Reprinted from Journal of the Institution of Electronics and Telecommunication Engineers, Vol. 27, No. 10, 1981, pp. 389-402, 1981 © IETE.

TIME/FREQUENCY SERVICES OF THE U.S. NATIONAL BUREAU OF STANDARDS AND SOME ALTERNATIVES FOR FUTURE IMPROVEMENT

R.E. BEEHLER*

IN THE first part of this paper, the current time and frequency (*T/F*) dissemination services of the U.S. National Bureau of Standards (NBS) are summarized, with special emphasis on the recently implemented time code distribution by satellite. While these services, and other similar ones maintained by other nations, continue to provide needed *T/F* reference signals to large numbers of diverse users throughout the world, demands for improved *T/F* services and international co-ordination capabilities are being generated by many technological application areas. Some of these include communications, navigation, space sciences, electric power networks, and scientific data monitoring of many types. Improvements that are needed may take many forms—*e.g.*, higher accuracy, wider coverage, higher reliability of reception, reduced interference, easier compatibility with automated systems, and lower costs to both users and suppliers of *T/F* reference signals. In the second part of this paper, a number of alternative techniques and systems offering potential improvements in the future are discussed. In all cases included here, these alternatives make use of satellite techniques. While this is not meant to imply that no further improvements are possible or practical in the existing, terrestrial-based services, it does reflect the current thinking of many *T/F* organizations that *substantial* improvements in future *T/F* dissemination and co-ordination will be most easily achieved using satellite-based methods and systems.

NBS T/F DISSEMINATION SERVICES

Radio Broadcast Services: WWV/WWVH

These two HF services have been in operation since 1923 and 1948, respectively, and serve large number of moderate-accuracy users throughout the Western hemisphere WWV, located in the state of Colorado, transmits 10 kW of power on 5, 10, and 15 MHz and 2.5 kW on 2.5 and 20 MHz. WWVH, located in Hawaii, transmits 10 kW on 5, 10 and 15 MHz and 5 kW on 2.5 MHz. All frequencies at each station carry the same program and are transmitted 24 hours/day. The use of multiple frequencies helps to insure that at least one of the transmissions can be received at most locations at any time even though HF propagation is often adversely affected by ionospheric disturbances. Two different types of transmitting antennas are used: the 5, 10, and 15 MHz antennas at WWVH are phased, vertical half-wave dipole arrays designed to produce a cardiod radiation pattern with maximum radiation to the west away from the U.S. mainland, while the 2.5 MHz antenna at WWVH and all WWV antennas are vertical half-wave dipoles that radiate omnidirectional patterns.

Transmitted accuracy is maintained to better than 1×10^{-11} (frequency) and 10 μs (time) at both stations with respect to the NBS Frequency Standard. Each station maintains its own local time scale based on a set of three commercial caesium standards. Long-term accuracy and stability with respect to UTC(NBS) is insured at WWV by making regular TV-Line 10-time synchronizations with the primary time scale in Boulder, CO using common reception of a TV transmission from Denver, CO. This comparison can be made routinely to 10-ns precision. The local time scale at WWVH is steered in long term by making use of more indirect measurement links between WWVH and UTC(NBS). These involve portable-clock, Loran-*C*, and TV-Line-10 links to a U S Navy time reference station near Honolulu, HI which maintains a local time scale that is known with respect to UTC(USNO), and thus, also, with respect to UTC(NBS). WWVH also monitors the WWVB 60-kHz signal from Ft. Collins, CO and the GOES (Geostationary Operational Environmental Satellites) time code transmission to provide further checks on its transmitted accuracy.

The hourly broadcast schedules of WWV and WWVH are shown in Fig. 1. The following types of information are included:

Voice Time Announcements

These occur just prior to each minute. A male voice is used for WWV and a female voice for WWVH to aid in distinguishing between the two stations in regions where they both may be received. Time announcements are given in Universal Co-ordinated Time.

Standard Time Intervals

Each second is marked by a short 5 ms pulse of 1000 Hz (WWV) or 1200 Hz (WWVH), except that the 29th and 59th seconds pulses are deleted, the first seconds pulse of each minute is 800 ms long, and the first pulse of each hour is 800 ms of 1500 Hz (both stations). There is a 40 ms protected "hole" around each pulse during which time all other modulations are deleted in order to avoid interference with attempting to pick out the received pulses;

Standard Audio Frequencies

In alternate minutes during most of the hourly format standard audio tones of either 500-Hz or 600-Hz are broadcast. In addition, there is one 45-second segment

---

*Time and Frequency Division, National Bureau of Standards Boulder, CO 80303 USA.

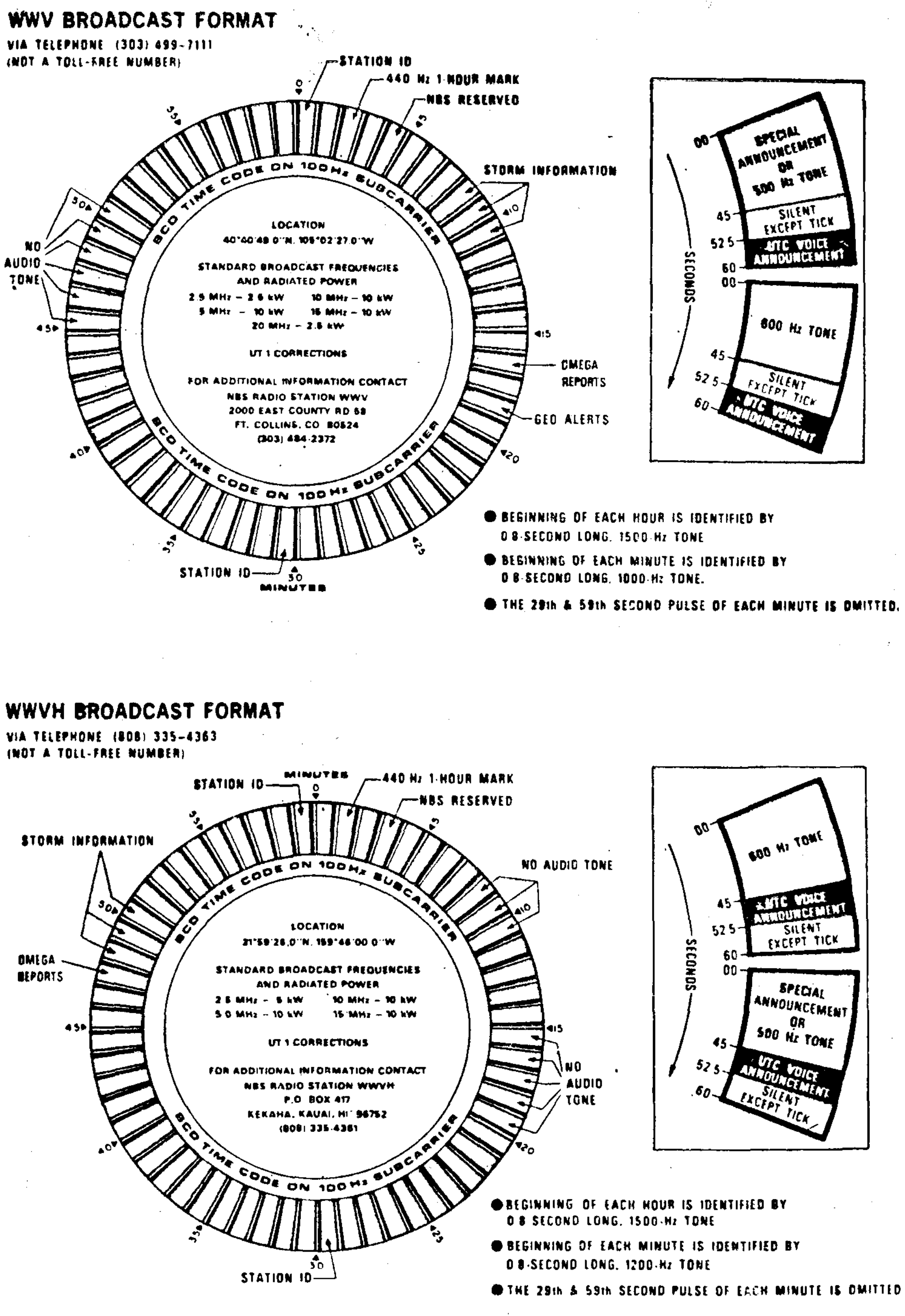

Fig. 1. *Broadcast schedules of WWV and WWVH.*

of 440 Hz each hour that can be used for tuning musical instruments.

UTI Time Correction

Although by international agreement, the WWV and WWVH time signals are maintained within ±0.9 s of the astronomical UTI time scale, information is included in the format which gives the difference between UTI and UTC with a resolution of 0.1s for those relatively few users who need this higher accuracy. WWV and WWVH encode this information by using an appropriate number of doubled seconds pulses each minute in accordance with CCIR Recommendation 460-2;

BCD Time Code

A binary coded decimal (BCD) time code is transmitted continuously by WWV and WWVH on a 100-Hz subcarrier. The 100-Hz subcarrier is synchronous with the code pulses so that 10-millisecond resolution is attained. The time code provides a standard timing base for scientific observations made simultaneously at different locations. It has application, for example, where signals telemetered from a satellite are recorded along with the time-code pulses. Data analysis is then aided by having accurate, unambiguous time markers superimposed directly on the recording.

The WWV/WWVH time-code format presents UTC information in serial fashion at a rate of one pulse per second. Groups of pulses can be decoded to ascertain the current minute, hour, and day of year. While the 100-Hz subcarrier is not considered one of the standard audio frequencies, the code does contain the 100-Hz frequency and may be used as a standard with the same accuracy as the audio frequencies. A description of the time code is contained in ref. 1.

Public Service Announcements

Selected 45-second time slots during the hourly format are made available to other U S government agencies for making appropriate public service announcements. At present these include: Marine weather warnings for certain areas of the Atlantic and Pacific Oceans (WWV and WWVH); geoalert messages giving information on selected geophysical events and some radio-propagation-related data (WWV); and status reports on the Omega Navigation System (WWV and WWVH). More detailed information on the WWV and WWVH services may be found in ref. 1.

A recent, large-scale survey of WWV and WWVH users (ref. 2) demonstrated conclusively that HF services, even with their propagation-related problems, nevertheless are critically important for large numbers of users. Figure 2 is a breakdown of the various users in each of several application areas, based on more than 12,000 responses to a detailed questionnaire. The miscellaneous "Other" category includes three major user groups: private citizens; catch-makers/jewellers; and amateur-radio operators. Of the various services offered within the WWV and WWVH formats, the most popular with users overall are the time-of-day voice announcements, one-second ticks, standard frequencies, and the marine-weather warnings, in that order.

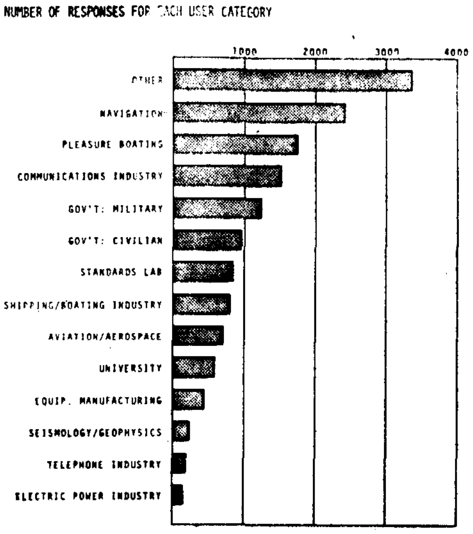

Fig. 2. *Breakdown of users.*

RADIO BROADCAST SERVICES: WWVB

This NBS LF service, operating continuously at a 13 kW level on 60 kHz, complements the HF broadcasts by providing higher accuracy and more reliable coverage primarily for the United States mainland and Canada. The format is designed to satisfy the more demanding needs of industrial and military calibration laboratories, scientific data monitoring applications, the electric power industry, and the communications industry, who are willing to pay higher costs (relatives to HF) in order to gain better performance.

The WWVB facility is co-located with that of WWV in Ft. Collins, CO and uses the same set of commercial caesium standards to maintain its transmitted accuracy of better than 1×10^{-11}. Since effects of the propagation medium are relatively minor in the LF region, frequency comparisons to better than 1×10^{-11} are possible at the users' sites with appropriate receiving equipment and techniques. Day-to-day stability of the WWVB signal is normally better than 5×10^{-12}.

The effective radiated power of 13 kW is transmitted from a 122-metre, top-loaded vertical antenna installed over a radial ground screen. In addition to the phase-stabilized carrier, the WWVB transmission includes time information in the form of a BCD time code. The time code is synchronized with the 60-kHz carrier and is broadcast continuously at a rate of one pulse per second. Each pulse is generated by reducing the carrier power 10 dB at the beginning of the second, so the leading edge of every negative-going pulse is on time. Details of the WWVB time code are presented in reference (*i*).

A WWVB modernization program is nearing completion which is designed to insure continued reliable operation of the facility for many more years. Both main and standby transmitters are being completely refurbished. A new electrical power system, one new caesium standard, and new time code generators are being provided.

Generally, the application areas for WWVB fall into two major categories, depending on whether the signal is needed primarily as a source of frequency information or time information. Typical users and applications in the first category include industrial, military, and civilian government standards labs; electric power companies needing a standard reference for their 60-Hz power frequency; calibration of electronic counter time bases and a variety of other moderate-accuracy oscillators; and the certification of communication system frequencies as required by law. Some typical uses of WWVB, where the emphasis is more on a timing reference with respect to UTC(NBS) include the synchronization of communication system; time co-ordination 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 commercial receiving equipment is available for either or both types of applications.

TELEPHONE TIME-OF-DAY SERVICES: WWV AND WWVH

One of the most popular services offered by the NBS is the telephone-accessible WWV and WWVH time-of-day announcements. Users dialling a regular commercial telephone number in the Boulder, CO (for WWV) or Kauai, HI (for WWVH) area receive the audio portion of the respective HF broadcast directly from the station format generation equipment. It should be noted that such calls are not toll-free calls, except in the local areas near the stations.

Popularity of this service has grown steadily to the point where we are receiving about 2,000,000 calls per year to WWV and about 120,000 per year to WWVH. Incoming calls are limited to three minutes each and it is necessary to provide sixteen lines in rotary to keep the "busy rate" down to an acceptable level (for the WWV services).

CALIBRATION OF NON-NBS TRANSMISSIONS AS TRANSFER STANDARDS

Many radio broadcasts exist which are not primarily intended as time and frequency standards, but which, nevertheless, are stabilized for other reasons and thus can be useful in time and frequency applications. Examples of such broadcasts include: the US Loran-*C* navigation system transmissions at 100 kHz; the eight-worldwide VLF broadcasts of the Omega Navigation System; and many television broadcasts. All of these signals are stabilized by means of atomic frequency standards.

NBS currently monitors on a regular basis two Omega stations, Hawaii and North Dakota; about six different Loran-*C* stations from several different chains; and the three major commercial television networks as distributed both from the US East and West Coast origination points. In the case of television broacasts, both the frequency of the colour subcarrier and the timing of the line-10 synchronization pulses are measured relative to NBS standards. By publishing these measurements in a monthly *T*/*F* Services Bulletin (ref. 3), NBS provides a means for users to compare their local measurements of the same signals with those of NBS and thus obtain traceability to NBS standards.

GOES SATELLITE TIME CODE DISTRIBUTION

As a complement to its other time and frequency services. NBS is now sponsoring a satellite-disseminated time code using the GOES (Geostationary Operational Environmental Satellite) satellites of the National Oceanic and Atmospheric Administration (NOAA) (Hanson *et al.* 1979, ref. 5). The time code is referenced to the NBS time scale and gives Co-ordinated Universal Time (UTC). 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 available to the entire Western hemisphere from two satellites on a near full-time basis.

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. 3.

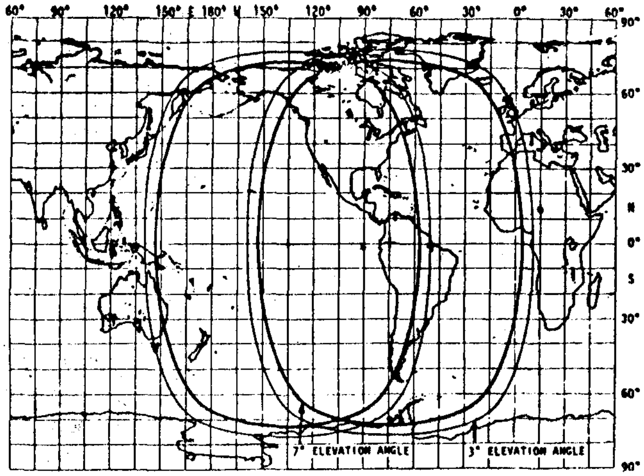

Fig. 3. *Coverage areas for GOES/East and GOES/West satellites.*

The GOES satellites collect environmental data from remote sensors. The time code is part of the interrogation channel which 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. NBS maintains atomic clocks, referenced to UTC (NBS), at this site to generate the time code. In addition, the Wallops Islands equipment contains an automated capability for monitoring Loran-*C* and TV signals as an aid in keeping the GOES clocks synchronized with UTC (NBS) and complete, telephone-accessible diagnostic information. 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 is given in ref. 1.

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.

Uncorrected: The path delay from point of origin (Wallops Island, Virginia) to the earth via the satellite is approximately 260,000 microseconds, 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 milliseconds.

Corrected for Mean-Path Delay: Accounting for the mean-path delay to any point on the earth's surface, but ignoring the cyclic (24-hour) delay variation, generally guarantees the signal arrival time to ±0.5 millisecond.

Fully Corrected: The cyclic delay variation is a result of the satellite orbit or path around the earth 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 by the user or automatically within the receiving equipment. This correction, in principle, provides path delays accurate to ±10 microseconds. The ultimate accuracy of the recovered time, however, depends upon knowledge of user equipment delays and noise levels as well as path delay. Approximately five years' experience with this system have also shown that much larger errors occur occasionally. These result from such sources as unusually poor quality orbit elements for the satellites as supplied to NBS by the tracking organizations, unannounced shifts from one satellite to another, and satellite manoeuvers. Occasional temporary time code shifts due to such causes have been observed at the several hundred microsecond level. However, the timing signal can usually be relied on to remain within ± 50 μs of UTC(NBS) over long periods of time *i.e.*, months (Beehler *et al.* 1979).

Figure 4 shows the variation of path-delay-corrected daily averages of (UTC(NBS-GOES/East) over a typical 45-days period. Fig. 5 shows the performance of GOES/East over a longer period of 258 days, but based only on a single measurement made at 0000UT each day. For comparison, Figure 6 shows how the received time code varied over one period of about 6 months when no corrections were made to the data for path delay.

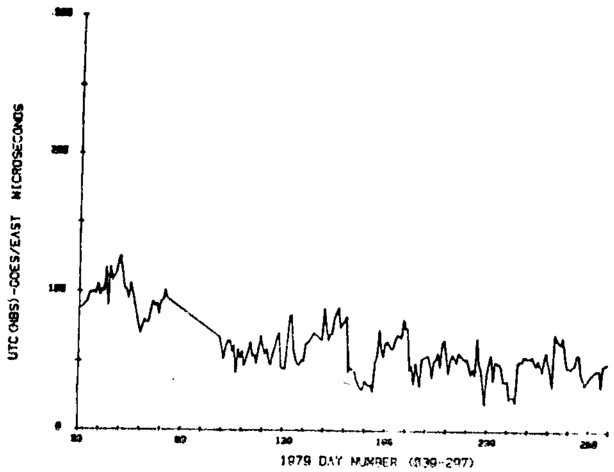

Fig. 4. *UTC (NBS)—GOES/East : Single daily measurements at 0000 UT.*

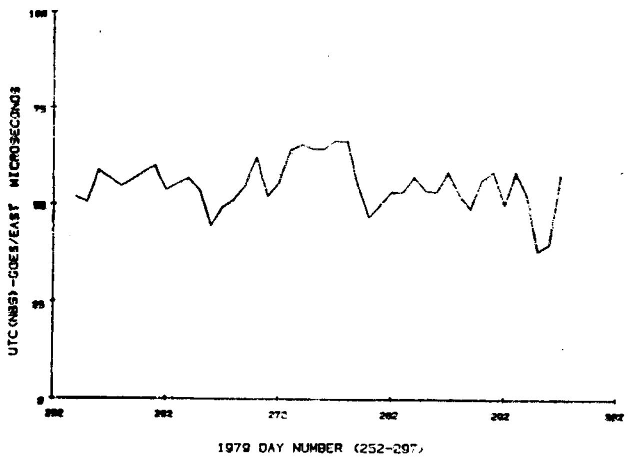

Fig. 5 *UTC (NBS)- GOES/East : filtered daily averages.*

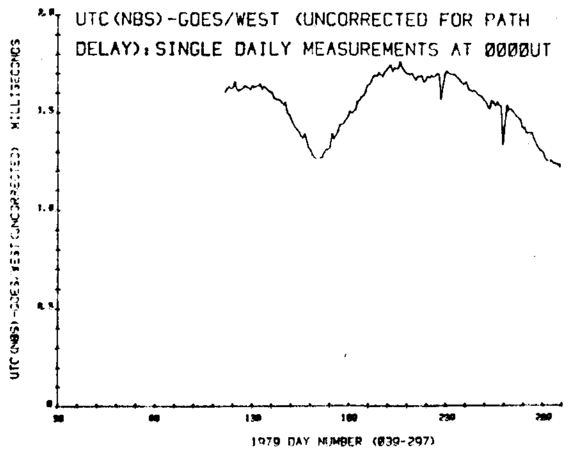

Fig. 6. *UTC (NBS)—GOES/West*

Commercial receivers are available in two different levels of complexity and performance. The simpler version requires the user to make any desired path delay corrections *e.g.*, for the mean-path delay to achieve ± 0.5 ms. Operation is automatic, including switching from one satellite to another if signal is lost. User cost is about $2200. The more sophisticated version contains microprocessors and calculator chips to decode the satellite position data in the format, compute the path delay to the user's specific site updated each four minutes, and correct the output 1 pps reference accordingly. User cost is about $4500. Both receivers can operate with very compact (≅ 0.3 × 0.3 m) plate antennas or reasonably small helix antennas.

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 co-ordination 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 US GOES satellites are a part, also includes operational satellites for the European and Japanese regions. These are known as Mateosat and GMS, respectively. At present, coverage does not extend to the Indian Ocean region. A number of replacement 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 US 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 the Indian Ocean satellite component of this overall system will still be added at some later time.

INFORMATION SERVICES

Because *T/F* techniques are so widely used in may technical applications, there is a substantial need for extensive contacts with equipment manufacturers and users of the various *T/F* services. NBS maintains an active effort to provide information about its own *T/F* services as well as other available alternatives. In addition to the normal technical publications, a variety of semi-technical and more popular brochures, reports, and talks are provided to explain NBS and other services and how to use them. Two recent examples include a tutorial book on time and frequency (Jespersen & Randolph 1977) and an extensive *T/F* Users Manual (ref. 8), which reviews many *T/F* services available and explains how to use them in a very practical way. Another information publication, the monthly *T/F* Services Bulletin, has been mentioned previously.

NBS also develops and presents specialized technical seminars relating to many aspects of time and frequency. One of the principal seminars on the topic of *T/F* calibration resources and methods has been given two times per year for several years and may be developed further into a travelling seminar for presentation at other locations.

SOME POTENTIAL IMPROVEMENTS IN CURRENT NBS SERVICES

At this point in time, the NBS *T/F* dissemination services are considered to be well established and major changes in the next few years are not anticipated. However, the following improvements are in progress or under consideration:

(*i*) The modernization of WWVB, previously mentioned, will be complete during 1981;

(*ii*) A time code referenced to UTC(NBS and designed for direct interfacing to computers and automatic data acquisition systems, may be made available via dial-up telephone links;

(*iii*) The voice-announcement-generation systems at WWV and WWVH may be replaced with solid-state, voice-chip systems. The idea is to replace existing mechanical recording/playback systems with all-electronic systems. Appropriate vocabularies would be constructed including all the necessary words and phrases used in the time, weather and other voice announcements. These words and phrases would then be spoken by a professional announcer one at a time, digitized, and stored in electronic memory. Any combination of words could then be automatically assembled by interfacing to an appropriate timing signal (for time announcements) or to some other input control device *e.g.*, a touch-tone telephone, to assemble a weather message originated in a remote location. Advantages of such a technique include: lower cost; increased reliability of all-electronic equipment; and the ability to generate professional quality public service voice announcements on WWV and WWVH even though the content is selected and updated from remote locations. It is also worth noting that such a voice-chip time-announcement system could also be incorporated within user receiving equipment to provide locally-generated announcements of time. Advantages include: the capability to generate local time announcements referenced to a received time code, rather than having to receive a wideband voice transmission; availability of time announcements in any language and the ability to easily select the language at each user's site; and the flexibility to generate an accurate voice-time announcement on demand and from almost any receivable time code;

(*iv*) The experimental adition of an NBS-referenced time announcement to selected National Weather Service (NWS) FM radio broadcasts in a few major metropolitan centres. One such test is currently under evaluation in Denver, CO, using a voice-announcement system, as described in (*iii*) above, locked to the WWVB time code. A similar test may be conducted in Hawaii, using a voice-announcement system operating from the received GOES satellite time code; and

(*v*) 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.

SOME POSSIBLE ALTERNATIVES FOR IMPROVED WORLDWIDE *T/F* DISSEMINATION AND COORDINATION USING SATELLITE TECHNIQUES

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 some of the more technically-demanding applications. As more sophisticated technology continues to be introduced throughout most societies, T/F dissemination and co-ordination capabilities, 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 achieved now due to the uncertainties and disturbances introduced by the propagation media. Even in the case of the 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 the form of increased mutual interference in some regions of the world.

In recognition of this need to explore other possibilities for improving time-transfer capabilities in the future, Study Group 7 of the CCIR (Consultative Committee for International Radio) has initiated a study of satellite-based alternatives for improving T/F dissemination and co-ordination. The emphasis of this study is on satellite systems and techniques which 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. In the remainder of this paper, some of this information that may be useful to those considering the implementation of satellite-based T/F services or time transfer links will be summarized. In what follows, it should be recognized that, since the IWP 7/4 study is still in progress as of February 1981, the content is primarily the responsibility of the author and should not be necessarily assumed to represent a consensus view of IWP 7/4. In most cases, however, the information is largely factual in nature and is based on publications or information from technical people familiar with each situation.

The various satellite alternatives are divided for convenience into three separate groups: (*i*) those which have primary application for high-accuracy time transfer; (*ii*) those which appear most useful for general T/F dissemination to large number of users; and (*iii*) 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. Following this will be a summary, in tabular form, 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.

Alternatives for High Accuracy, Point-to-Point T/F Transfer

Communication Satellites

The availability and use of communication channels provided 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 10-60 minutes at a time and once or twice per week. Other variations of the techniques are also possbile, 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 kb/s are often available as a "Standard" channel, but bit rates of 1.5 Mb/s and higher are often available.

In some situations (in the U.S., for example) international comparison links via communications satellite may require a two-hop process with one link from the time laboratory to an Intelsat terminal via domestic satellite and a second link from the intelsat terminal to the other country via the Intelsat system. Since many commercial satellite systems are now in operation with proven technology, the implementation of operational timing links among major laboratories would be relatively straightforward.

Many domestic, regional, and international satellite common carriers are in operation and have communication channels available for lease. Earth stations are readily available for many sources either on a purchase or lease basis. Earth station technology is developing rapidly, and there is a strong trend towards using smaller systems (5-10 metres) located at the end point of use [*e.g.*, the timing laboratory]. The 4/6 GHz bands are being heavily used, resulting in some significant frequency co-ordinaion problems in certain areas. Some newer systems (*e.g.*, Intelsat-V, Satellite Business Systems (U.S.), and Advances WESTAR (U.S.) will operate in the 11/14 GHz bands to alleviate crowding and will make use of higher-speed

TDMA techniques. Frequency-reuse techniques are helping to create more available channels out of the same limited spectrum space. As satellite communications capacity and use increase, costs per channel are decreasing.

GPS (Global Positioning System)

The GPS (also known as NAVSTAR) is being developed by the U.S. Department of Defence as a high-accuracy, continuously available navigation/position-location system (Milliken & Zoller 1978). The system will include a total of 18 operating satellites, arranged in 3 orbital planes. The 18 satellites in 12-hour orbits will result in several being in view of any specific location at any time. Each satellite will contain atomic clocks (caesium, 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 stations and control stations which will provide updated timing corrections to the onboard 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 relatively small ominidirectional 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 in such a way that its navigation and time-transfer potential can be made available at two different accuracy levels.

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

As of December 1980, six GPS satellites are in orbit and are being evaluated. All carry Rb standards and some also have Cs standards. Full system implementation (18 satellites) is projected for the mid-1980s. 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 signals is received simultaneously at two (or more) sites (Allan & 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 sychronization accuracy should be possible. 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.

LASSO (Laser Synchronization from Geostationary Orbit)

The concept, 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 which are to be synchronized (Serene & Albertinoli 1979). 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 the 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. 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 teletype or other terrestrial links.

The LASSO project has been approved by ESA as an experiment to be launched along with the SIRIO-2 satellite in late 1981. The satellite will be located for a few months in geostationary orbit at 25°W longitude to enable some North and South American LASSO participation. After that, SIRIO will be moved to about 20°E longitude for its prime meteorological mission. A number of organizations plan to participate in the LASSO experiment but in most cases, the laser facilities are not co-located with the principal timing centres. There are no plans at this time for future *operational* use of the LASSO technique, but it is anticipated that a standard LASSO spacecraft equipment package could be added to other future satellites-of-opportunity fairly easily and inexpensively.

US Space Shuttle *T/F* Transfer Experiment

The US NASA organization proposes to perform a time-transfer experiment using one of the US Space Shuttle vehicles with the intent of demonstrating feasibility of 1ns time transfers and 1×10^{-14} frequency comparisons on a global basis (Decker *et al.* 1980). The technique would include hydrogen-maser clock systems on the spacecraft and on ground, use of three separate microwave CW signals (two-way and one-way links) for Doppler cancellation and *T/F* transfer, and a laser link for calibration of the microwave links and comparisons of different techniques.

The initial experiment is being proposed for one of the low altitude, orbiting Space Shuttle flights (perhaps in the mid-1980's) but has not yet been approved. If the technique is successfully demonstrated via the Space Shuttle, it may then be feasible to adapt the basic technique and equipment for later operational missions, presumably using higher orbits to allow a longer observation time for each pass over a participating ground station.

Use of New *T/F* Allocations in the 13-31 GHz Region

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

(*a*) 13.4-14.0 HGz (Earth-to-space);
(*b*) 20.2-21.2 GHz (space-to-Earth);
(*c*) 25.25-27.0 GHz (Earth-to-space); and
(*d*) 30.0-31.3 GHz (space-to-Earth).

In each case, the *T/F* allocations are secondary allocations, so that considerable co-ordination 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 well into the future when extreme time transfer accuracies (<1ns) may be needed and technically feasible.

Alternatives for General T/F Dissemination

Time Signals From Meteorological Satellites

The current programme of the US National Bureau of Standards to disseminate moderate-accuracy timing signals from two operational GOES meteorological satellites has been described earlier in this paper. Possibilities for extending the time code coverage via the European Meteosat and Japanese GMS satellites were also mentioned.

Use of 400.1 MHz Transponders on Satellites-of-Opportunity

In 1971 Space World Administrative Radio Conference 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.

At the present time, there are no known plans for implementing actual services using this allocation.

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 manoeuvers 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 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 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. The *T/F* service may become available by 1983.

Alternatives Useful for Both High-Accuracy and General Dissemination

TRANSIT

The US TRANSIT Navigation System currently employs five operational, polar-orbiting satellites which continuously transmit navigation/timing signals on the dual frequencies of 150 and 400 MHz (Laidet 1972). 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 within ±10 μs of UTC(USNO).

The TRANSIT system is fully operational with five satellites and should continue to provide service for many more years. Support is provided by the US Navy which also publishes corrections relating the time of each TRANSIT satellite to UTC(USNO).

Time comparison experiments conducted with an experimental improved TRANSIT(NOVA) satellite have indicated that accuracies of better than 100 ns are achievable (Taylor 1974). This improved performance, relative to the *operational* TRANSIT results, is due mainly to use of spread-spectrum, PRN-coded satellite signals and sophisticated receivers.

Two NOVA satellites are scheduled for launch during 1981. If at least one of these operates successfully, at least one additional satellite will be added later. As to this time, there is no approved operational requirement for adding the PRN code to TRANSIT and it remains uncertain whether such improved signals (for timing) will be available on a long-term basis.

TDRS (Tracking and Data Relay Satellite) System

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 1980's (Chi 1979). 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 centre 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 (≅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 on to 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 ns 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 co-ordinated by NASA, the BIH or some other interested organization.

Fixed location users on the earth might also have the option to use 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 approved as an operational system and will be implemented in 1982/1983 using leased communication capacity from a US commercial satellite operator. Prototype user timing equipment is being developed under NASA sponsorship. Timing experiments will be performed via the TDRS system using this prototype equipment during the next several years. It is not known at this time what, if any access, *T/F* users may have to the TDRS system.

TV Broadcast Satellites

Terrestrial time comparisons, both within local areas and over much longer distance, 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 ≅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 TV transmitters can be observed that are interconnected in a TV network. With the present trend towards 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 centres to provide their own high-accuracy satellite position information by comparing reception times of selected TV pulses. Still another approach for using TV broadcast satellites, in this case with emphasis more 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 sufficient for many public time keeping needs.

TV 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 (Saburi *et al.* 1979) and are planned for India and Europe. The vertical interval time code has been tested experimentally in the US (Howe 1972) and may be implemented later on some European TV satellites as they become operational.

COMPARISON OF THE ALTERNATIVES

Table 1 summarizes in concise form some of the principal advantages and disadvantages of the various satellite alternatives. Table 2 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 1. *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. Longterm 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 operational systems.	Present costs, though decreasing, are relatively 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* labs. Highest accuracy requires a difficult calibration of ground station delays. High current demand for available channels.
2. *a.* GPS Normal Mode	May have high accuracy capability. Worldwide, continuous coverage. Ample redundancy and system support. One-way technique. Longterm continuity of system. Strong receiver development effort likely if access and accuracy not unduly restricted. Small antennas feasible. On-site operation.	May be restrictions on access and available accuracy for non-U.S.-military users. Present receiver costs >$50k. Complex signal format. One-way method requires path delay determination by users.
b. Commonview Mode	Potentially lower receiver costs (<$25k). High synchronization accuracy for distances of several thousand km. Convenient on-site operation. Any ephemeris errors partly compensated for. Requires only knowledge of *differential* path delay.	For best results sites should be within ≅$2000 km. Primarily for regional synchronization. May be restrictions on access and available accuracy for non-U.S.-military users. Requires some coordination and scheduling among labs.
3. LASSO	Potentially one of the most accurate alternatives. May allow <1ns 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 labs. Laser operations subject to weather conditions. Experiments planned but no operational plans. Lack of laser experience. Possible safety hazards to aircraft.
4. Space Shuttle Experiment	Potentially one of the most accurate alternatives. Use of multiple frequencies reduces uncertainties. Not weather sensitive. Uses H masers for stability. Allows direct frequency comparisons.	Only a proposal at present; no plans for operational mode. Expensive, complex equipment required. Shuttle use for experiment limits observation time during each pass.
4. Use of New 13-31 GHZ Allocations	Frequencies are internationally allocated for *T/F* use. Large bandwidths would permit measurement precisions of <100ps. 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 5-10 years.

Table 1 (*Contd.*)

Satellite Alternative	*Principal Advantages*	*Principal Disadvantages*
6. Meteorological Satellites	Low user cost. Some commercial receivers already available. Continuous service available from geostationary satellites. Time code already operational on some GOES satellites; could be expanded to Meteosat and GMS using same equipment. GOES time code contains complete time-of-year information referenced to UTC. Relatively secure longterm 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 co-operation of non-*T/F* organizations.
7. 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 a least international coverage with multi-language capability. On-site use.	No present known plans for operational implementation. Need to identify appropriate satellites and develop co-operative 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.
8. 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 plans implementation operationally via INSAT. On-site use.	Availability of transponders uncertain. Requires agreements and active co-operation 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.
9. *a.* Transit 1980 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. Longterm TRANSIT operation likely.	Polar orbits result in timing signals being available only periodically at a given location. Time information has 30-minute ambiguity. Receivers must handle Doppler shifts.
b. Improved TRANSIT (NOVA)	High accuracy possible with onewayte chnique. Global coverage. including high-latitude regions. Simple antennas; on-site operation. Should provide improved performance with present receivers two NOVA satellites scheduled for launch.	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.
10. *a.* TDRS Two-way mode	Coverage of nearly all major timing centres via two geostationary satellites. High potential accuracy capability ($\simeq 10$ ns). System fully approved. Has at least a 10-year projected life. In-orbit space.	Two-way technique requires careful ground equipment calibration. Relatively high user costs. Access to TDRS would require NASA permission. Two labs can compare time only indirectly via a third station.
b. One-way mode	Access to TDRS much easier in one-way mode. Simpler, cheaper equipment. Wide coverage. May include a time code.	Availability to non-NASA users not known. Limited accuracy capability. User costs uncertain at this time.
11. TV Broadcast Satellite *a.* High accuracy mode	Some forms of user equipment for TV timing measurements already developed. Many TV satellites planned throughout 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 confined to regions or, in some cases, individual countries.

Table 1 (*Contd.*)

Satellite Alternative	*Principal Advantages*	*Principal Disadvantages*
b. General dissemination mode :	Equipment already developed for using TV 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 TV 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 co-operation of vertical-interval time code.

Table 2. *SELECTED COMPARISON INFORMATION FOR SATELLITE ALTERNATIVES*

Satellite Alternative	*Coverage*	*Accuracy Capability*	*User Cost Estimates*	*Feasible for On-site Use*	*Operational or Experimental*
1. Communication Satellites	Regional or global (networks)	10—50 ns	\$25—\$100k for on-site terminal \$500/hour for transponder time (TV channel)	Depends on specific satellite system and location. Expensive.	Operational
2. *a.* GPS Normal mode	Global; continuous	Possibly $\approx$100 ns if not degraded; otherwise, possibly 1-3 μs.	Present timing receiver >\$50k. Should decrease with development.	Yes	6 satellites now in orbit. Full implementation sometime after 1985.
b. Common-view mode	Mainly regional, but also intercontinental at reduced accuracy. Best results for up to a few thousand km.	Depends on specific geometry of link. Possibly $\cong$10 ns if not degraded.	One receiver development involves parts cost of $\cong$\$5k. Includes antenna.	Yes	See above
3. LASSO	Europe, Africa, S. America, eastern U.S. and Canada initially for a few months. Europe and Africa later.	$\cong$1 ns projected	Very expensive; full laser stations $\cong$\$1m. Usually requires auxiliary timing links to laser sites.	Not in general. Requires laser station.	Experimental during 1981/1982. Could develop operational add-on package later.
4. Space shuttle experiment	Depends on specific flight. Possibly covering ± 57° in latitude.	<1 ns (time) and 1^{-14} (frequency) projected.	Requires 3-frequency microwave ground facility; two way links to shuttle. Expensive.	Possibly, with further equipment development for later use.	Proposed experiment; no plans for operational system.
5. Use of New 13-31 GHz Allocations	Depends on satellite system used.	Precision: 10—50 ps. Accuracy: limited by delay uncertainties.	Expensive until further development	Probably.	No present plans for operational or experimental use.
6. Meteorological satellites	Depends on system. Hemispheric for U.S. GOES time code. Possible expansion to Europe, Japan.	±16ms (uncorrected) ±0.5ms (corrected for main path delay) ±50μs (fully corrected).	\$2200 (1ms accuracy) \$4500 (50μs accuracy) Antennas included.	Yes	GOES satellite system is operational. Time code on U.S. satellites since 1975.
7. Use of 400.1 MHz Allocation	Depends on satellite system used.	Basic level : 1ms Probably could achieve <1μs via PRN code.	Basic level : <\$500. PRN code: <\$3000.	Yes	Allocation exists but no known plans for use.
8. VHF Transponder or dedicated 10 kHz channel on communication satellite	Regional	$\cong$1 μs possible. Could also disseminate less accurate code or voice.	Should be fairly low	Yes	India plans use of 10kHz channel on INSAT ∼1983.

Table 2. (*Contd.*)

Satellite Alternative		*Coverage*	*Accuracy Capability*	*User Cost Estimates*	*Feasible for On-site Use*	*Operational or Experimental*
9. Transit	1980 Operational system	Global, including high latitudes, on an intermittent basis.	30μs (signal satellite) 10μs (satellite ensemble)	$\cong$\$12k for fully automatic receiver and omni-directional antenna.	Yes	Operational
	Improved TRANSIT (NOVA)	Same as above, except only two satellities are now planned initially.	$<$100ns	\$15k-\$50k after initial receiver development	Yes	Experimental
10. TDRS	Two-way mode	Nearly worldwide, except for 30°—120° E. longitude.	Probably $\cong$10ns	Not determined but probably $>$\$25k.	Yes, in most cases	Operational in 1982/1983.
	One-way mode	Same as above	$\cong$1—10μs	Not determined, but relatively inexpensive.	Yes	Same as above.
11. TV Broadcast satellite	High accuracy mode	Regional	Depends on quality of ephemeris data. Probably $<1\mu$s and possibly $\cong$100ns.	At present: $\cong$\$3.3k. Should be reduced significantly in production quantities.	Yes 1-metre 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.

REFERENCES

1. *National Bureau of Standards Special Publication 432.* Available upon request from: T/F Services Group, Mail Stop 1-4036, NBS, 325 Broadway, Boulder CO 80303.
2. *National Bureau of Standards Technical Note 674.* Available upon request from: T/F Services Group, Mail Stop 1-4036, NBS, 325 Broadway, Boulder, CO 80303.
3. *National Bureau of Standards Time and Frequency Service Bulletin* (monthly). Available upon request from: T/F Services Group, Mail Stop 1-4036, NBS, 325 Broadway, Boulder, CO 80303.
4. **Hanson (D W), Davis (D D) & Cateora (J V).** NBS Time to the Western Hemisphere by Satellite. *Radio Science.* **14**, 4; 1979; 731-740.
5. *National Bureau of Standards Publication TFS-602.* Available upon request from: T/F Services Group, Mail Stop 1-4036, NBS, 325 Broadway, Boulder, CO 80303.
6. **Beehler (R E)** *et al.* Time Recovery Measurements Using Operational GOES and TRANSIT Satellites. *Proc. 11th Annual Precise Time and Time Interval Applications and Planning Meeting.* 1979; 283-314.
7. **Jespersen (J) & Fitz-Randolph (J).** *From Sundials to Atomic Clocks: Understanding Time and Frequency.* National Bureau of Standards Monograph 155 (December 1977). Available form Superindentent of Documents, US Government Printing Office, Washington, DC 20402. Stock no. 003-003-01650-1.
8. *National Bureau of Standards Technical Note 559.* Available upon request from: T/F Services Group, Mail Stop 1-4036, NBS, 325 Broadway, Boulder, CO 80303.
9. **Milliken (R J) & Zoller (C J).** Principle of Operation of NAVSTAR and System Characteristics. *Navigation.* **25**, 2, 1978; 95-106.
10. **Allan (D W) & Weiss (M A).** Accurate Time and Frequency Transfer during Common-view of a GPS Satellite. *Proc. 34th Annual Frequency Control Symposium* (USAERADCOM, Ft. Monmouth, NJ 07703, May 1980).
11. **Serene (B) & Albertinoli (P).** The LASSO Experiment. *Proc. 11th Annual Precise Time and Time Interval Applications and Planning Meeting.* 1979; 145-170.
12. **Decker (R)** *et al.* A Space-System for High-Precision Global Time and Frequency Comparison of Clocks. *Proc. 12th Annual Precise Time and Time Interval Applications and Planning Meeting.* 1980.
13. **Laidet (L M).** Worldwide Synchronization Using the TRANSIT Satellite System. *Proc. IEEE* (Lett.), **60**, pp. 630-632, May 1972.
14. **Taylor (R J).** Satellite-to-Ground Timing Experiments, *Proc. 28th Annual Symposium on Frequency Control* (*US Army Electronics Command, Ft. Monmouth, NJ* 07703, May 1974), pp. 384-388, 1974.
15. **Chi (A R).** Satellite Time Transfer via TDRSS and Applications, *Proc. 11th Annual Precise Time and Time Interval Applications and Planning Meeting.* 1979; 45-62.
16. **Saburi (Y), Yasuda (Y), Kobayashi (S) & Sato (T).** T & F Comparisons via Broadcasting Satellite and Navigation Technology Satellite. *Proc. 11th Annual Precise Time and Time Interval Applications and Planning Meeting.* 1979; 315-328.
17. **Howe (D A).** Nationwide Precise Time and Frequency Distribution Utilizing an Active Code within Network Television Broadcasts. *IEEE Trans.* **IM-21**. 1972; 263-276.

(Paper No. 4(81) 10 : 128C : 251)