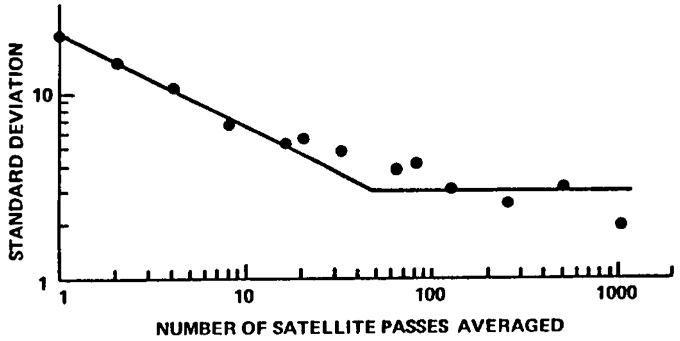

FIG. 13-7 Standard deviation of received transit signals as a function of the number of satellite passes averaged (all satellites included).

Day	Mean (μsec)	σ (μsec)
037–100	-3.9	6.6
100–165	-2.7	3.4
165–220	-8.2	6.1
221–268	-13.1	5.3
268–274	-22.8	3.8

which are important components in many cases, will have to show corresponding improvement. At least in the case of present terrestrial-based T/F services, however, such improvements will be extremely difficult and expensive or, in some instances, virtually impossible due to fundamental limitations. For example, the accuracy of time transfer via HF and LF radio propagation will, in general, always be limited to about the levels achievable now due to the uncertainties and disturbances introduced by the propagation

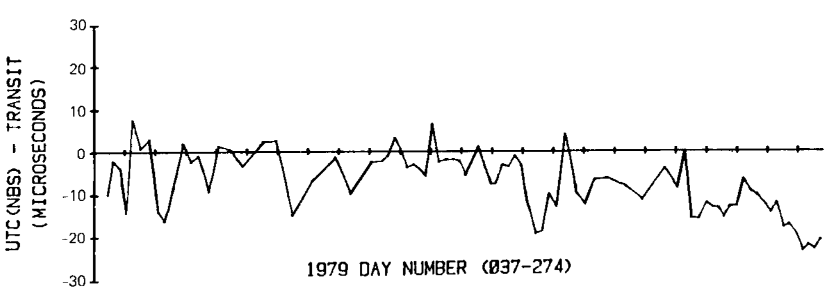

FIG. 13-8 Time stability of transit-timing signals averaging 30 satellite passes per point referenced to UTC (NBS), Boulder, Colerado.

media. Even in the case of a need for improved coverage, where one might expect to alleviate the problems by simply implementing more HF radio stations, we are already seeing the disadvantages of this approach, in some regions of the world, in the form of increased mutual interference.

In recognition of this need to explore other possibilities for improving time-transfer capabilities in the future, Study Group 7 of the Consultative Committee for International Radio (CCIR) has initiated a study of satellite-based alternatives for improving T/F dissemination and coordination. The emphasis of this study is on satellite systems and techniques that offer reasonable promise of supporting operational, long-term needs as contrasted with short-term experiments. A special Interim Working Party (IWP) 7/4 has been established to perform this study and, while this task is not yet concluded, some useful background information on various satellite alternatives has been accumulated and is being evaluated. Part of the work of this committee has been used in developing this section (CCIR, 1982).

The availability and use of communication channels provided by operational communication satellite systems is growing dramatically.[§] For high-accuracy, point-to-point time comparisons, two sites can arrange simultaneous exchange of timing signals through a 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. 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 the 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/sec are often available as a "standard" channel, but bit rates of 1.5 Mbit/sec and higher are often available. In one-hop two-way situations, time stabilities of less than 1 nsec have been achieved when taken over several minutes of data (Costain *et al.*, 1979b). The time-transfer accuracy is still being researched and investigated, but it appears that 6 nsec or better is achievable (Imae *et al.*, 1982).

The Global Positioning System (GPS), also known as NAVSTAR, is being developed by the U. S. Department of Defense as a high-accuracy, con-

---

[§] Steele *et al.* (1964), Smith *et al.* (1977), Markowitz *et al.* (1966), Saburi *et al.* (1976a,b), Easton *et al.* (1974), Yamamoto *et al.* (1976), Detoma and Leschiutta (1980), Mathur *et al.* (1980), and Brunet (1979).

tinuously available navigation–position-location system (Ward, 1976; Buisson *et al.*, 1976; Grenchik and Fang, 1977; Milliken and Zoller, 1978). The system will eventually include 18 operating satellites, arranged in 3 orbital planes at nominally 55° degrees inclination to the ecliptic. The 18 satellites in 12-hr orbits will result in several satellites being in view of any specific location at any time. Each satellite will contain atomic clocks (cesium, rubidium, and hydrogen devices are all being investigated) to generate extremely well-characterized timing signals as part of the navigation message format. The system will be supported by an extensive network of monitoring and control stations that will provide updated timing corrections to the onboard atomic clocks. GPS time will be kept within 100 nsec of UTC (USNO). The complex GPS signal format is transmitted to users on frequencies of 1575 and 1228 MHz and can be received with relatively small omnidirectional antennas. Coded information is included, giving clock corrections, ionospheric corrections, and satellite ephemeris data for calculating the one-way propagation delay. The GPS signal is designed to provide navigation and time information at two different accuracy levels.

It is important to understand that the U. S. Department of Defense has not yet formally announced decisions that could have a major impact on the time-transfer capabilities of GPS for nonmilitary users. Examples of questions that remain to be officially answered include the extent to which access to the GPS timing information may be controlled for nonmilitary users and the extent, if any, to which the full timing accuracy of the GPS may be intentionally deteriorated for nonmilitary users. Because this information is *not* available at present, the background information in this chapter is based on generally available publications and reasonable projections from a variety of (nonofficial) sources. In particular, where timing accuracies are projected or referred to, it must be understood that what eventually becomes available from the GPS, assuming full implementation of the system, could be substantially different from that expected to date or projected herein.

As of February 1983 six GPS satellites were in orbit and being evaluated. All carry rubidium standards and quartz crystal oscillators, and two also have cesium standards. Full implementation (18 satellites) is projected for the last quarter of 1988. A variety of GPS navigation and timing-receiver developments, intended for various applications, are in progress.

There are four basic approaches to using signals from the GPS satellites. The first three approaches utilize the *clear-access* signal. As shown in Fig. 13-9a, one simply extracts GPS time from the satellite. This approach should have an accuracy, internationally, of about 100 nsec. The second approach, shown in Fig. 13-9b, is what could be called the *clock flyover* mode; the same clock is used at both sites (Besson, 1970, 1974; Besson *et al.*, 1978). Any two sites on the surface of the earth would be able to observe the same clock

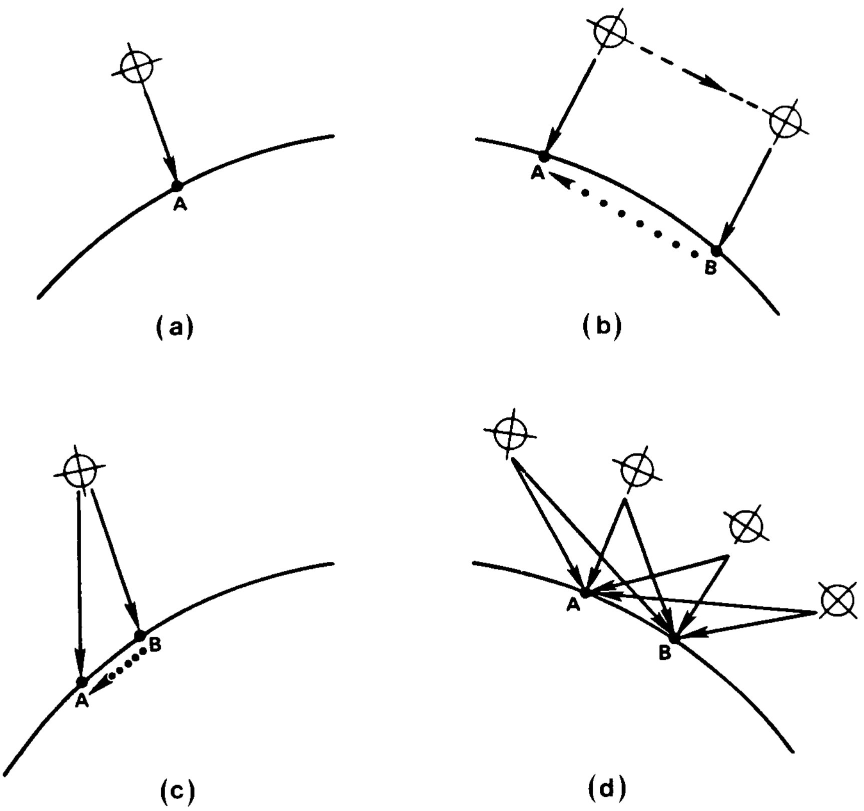

FIG. 13-9 Alternative methods of using GPS for time transfer. (a) GPS time (~100 nsec), (b) clock flyover (~50 nsec), (c) differential common view ($\lesssim$ 10 nsec), (d) VLBI techniques over short baselines ($\lesssim$ 1 nsec).

within a 12-hr interval. It is projected that accuracies on the order of 50 nsec could be achieved in this mode by comparing the received GPS times of the two ground-station clocks. The third approach, shown in Fig. 13-9c, is called the common-view approach, that is, both ground-station clocks observe the same satellite simultaneously (Allan and Weiss, 1980; Davis *et al.*, 1981; Starker *et al.*, 1982; Clements, 1982). In this case the time error of the satellite clock has no effect on the time-transfer error, and the ephemeris error is reduced by approximately an order of magnitude, depending on geometries and propagation circumstances. Accuracies of about 10 nsec are believed achievable using this approach. For short baselines, this approach should yield accuracies approaching 1 nsec as the common-mode cancellation of errors improves for both the satellite ephemeris error and the ionosphere propagation errors. If the ionospheric delay could be measured, errors less than 1 nsec might be achievable (Buennagel *et al.*, 1982).

The last approach, shown in Fig. 13-9d, is being developed for geodesy purposes and is the same idea as that employed in very-long-baseline interferometry (VLBI) (Mac Doran, 1979). In this case, however, the baselines are very short and one simultaneously looks at four satellites from two ground stations using wideband receivers tuned to the full GPS signal. The potential accuracies are in the subnanosecond range, but the equipment employed is more complex than with the other methods, since a computer cross-correlator and radiometers similar to those used in VLBI are needed. The common-view approach is the most cost-effective. Figure 13-10 shows a calculated time transfer using the common-view approach, as would result from the satellite ephemeris errors between the BIH and NBS (with a baseline angle of 74.4°). There are time-transfer errors of about 4 nsec from a 25-nsec rms ephemeris uncertainty when the satellite is nominally midway between the two sites. Differential propagation fluctuations will add additional uncertainties of several nanoseconds to the measurement.

The laser synchronization from stationary orbit system (LASSO), as proposed to the European Space Agency (ESA) by the BIH, employs a laser retroreflector mounted on a suitable geostationary satellite and laser-telescope-equipped ground stations that are to be synchronized (Serène and Albertinoli, 1979). Each ground station arranges to transmit laser pulses to the spacecraft, detect the returned pulses, and measure the round-trip delay

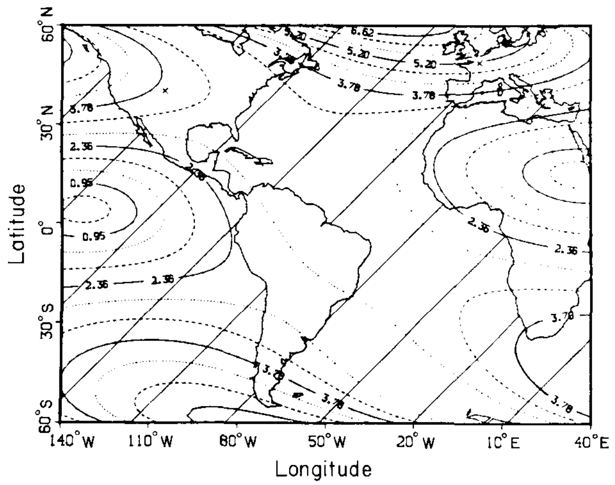

FIG. 13-10 Profile map showing the rms time-transfer error between Boulder, Colorado, and Paris, France, by simultaneously viewing the same GPS satellite, which has an rms position error equivalent to 25 nsec. The contour lines are for the overhead position of the GPS satellite.

time. On the spacecraft the pulses received from the ground stations are detected and their times of arrival are measured in terms of a spacecraft clock. 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. The spacecraft timing data can be sent to the ground stations after the fact by normal telemetry channels, and the ground stations can exchange their data via modern or other terrestrial links.

A spacelab experiment featuring cesium and rubidium atomic clocks is scheduled to be launched in June 1985. The work is being sponsored by the Bundesministerium für Forschung und Technologie of the Federal Republic of Germany and is a part of a joint agreement between ESA and NASA. The objectives of the experiment are to synchronize distant ground stations with an accuracy of better than 10 nsec. Spread-spectrum signals will be used (Starker *et al.*, 1982).

The NASA Office of Space and Terrestrial Applications (OSTA) is considering a Space Shuttle experiment called STIFT to demonstrate techniques for global high-precision comparison of clocks and primary frequency standards (Decher *et al.*, 1982). The experiment would involve a hydrogen-maser clock on board the Shuttle. Transmission of microwave and pulsed-laser signals would be used to compare the space clock in the Shuttle with a clock in a ground station. The goal of the proposed experiment is to demonstrate time transfer with accuracies of 1 nsec or better and frequency comparison of clocks at the 10^{-14}–10^{-16} accuracy level (Allan *et al.*, 1981).

There are special opportunities with communication satellites. One suggestion that has been made is to use to VHF transponders on such satellites for time dissemination. These transponders are used mainly during initial orbit-insertion maneuvers and thus may be available for other ancillary applications once the satellite is well established in its operational orbit.

In one specific case (India) an arrangement has been worked out for access by the National Physical Laboratory (NPL) in New Delphi to a portion of the communications spectrum on the Indian National Communications Satellite (INSAT) for the specific purpose of time dissemination on an operational basis. A 10-kHz channel will be made available on the *S*-band frequency channel, and planning is underway to provide a complete timing signal, including position information on the satellite for one-way path-delay correction by users. Experiments are still being conducted in preparation for implementing this T/F service on the INSAP-1B satellite (Jain and Kumar, 1981; Mathur, 1981).

Time-comparison experiments conducted with an experimental, improved TRANSIT (NOVA) satellite have indicated that accuracies of better than

100 nsec are achievable (Taylor, 1974; Rueger and Bates, 1979). This improved performance, relative to the *operational* TRANSIT results, is due mainly to use of spread-spectrum, pseudo-random-noise-coded satellite signals and sophisticated receivers.

One NOVA satellite was launched during 1981 with the pseudo-random-noise (PRN) capability. As of this writing, there is no approved operational requirement for keeping the PRN code turned on, and it remains uncertain whether such improved signals (for timing) will be available on a long-term basis.

The TDRS system is being implemented to provide two-way relay of tracking and other types of data between NASA ground facilities and low-altitude orbiting satellites in the 1980s. The system will include two operational geostationary satellites at 41° W and 171° W longitude and a dedicated spare in orbit with the master control center at White Sands, New Mexico. With these locations the TDRS system could provide timing links to laboratories all the way from Japan and Australia through North America, to and including all of Europe. While the TDRS system is mainly intended to communicate with orbiting spacecraft, some NASA tracking stations will also be in the system. The possibility may exist for timing organizations to also participate as users. In one possible high-accuracy, two-way mode each timing user could have an S-band ($\simeq$2-GHz) transponder with suitable auxiliary systems on-site. A timing signal consisting of an identified point in a PRN code sequence could be transmitted at K band from the master control station to the TDRS satellite and then to a timing user at S band. This user could then measure the time of arrival in terms of his local clock, encode this information onto the TDRS signal, and return the signal to the control station via the satellite once again. The user could also generate a local timing signal and transmit it to the control station. Propagation delays can be accurately dealt with, and time-transfer accuracies of about 10 nsec should be possible. For operational use, one could envision a periodic sequence of measurements comparing each timing laboratory in turn with the master clock reference in New Mexico. Such regular comparisons could perhaps be scheduled and coordinated by NASA, the BIH, or some other interested organization (Chi, 1979; Laios, 1972).

Fixed-location users on the earth might also have the option of using the TDRS signals in a lower-accuracy, one-way mode by making suitable computations and corrections for path delay. There is some possibility that a time-of-day code may be added to the TDRS capabilities.

The TDRS system is currently in the implementation stage with one of the two principal satellites in orbit. Since some operational aspects of the full TDRS system are still under discussion, the potential role for future time comparisons and distribution remains unclear.

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 TV transmission format. When both sites are within common view of a single TV transmitter, clock time differences can be measured to accuracies of $\simeq 100$ nsec or better, assuming the differential propagation path delay can also be determined. This method is also useful at larger distances, where two different TV transmitters that are interconnected in a TV network can be observed. With the present trend toward developing TV broadcast capabilities from dedicated satellites, it may become feasible to apply the same TV time-synchronization methods to the satellite TV case. The satellite TV 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 TV 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 TV pulse, which would then be used to transfer time to individual users via one-way reception of the pulse. A third possibility would be for several timing centers to provide their own high-accuracy satellite-position information by comparing the reception times of selected TV pulses. Still another approach for using TV broadcast satellites—in this case with more emphasis on general time dissemination—involves encoding time-of-day information into the TV signal vertical-blanking interval. It can then be received and decoded over wide reception areas with modest accuracy, which is sufficient for many public timekeeping needs.

Television broadcast satellites are currently under development to serve a number of countries and regions throughout the world. T/F dissemination experiments using such satellites are being conducted in Japan (Ishida *et al.*, 1979; Saburi *et al.*, 1979) and are planned for India and Europe. The vertical-interval time code has been tested experimentally in the United States and may be implemented later on some European TV satellites as they become operational.

A proposal for international time and frequency coordination using geostationary meteorological satellites is being pursued. An accuracy of 10 nsec worldwide as frequently as every 3 hr on a continual basis is anticipated.

The international system of satellites of interest is provided by Japan, the United States, and the European Space Agency (ESA). The satellites are all geostationary and include METEOSAT, operated by ESA and located 0° E longitude, Japan's Geostationary Meteorological Satellite (GMS), located at

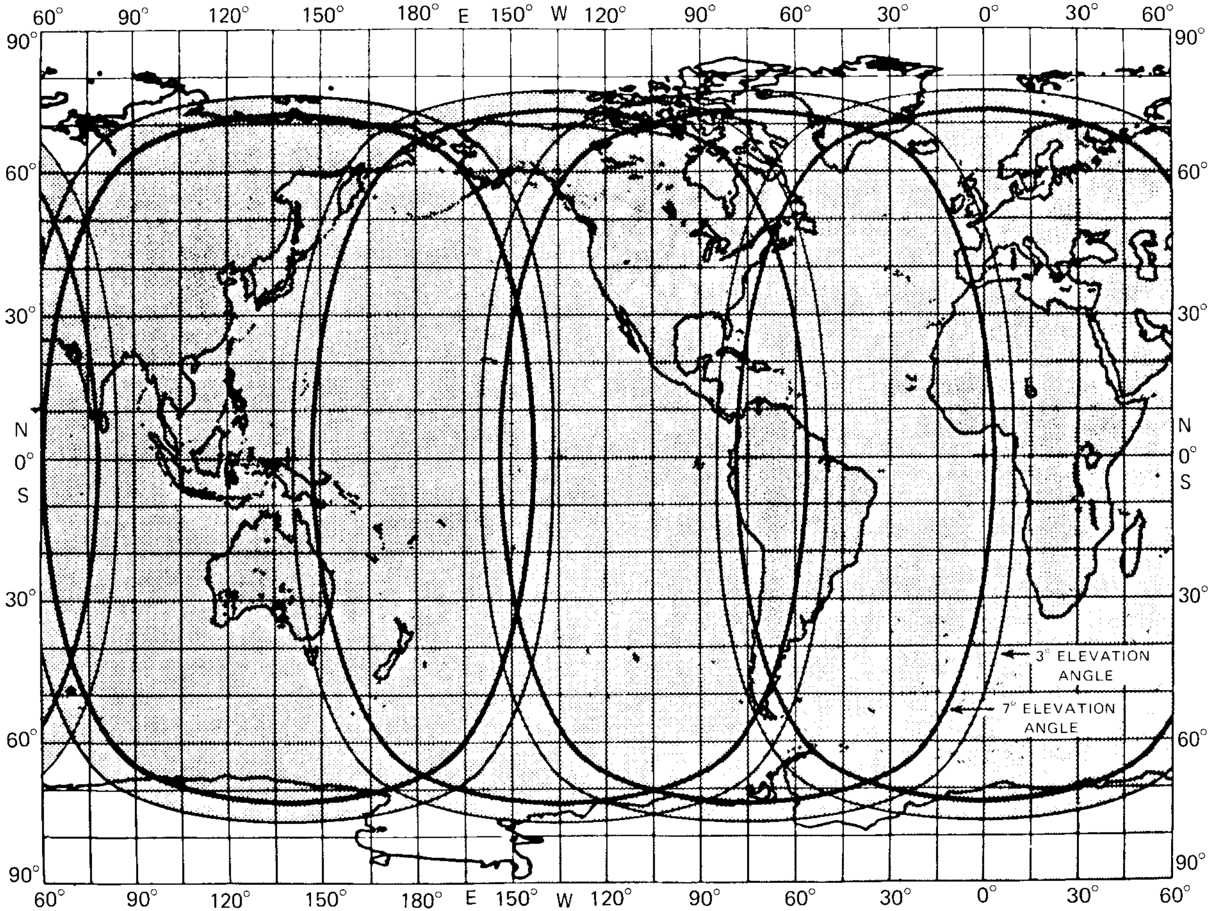

FIG. 13-11 Area coverage by the currently existing meteorological satellites, illustrating the near total coverage for time transfer possible if these satellites could be linked into a common timing system as is proposed.

140° E longitude, and two Geostationary Operational Environmental Satellites (GOES), operated by the United States and located at 225° E and 285° E longitude. Each of these satellites is supported by a ranging system for determining the satellite position at fixed intervals of time, usually every three to four hours. These data are then used to generate a set of orbital elements for the purposes of stationkeeping and position prediction. The approximate earth coverages of these satellite systems are shown in Fig. 13-11.

13.3.3 Deep-Space Radio-Source Techniques

Most deep-space experiments involved either geodesy or the study of deep-space signal sources. Most of these projects are involved with very-long-baseline interferometry (VLBI) techniques. In the long term a cooperative effort between the VLBI community and the T/F community could lead to significant benefits for both. The philosophy of the VLBI community is to use at each site very good frequency standards, typically hydrogen masers, whose frequencies are nominally syntonous (i.e., the frequencies are the same) with each other, and then to store the received radio-source data from large antenna on magnetic tape and cross-correlate the data after the fact. Once cross-correlated, they are in effect finding time resolution between the signals that is subnanosecond. Ten-picosecond resolution has been achieved. The potential for this technique to do extremely precise remote synchronization is incredibly high. The problem is to have real-time clocks at each site at that level of synchronization. Also, any of the techniques involved in studying deep-space radio sources have the very significant disadvantage that the signal strength is about 10^5 smaller than signals from satellites. Hence, almost all of these techniques require extremely sophisticated equipment, very-low-noise electronics, and usually very large antenna surfaces in order for the receiver to have adequate gain to receive the signals.

13.4 COORDINATE TIME FOR THE EARTH

As the accuracies of time and frequency methods for communicating between clocks at remote locations have improved, the relativistic corrections have become operational realities (Ashby, 1975; Ashby and Allan, 1979; Saburi *et al.*, 1976a,b). The September 1980 Consultative Committee for the Definition of the Second (CCDS) agreed upon a declaration establishing international atomic time (TAI) as a coordinate time scale to conform with the definition of the second as realized at the geoid (mean sea level) on the rotating earth and that the reference frame for this coordinate time scale would be a geocentric reference time frame. It was further declared that all of the appropriate relativistic correction be applied so that TAI could be realized as a coordinate time scale on the surface of the earth. If TAI is used as a reference, the following equations allow one to reference to TAI unambiguously at nanosecond levels of accuracy. If clocks at two remote sites wish to have self-consistent coordinate measurements, then they must also use these equations if nanosecond or better accuracy and consistency are desired.

Since TAI has been designated as a coordinate scale (i.e., a time scale defined in space and time in the vicinity of the earth), this implies that UTC is also a coordinate scale, to be distinguished from Universal Time Coordinated. That is, UTC uses the same second based on the definition that TAI uses, but leap seconds are added to UTC so that it is "coordinated" with UT1 for navigational reasons.

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

$$\Delta t = \int_P^Q ds\left[1 - \frac{\Delta V(\mathbf{r})}{c^2} + \frac{v_e^2}{2c^2}\right] + \frac{2\omega}{c^2} A_E, \qquad (13\text{-}1)$$

where c is the speed of light, ω the angular velocity of rotation of the earth, v_e the velocity of the clock with respect to the ground, $\mathbf{r}$ a vector whose origin is at the center of the geoid and whose terminus moves with the clock from P to Q, A_E the equatorial projection of the area swept out during the time transfer by the vector $\mathbf{r}$ as its terminus moves from P to Q, $\Delta V(\mathbf{r})$ the potential difference between the location of the clock at $\mathbf{r}$ and the geoid as viewed from an earth-fixed coordinate system, with the convention that $\Delta V(\mathbf{r})$ is positive when the clock is above the geoid, and ds 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 traveling with the clock. The area 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, $\Delta V(\mathbf{r})$ 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 $\Delta V(\mathbf{r})$ must be calculated to greater accuracy as follows:

$$\Delta V(\mathbf{r}) = -GM_e\left(\frac{1}{r} - \frac{1}{a_1}\right) - \frac{1}{2}\omega^2(r^2\sin^2\theta - a_1^2) + \frac{J_2 GM_e}{2a_1}\left[1 + \left(\frac{a_1}{r}\right)^3(3\cos^2\theta - 1)\right], \qquad (13\text{-}2)$$

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

When transferring time from point P to point Q by means of a clock whose distance from the center of the earth is less than 50,000 km (about 8 earth radii), the coordinate time elapsed during the motion of the clock is

$$\Delta t = \int_P^Q ds \left[1 - \frac{V(\mathbf{r}) - V_g}{c^2} + \frac{v^2}{2c^2} \right], \tag{13-3}$$

where $V(\mathbf{r})$ is the potential at the location of the clock and v is the velocity of the clock, both as viewed [in contrast to Eq. (13-1)] from a geocentric *nonrotating* reference frame, and V_g is the potential at the geoid, including the effect on the potential of the earth's rotational motion. Note that $\Delta V(\mathbf{r}) \neq V(\mathbf{r}) - V_g$, since $V(\mathbf{r})$ does not include the effect of the earth's rotation. This equation applies to clocks in geostationary orbits.

When transferring time from point P to point Q by means of an electromagnetic signal, the process can be viewed either from a geocentric, earth-fixed, rotating reference frame, or from a geocentric, nonrotating, local inertial frame. From the viewpoint of a geocentric, earth-fixed, rotating frame, the coordinate time elapsed between emission and reception of an electromagnetic signal is

$$\Delta t = \frac{1}{c} \int_P^Q d\sigma \left[1 - \frac{\Delta V(\mathbf{r})}{c^2} \right] + \frac{2\omega}{c^2} A_E, \tag{13-4}$$

where $d\sigma$ is the increment of standard length, or proper length, along the transmission path, $\Delta V(\mathbf{r})$ the potential at the point $\mathbf{r}$ on the transmission path less the potential at the geoid [see Eq. (13-3)] as viewed from an *earth-fixed* coordinate system, and A_E the area circumscribed by the equatorial projection of the triangle whose vertices are (1) at the center of the earth, (2) at the point P of transmission of the signal, and (3) 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, $2\omega/c^2 = 1.6227 \times 10^{-6}$ nsec/km^2; this term can contribute hundreds of nanoseconds for practical values of A_E.

13.5 LEVELS OF SOPHISTICATION AND ACCURACIES FOR THE USERS

We shall divide the anticipated users into two groups. There are those who wish to buy commercially available equipment, "plug it in," and hope it works! The second group consists of those who are willing to expend some effort,

TABLE 13-5

Characteristics of the Major T/F Dissemination Systems

Dissemination techniques		Frequency syntonization accuracy	Time transfer accuracy	Ambiguity	Coverage for stated accuracy
VLF radio	GBR, NBA, OMEGA, etc.	1×10^{-11}	Envelope 1–10 msec	1 cycle	Nearly global
LF radio	Standard frequency broadcast (e.g., WWVB)	1×10^{-11} phase 24 h	Envelope 1–10 msec	Year	USA—limited (WWVB)
	LORAN-C	5×10^{-12}	1 µsec (ground) 50 µsec (sky)	TOC 15 min phase 10 µsec	Special areas
HF/MF radio	Standard frequency broadcast (e.g., WWV)	1×10^{-7}	1000 µsec	Code—year voice—1 day tick—1 sec	Hemisphere
Television (VHF/SHF radio)	Passive line-10	1×10^{-11}	1 µsec	33 msec	Network coverage
Satellite (UHF radio)	GOES	3×10^{-10}	50 µsec	1 year	Western hemisphere
	Transit	3×10^{-10}	30 µsec	15 min	Global
Portable clocks	Physical transfer	1×10^{-13}	100 nsec	N/A	Limited by transportation

TABLE 13-6

International Time and Frequency Comparison ($\ll 1$ μsec)

System	Time-transfer accuracy (nsec)	Time stability (nsec)	Frequency syntonization accuracy	Coverage for stated accuracy
GPS (common view)	10	1	$\lesssim 10^{-14}$	Global
Shuttle (STIFT)	1	0.001	$\lesssim 10^{-14}$	To ±57° latitude
GOES (trilateration)	10	a few	$< 10^{-13}$	All but near the poles
LASSO	1	0.1	$\lesssim 10^{-14}$	Depends on implementation
GPS	40[a]	10	$\sim 3 \times 10^{-13}$	Global
2-way (communication satellite)	10	$\lesssim 1$	$\sim 10^{-14}$	All but near the poles
Portable clock	100	N/A	$\lesssim 10^{-12}$	Global (best accuracy within reasonable driving vicinity of airports)
Loran-C	500	$\lesssim 40$	$\lesssim 10^{-12}$	Excludes most of Asia and Southern Hemisphere

[a] This inaccuracy may increase if the GPS C/A code is deteriorated for strategic reasons.

perhaps because of broader coverage or higher levels of accuracy that may be needed in the particular comparison or dissemination system being employed.

13.5.1 Typical User Applications

Table 13-5 summarizes the main characteristics of major time and frequency dissemination systems. Specific examples are given for U.S. controlled systems. The entries in the table are nominal values. Depending on the specific technique employed, the actual accuracy values achieved may be as much as an order of magnitude better or worse than the nominal values listed, and there may be specific departures from the values given resulting from unusual circumstances.

13.5.2 Sophisticated and High-Accuracy Techniques

The techniques listed in Table 13-6 are experimental in nature and may be very labor intensive, requiring very sophisticated users on each end as T/F comparisons are made between clocks. The table gives some indication of the coverage and possible accuracies that might be achieved by the experimental systems that are being tested or are anticipated.

13.6 SUMMARY

Over the last several decades frequency standards have improved about one order of magnitude every seven years. The uses and needs of accurate time and frequency standards have, in a general sense, tracked this improvement. The use and need areas have usually been in the navigation and communication fields. As high technology continues to increase its demands on these and related fields, the need for improved T/F standards will persist as well as the need for improved methods of synchronization and syntonization between remote sites. These improved methods will draw heavily upon satellite techniques for comparing, calibrating, and measuring the improved clocks and oscillators. There are some attractive options being developed, and the potential appears nearly unlimited. With these increasing demands the use of terrestrial techniques will undoubtedly diminish, especially as radio interference becomes more and more of a problem.

To illustrate this trend, consider the backbone T/F dissemination techniques of the past. These have been the MF and HF transmissions, for example, JJY, CHU, WWV, and WWVH, with accuracies of about a millisecond in time and parts in 10^8–10^9 in frequency. These accuracies cannot be improved, because of terrestrial propagation problems, and the expense to run them soars with the energy costs. Increasing the transmission power only increases the costs and the radio frequency interference problems. In contrast, there is now being developed, using satellite techniques, a low-cost operational system with worldwide coverage that is anticipated to have 1-μsec accuracy in time and a few parts in 10^{12} in frequency. Experimental-satellite T/F systems have already demonstrated two to three orders of magnitude better accuracy performance than even this new anticipated operational satellite technique. On the "drawing boards" are satellite techniques with accuracies that push into the few picoseconds region in time and the parts in 10^{16} region in frequency. It has only been recently, with the advent of satellite techniques, that remotely located atomic clocks have been able to be compared at state-of-the-art levels of accuracy with averaging times of only a few days. With terrestrial means it took months.

In order for this congruency between remote T/F measurement methods and improving clocks to continue, it will clearly be necessary to continue developments in both fields. Fortunately, this seems to be happening.

ACKNOWLEDGMENTS

The author is indebted to Roger Beehler, Wayne Hansen, and Dr. Arthur Ballato for their careful reading of this chapter and for their valuable comments and contributions. Trudi Peppler helped greatly in updating and preparing some of the tables and references. This chapter draws upon the work of a large number of people to whom the author gives acknowledgment. The bibliography for this chapter gives reference to them. Figure 13-3 was kindly made available by True Time Instruments, a Division of Kinemetrics.