THE STANDARDS OF TIME AND FREQUENCY IN THE USA

J. A. Barnes
Time and Frequency Division
National Bureau of Standards
Boulder, Colorado 80302

and

G.M.R. Winkler
Time Service Division
U. S. Naval Observatory
Washington, D.C. 20390

Summary

The National Bureau of Standards (NBS) and the U. S. Naval Observatory (USNO) are the two organizations chiefly involved in distributing accurate and precise time and frequency information within the USA. The NBS is responsible for the "custody, maintenance, and development of the national standards" of frequency and time (interval) as well as their dissemination to the general public. The mission of the USNO includes the "provision of accurate time" as an integral part of its work concerned with the publication of ephemerides in support of navigation and in the establishment of a fundamental reference system in space.

Both agencies provide the U.S. contribution to the Bureau International de l'Heure (BIH) [International Time Bureau], which has the responsibility of publishing definitive values of Universal Time (UT), International Atomic Time (IAT), and Coordinated Universal Time (UTC).

Key words Astronomical Time, Atomic Time, Frequency, International Atomic Time, Management, NBS, Standard Time, Time, USNO.

Introduction

The national responsibilities for the provision of standards of time and frequency (T&F) in the USA rests with two organizations of widely different background, professional traditions, and outlook.

The measurement of T&F permeates all scientific observations. It is fundamental to any system of measurement standards and it is an indispensable element in fundamental astronomy, geodesy, and navigation.

It follows from this wide range of applications and interfaces with all disciplines of science and technology that requirements for standards of T&F can only be satisfied in some form of compromise.

A short discussion of principles and terminology, followed by a minimum of historical accounts will enable us to review the present distribution of work and responsibilities of the two agencies involved, the National Bureau of Standards (NBS) and the United States Naval Observatory (USNO).

Terms of Reference

We call a time scale any system which allows the unambiguous ordering of events. Calendars are (rather coarse) time scales. Indeed, the daily movement of the sun, stars, and the moon provides the Time Scale prototype, even though the standard intervals are not uniform. Uniformity is a requirement which is becoming increasingly more important for two reasons, one scientific and the other operational.

The widescale application of manifestly non-uniform time scales is impractical without corrections which render the scales uniform. Wide applications of time scales require synchronization of clocks. Once synchronized, such clocks become the vehicle of access to all kinds of time scales. Thus, the study of synchronization would also be properly said to belong to the broader study of time in general.

As generally used, a time scale is a system which allows one to assign "dates" to events. There are astronomical time scales and clock time scales. A sensible use of the unqualified word "time" is the use which embodies all of these various aspects of time scales, time measurement, and even time interval (or duration). This is certainly consistent with the dictionary definition of the word. Thus, it is misleading to say that "time" is determined only by astronomical means. Indeed, there are many different time scales--astronomical time, biological time, geological time, atomic time, etc.

On the other hand the calendar and fraction of a day is the legal standard to which we ultimately refer most events for "dating".

The date of an event on an earth-based time scale is obtained from the number of cycles (and fractions of cycles) of the apparent sun counted from some agreed-upon origin. Similarly, atomic time scales are obtained by counting the cycles of a signal in resonance with certain kinds of atoms. One of the obvious differences between these two methods is that the cycles of atomic clocks are much, much shorter than the daily cycles of the apparent sun. Thus, the atomic clock requires more sophisticated devices to count cycles than are required to count solar days. The importance of this difference is a matter of technological convenience and is not very profound.

It is of technological significance that atomic clocks can be read with much greater ease and with many thousands of times the precision than the earth clock. In addition, the reading of an atomic clock can be predicted with about 100,000 times better accuracy than a clock defined by the rotation of the earth.

In the U.S. literature on navigation, satellite tracking, and geodesy, the word "epoch" is sometimes used in a similar manner to the word "date". There is considerable ambiguity, however, in the word "epoch" and we prefer the use of the word "date", if both day and time of day are given for an event.

Clocks, then, are devices capable of generating and counting time intervals. In order to do this in a most uniform manner, modern clocks derive their frequency (rate) reference from inner atomic processes, shielded as much as possible from external disturbing influences. Such clocks must also contain counters and displays of accumulated time intervals. Since repetitive phenomena are involved here, time, in one way or another, is always identified with angles whether we deal with the rotating earth or with 1 MHz signals from a frequency standard. Our conventional hours, minutes, and seconds are angular measures ("hour angle") of astronomy ("Universal" Time, UT).

This identification with the angular orientation of the earth is why celestial navigators require earth-based time signals. Recently, more sophisticated uses of UT have come into being as in geodetic astronomy, star and satellite tracking, and very-long-baseline radio interferometry (VLBI) which require (and can also provide) UT with millisecond accuracy. Since the rotation of the earth is not strictly uniform (variations in the length of the day are of the order of a part in 10^8) a problem exists in relation to clock time which can be kept stable to a few parts in 10^{13}.

Additional difficulties with clock time arise if it is to be used in the prediction of cosmic phenomena as, for example, orbital position of celestial bodies or times of arrival of signals from "pulsars". These latter signals can be resolved today with a precision of better than 5 μs.

It is clear that such uses demand a clock time which offers more than just means for synchronization which would be sufficient for electronic systems applications.

Time Scales for Systems Synchronization Uses

Not so long ago people were content simply to let the sun govern their lives. When the sun came up, it was time to begin work; when the sun set, it was time to stop.

With the growth of commerce and city life and the advancement of technology, a community could have its own clock set to agree roughly with the sun. Thus developed the idea of local time and each community could have its own local time. Clearly, when almost all dealings and communications take place within a given community, this is a workable solution.

With the advent of railroads and hence more rapid communications, this "crazy-quilt" maze of individual local times had to come to an end. The railroads are generally credited with unifying the various local times into time zones which have presented a much more workable national time system (November 1883).

What one sees clearly in this historical sequence is that, as communications become more rapid and more far-reaching, the greater are the demands for an all-pervasive and unifying convention of synchronizing clocks with each other. This convention is a matter of convenience. There is nothing sacred or absolute about what our clocks read; it's just important that they read the same time (or have a well-defined time difference as between time zones).

In the days when the railroads were the primary means of transportation across the North American continent, an accuracy of a few seconds of time was important and sufficient. Nowadays, with the existence of sophisticated telecommunications equipment capable of sending and receiving several million alphanumeric characters each second, there are real needs for clock synchronizations at accuracy levels of a millionth of a second and better.

Time Scales for Celestial Navigation and Astronomical Uses

Time is essential for celestial navigation. Basically, the reason is as follows: If one knows what time it is (i.e., solar time) at some reference point, say the Meridian of Greenwich, and one also knows his local time, say from a sundial, then one can figure his longitude simply by remembering that the earth makes one complete revolution on its axis in about 24 hours.

For example, noon Greenwich Mean Time is 2 a.m. Hawaiian Standard Time, or 10 hours different. Thus, it's easy to calculate that Hawaii is about 10/24 of the way around the world from Greenwich, England--in other words, about 150° west of the Prime Meridian.

If a person were to measure the actual position of the sun in the sky using, say, a navigator's sextant, then he could get a rather accurate determination of local solar time. The problem, then, would be to know the correct time on the Greenwich Meridian.

Approximately 200 years ago, a man in England named Harrison was awarded £20,000 for building a chronometer which allowed the accurate determination of longitude while at sea. Until radio made its appearance, navigation at sea was very dependent upon good clocks.

Nowadays, there are many standard time broadcast stations in the world. The best known standard time broadcast stations in North America are operated by the National Bureau of Standards (USA) and the National Research Council (Canada): WWV is located in Fort Collins, Colorado; WWVH is now located on the west coast of the island of Kauai, Hawaii; and CHU is near Ottawa.

If Universal Time (UT) could be measured with sufficient accuracy and convenience, then UT could also be used for time systems synchronization. In actuality, University Time is difficult to measure, and accuracies at this time are limited to one millisecond (after the fact).

Compromise Time Scales

We discussed two very different uses for time. The first use allows very high speed and extended electronic systems to function. The needs here are for extremely accurate and/or precise synchronization and measurements of time interval. The second use was for celestial navigation and astronomy. Here the need for precision is less but there are now additional requirements for "epoch" which cannot be set arbitrarily.

Because of the conflicting requirements imposed on time scales by these two categories of time scale users, there has been a great deal of effort to obtain a compromise time scale which adequately reflects the needs and relative importance of these two groups of users. As one might well imagine, with the growing importance and sophistication of communications systems and the implementation of electronic navigation systems (to supplement direct celestial navigation), the trend in the compromise time scales has been away from time scales based solely on the earth's rotation (i.e., astronomical time scales) and toward a pure atomic clock time scale. In particular, it is quite instructive to explain here briefly the new compromise time scale (called UTC) which became effective internationally on January 1, 1972.

As we mentioned above, the spinning earth does not make a very good clock. In point of fact, commercial atomic clocks in common use today are about one hundred thousand times more uniform than the spinning earth. Nonetheless, navigators need earth time (i.e., earth position relative to the stars) in real time no matter how erratic and unpredictable it might be.

We find ourselves in a rather familiar situation. There is not a whole number of days in the year and we don't want the calendar to get badly out of step with the seasons. Similarly, there is not a whole number of seconds in a solar day and we don't want our clocks to get badly out of step with the sun. The solution is analogous to the leap year with its extra day; we have an extra second--a leap second.

In fact, since January 1, 1972, the internationally accepted and used clock time scale can, on occasion, incorporate leap seconds to keep our clocks in approximate step with the sun, thus satisfying the needs of the navigators. In contrast to leap years which occur at defined intervals, the need for leap seconds is not precisely predictable but there should not be more than one in about a year's time. This lack of predictability arises because the earth doesn't spin at a constant rate. In any event leap seconds are going to be with us for a while. They allow a time scale (UTC) running at a constant rate, but whose time still approximates a clock defined by the rotating earth.

Time and Frequency (T&F) Activities of the National Bureau of Standards and the U. S. Naval Observatory

The Formal Missions of T&F Activities of the NBS and USNO

T&F Activities of NBS. In Title 15 of the United States Code[1], §272, it states: "Sec. 2. The Secretary of Commerce is authorized to undertake the following functions:

"(a) The custody, maintenance, and development of the national standards of measurement, and the provision of means and methods for making measurement consistent with those standards, including the comparison of standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions with the standards adopted or recognized by the Government." In particular the authorization specifies: "(11) the broadcasting of radio signals of standard frequency".

In Department of Commerce Order, DO 30-2A (October 1, 1968), the above authority is delegated to the Director of the National Bureau of Standards.

The four independent base units of measurement currently used in science are length, mass, time, and temperature. Except for fields of science such as cosmology, geology, navigation, and astronomy, time interval is the most important concept, and (astronomical) date is of much less importance to the rest of science. This is true because the "basic laws" of physics are differential in nature and usually involve small time intervals. In essence, physical "laws" do not depend upon when (i.e., date) they are applied.

Based on these laws and extensive experimentation, scientists have been able to demonstrate that frequency can be controlled and measured with the smallest percentage error of any physical quantity. Since most clocks depend on some periodic phenomenon (e.g., a pendulum) in order to "keep time", and since one can make reliable electronic counters to count the "swings" of the periodic phenomena, we can construct clocks with an elapsed time accuracy of the frequency standard.

In fact, the international definition of the second (unit of time interval) is based on the resonance frequency of the cesium atom. The present definition states:

> "The second 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 (13th CGPM [1967], Resolution 1)."

The second must therefore be considered as one of the most important base units of the "Système Internationale" (SI), the measurement system used for all scientific and technological measurements.

In response to this state of affairs, there is a Time and Frequency Division within the National Bureau of Standards.

Within this Division (see Fig. 1) there is a Section (273.04) devoted to the operation of the NBS standard of frequency and time interval and the operation of time scales based on it. Also within this Section is located the research and development effort of the NBS to improve the primary frequency standard and the associated time scales. Thus, this Section can fairly be said to have the responsibilities of "custody, maintenance, and development of the national standards" of frequency and time interval.

There is a Section (273.02) which disseminates the standard frequencies and the time scales of Section 273.04 via radio (WWV, WWVH, and WWVB), and via telephone (303-499-7111). More detailed information may be obtained by requesting Special Publication 236 from:

Time and Frequency Broadcast
Services Section, 273.02
National Bureau of Standards
Boulder, Colorado 80302.

Within the Time and Frequency Division there is a Section (273.01) which conducts research and development activities on new methods of disseminating time and frequency information. As examples, this Section developed the TV line 10 synchronization pulse technique[2] based on the work of Tolman et al.[3]; and this Section devised and perfected a more extensive TV time system[4] which actively encodes time signals in the vertical interval.

All of the activities of these Sections are coordinated both nationally and internationally through the Time and Frequency Division Office (273.00).

In a formal sense, the mission of the Division and the individual Sections are summarized in Appendix A.

The Position of the U. S. Naval Observatory in the Federal Government. The U. S. Naval Observatory performs the same public functions as the national observatories of the principal countries of the world. Its nearest counterparts are the Royal Greenwich Observatory (United Kingdom), the Pulkovo Observatory (USSR), and the Paris Observatory (France). It is the sole authority in the United States for astronomical data required for public and legal purposes, such as times of sunrise and sunset, moonrise and moonset, and almanacs required for marine and air navigation, and for land surveying.

Its official mission[5] spells out that the primary function of the U. S. Naval Observatory is to provide for public use accurate time and other astronomical data which are essential for safe navigation at sea, in the air, and in space. To carry out this function, it is necessary for the Observatory to maintain continual observations of the positions and motions of the sun, moon, planets, and principal stars. From some of these observations astronomical time is determined.

The determination and dissemination of precise clock time, which the Observatory has developed to very high precision is essential to many military operations, including especially the fields of electronic navigation, communications, and space technology. In response to these needs, the Department of Defense has charged the USNO with single management responsibilities for T&F in the Department of Defense[6].

The Naval Observatory concentrates on astrometry (precise measurements of angular distances between celestial objects), celestial mechanics (theories and calculations of the motions of celestial bodies), and astrophysics. It operates the most modern and precise special-purpose astronomical equipment in the world, most of which has been designed by its staff, and is comprised of about 20 telescopes of various kinds at its stations in Washington, Arizona, Florida, and Argentina.

The Observatory is also a computing center and publishing house, calculating and publishing each year 1000 pages of navigational data, 500 pages of astronomical predictions, and averaging 250 pages of research papers, all of which are published in book form, as well as numerous research papers in astronomical periodicals.

a. The USNO Time Service Division, Background: There has been a continuous evolution from the first public "time service", the dropping of the USNO time ball at noon (1844) to the many services rendered today (Appendix B). Many of these services and operations were the first of their kind; for example:

In 1904 the first worldwide radio time signals broadcast from a U. S. Navy station were based on a clock provided and controlled by the Observatory.

A "Photographic Zenith Tube" (PZT) has been used by the Observatory since 1915 for the determination of latitude and since 1933 for the determination of latitude and Universal Time (UT). The "Dual Rate Moon Camera" was invented by William Markowitz in 1951 and it became the instrument with which the frequency of cesium, which today is the basis for the definition of the second, was determined with respect to the ephemeris second. This assured a clock rate which allows the use of atomic time (A.1 and now IAT) as an extrapolation of ephemeris time[7]. The first atomic time scale (A.1) using the value for the cesium frequency, later adopted internationally, also applied the principle of an "average clock"[8]. Originally, A.1 was determined from all available cesium clocks throughout the world.

The USNO clock time scale is still derived from a set of "standard" clocks (selected commercial cesium standards). In contrast, the NBS atomic time scale is based on a laboratory cesium standard and a set of commercial cesium standards which serve as a memory of the rate of the primary standard. Only USNO clocks are used today for the USNO clock time reference[9]. There are also other substantial differences in basic philosophy between NBS and USNO which may be resolved only after much more experience becomes available[10].

b. Organization of USNO Time Service Division: There are four sections within this Division (see Fig. 2):

(1) Control of Time (Electronics) Section: This section is responsible for all electronics support and instruments. It monitors T&F transmissions of United States Naval electronic systems and other precise T&F transmissions (WWVL, GBR, foreign time signals,

etc.) and prepares control messages to stations controlled directly by USNO. It prepares Time Service Announcements, Series 2, 3, 4, 5, 8, 9, and 16 (Appendix B).

(2) Precise Time Operations Section: This section is responsible for external liaison and portable clock operations. It carries the main load of PTTI management responsibilities as assigned by the Department of Defense Directive[6].

(3) Astronomy - Washington: This section is responsible for observations with the PZT, Astrolabe and Moon Camera in Washington. It is responsible for all computer software including automatic data acquisition and control system, and is responsible for the atomic clock time scale under direct supervision of the Assistant Director. It is also responsible for Time Service Announcements, Series 1, 6, 7, 10, 11, 12, 13, and 17 (Appendix B).

(4) Richmond, Florida (near Homestead): This is a largely independent Observatory capable of all Washington time operations on a smaller scale. It is a station with one of the most favorable climatic conditions anywhere (320 clear nights per year, compared to Washington with about 210). In addition, background radio noise is low and this makes the station valuable as a monitor site.

The above listed activities produce only part of the information which is published daily, weekly, monthly, and irregularly by the USNO Time Service Division (Appendix B). A great number of messages and notes are received regularly from cooperating stations all over the world whose contributions make it possible to achieve today a truly "worldwide continuity of precision" in time measurements with which the USNO is specifically charged[6].

T&F Activities of NBS and USNO Compared

As listed in the previous section, the main interactions of the two agencies can be summarized in Fig. 3.

Both agencies provide input to the BIH (at the Paris Observatory) which is charged to provide a central international reference point for time and related matters. NBS and USNO are both substantial contributors to the International Atomic Time Scale, IAT, of the BIH which serves now as reference for UTC.

NBS provides input in regard to absolute accuracy of the rate of IAT (and the U.S. clock time scales as well). USNO provides UTO and latitude information.

In conformance with the specific mission statements, as cited above, time and absolute frequency are central but not exclusive areas of concern, competence, and responsibility of USNO and NBS respectively. Both areas are very closely linked, which requires equally close cooperation between the two agencies. For example, the NBS broadcasts of standard frequency have as a most logical extension a 24-hour standard time signal broadcast. Commensurate with the NBS introduction of these and similar services (a TV and a satellite T&F dissemination are being actively investigated by NBS), the USNO has reduced or eliminated some of its own dissemination services. Today, the Naval time signals are on the air for only 5 minute periods every 1, 2, or more hours (but on about 30 frequencies). They are intended to supplement WWV and WWVH. These services of NBS are very important to the USNO and its "customers" (navigators, geodesists, astronomers, etc.).

It is noteworthy that Table 1, which summarizes the main points of this discussion, represents only a historical ideal. Clock coordination has diminished the direct significance of USNO's role as a national time standard since UTC(NBS) - UTC(USNO) time difference is less than 6 μs since June 1968 and since both agencies provide independent clock time input to the BIH. On the other hand, the real standard of frequency is now the cesium atom and there is no longer a U.S. frequency standard (or a U.S. second) just as there is no U.S. meter. However, there is U.S. input to the absolute SI second from a primary frequency standard at the NBS.

Coordination of T&F

Each agency, NBS and USNO, derives an entirely independent local atomic time scale: AT(NBS) and A.1 (USNO). AT(NBS) is based on (occasional) calibrations of its operational standards (8 commercial cesium clocks) with the NBS primary frequency standard. A.1 (USNO) is based on a set of 16 best commercial cesium clocks selected as "standards" from about 70 cesium clocks available to the USNO. A.1(USNO) results from an adjusted, iterated averaging procedure which makes the average rate of the time scale independent of the particular clocks used and assures very great reliability. Both of these inputs are used by the BIH to compute the IAT and UTC scales.

The agencies' coordinated clocks are derived with a deliberate coordination offset ($\leq 10^{-12}$). The International Radio Consultative Committee (CCIR) and the International Astronomical Union (IAU) recommend 1 ms as the maximum tolerance. UTC(NBS) and UTC(USNO) have been closer than 6 μs since 1968, and also are now within a few microseconds of UTC(BIH). It is the intent to achieve even closer coordination in the future. Fig. 4 depicts the general situation.

In addition to clock time, the BIH internationally and the USNO in the USA furnish UT1 and coordinates of the pole in the three levels of "Predicted", "Preliminary" (BIH "Rapid Service"), and "Final". In view of the fact that the BIH values are averages of some 50 observatories, its values are precise to better than 1 ms in UT1 and about 0".01 in x and y (polar coordinates). The results of the International Latitude Service (ILS, now IPMS) can be considered more accurate but less precise than BIH in the polar coordinates since the definition of the Standard Pole (OCI) refers to the 5 latitude stations and not to the BIH observatories.

With the increase of participating observatories, the relative importance of these U.S. contributions has decreased. We can expect similar developments with respect to the U.S. local atomic time scales as more national timekeeping agencies contribute to the IAT.

International Organizations Involved in Standard Time and Frequency

Introduction

The general subject of time and frequency is important in three fundamentally different ways. Firstly, it is important as one of the 4 independent base units in metrology (i.e., length, mass, time, and temperature); that is, it is important to the Système Internationale (SI) of units of measurement. Secondly, time and frequency are important scientifically in their own right, not just as they influence measurements; and thirdly the methods of dissemination of standard time and frequency are important from a regulatory aspect such as the assignment of radio spectrum for broadcast purposes of standard time and frequency.

International Organizations

Correspondingly, one can find three separate chains of international involvement with time and frequency (see Fig. 5).

Organizations of the Treaty of the Meter (Standards). The USA was one of the original signers of the Treaty of the Meter in 1875. This treaty established an international standards laboratory (Bureau International des Poids et Mesure, BIPM) which is governed by an international committee (Committee International des Poids et Mesure, CIPM) composed of representatives of the member nations. Advisory to the CIPM are various technical, consultative committees (e.g., the Consultative Committee for the Definition of the Second (CCDS), the Consultative Committee for the Definition of the Meter (CCDM), etc.).

Policy decisions such as financial assessments of the member nations and final endorsements of new definitions of standards are handled by a General Conference of Weights and Measures (CGPM).

Scientific Organizations. Receiving support and financial assistance from the United Nations Educational, Scientific, and Cultural Organization (UNESCO) there is the International Council of Scientific Unions (ICSU). Also, in our area, there are four scientific unions (see Table 2 for abbreviations): URSI, IAU, IUPAP, and IUGG. Within these scientific unions, T&F matters are primarily confined to URSI Commission 1 and IAU Commission 31.

ICSU has established a number of permanent services administered by the Federation of Astronomical and Geophysical Services (FAGS). These permanent services include the Bureau International de l'Heure (BIH), the International Polar Motion Service (IPMS), and others.

Historically, the BIH has had the responsibility of coordinating and calculating the final and formally adopted measurements of time. With the advent of atomic clocks and with the recommendations of the IAU, the BIH established its own atomic time scale (IAT) which is based, ultimately, on a weighted average of various local atomic time scales. The CGPM has endorsed the IAT scale for defining International Atomic Time (date) and the CGPM will also provide some financial assistance to the BIH.

International Radio Consultative Committee (CCIR) (Regulatory). Advisory to the International Telecommunications Union (ITU) is the CCIR with its numerous Study Groups. Study Group 7 of the CCIR is concerned with standard frequency and time broadcasts.

The recommendations of CCIR specify the acceptable formats for standard frequency and time broadcasts as well as the tolerances of the broadcast scales relative to the time scales of the BIH. Although these recommendations do not have the force of international law, almost all countries carefully adhere to them.

For each of the international organizations cited above there exist either national delegates or national committees which formulate the national policy to be presented to the international organizations.

Summary

Time and Frequency is a complex field with widely different requirements. Historically, two agencies have provided the standards of time and frequency in the USA; they are the USNO and the NBS respectively. Their roles have evolved, however, into more diversified interests. The need to coordinate with the rest of the world and the new "natural" standards of time (the second) and length (the meter) produce a strong pressure for adjustment in the interest of improving our public services. This, together with the different professional backgrounds of the two agencies, has emphasized different tendencies. Operations and worldwide organization of resources have always been favored by astronomers, particularly those who use clocks as a means and not as an end.

On the other hand, questions of absolute accuracy in the realization of a measurement standard, research in the physics of clocks, and education in the use of standards is emphasized at NBS. Both agencies conduct research which is complementary rather than competitive not only because management wants it, but because of their different professional outlook and resources.

References

1. Title 15, U. S. Code §272.

2. D. D. Davis, B. E. Blair, and J. Barnaba, "Long-term continental U.S. timing system via TV networks," IEEE Spectrum, vol. 8, no. 8, August 1971, pp. 41-52.

3. J. Tolman, V. Ptacek, A. Soucek, and R. Stecher, "Microsecond clock comparison by means of TV synchronizing pulses," IEEE Trans. Instrum. & Meas., vol. IM-16, no. 3, September 1967, pp. 247-254.

4. D. D. Davis, J. L. Jespersen, and G. Kamas, "The use of television signals for time and frequency dissemination," Proc. IEEE (Letter), vol. 58, no. 6, June 1970, pp. 931-933.

5. USNO Mission: "Make such observations of celestial bodies, natural and artificial, derive and publish such data as will afford to United States Naval vessels and aircraft as well as to all availing themselves thereof, means for safe navigation,

including the provision of accurate time; and while pursuing this primary function, contribute material to the general advancement of navigation and astronomy."

6. DOD Directive 5160.51 dated August 31, 1971; and Code of Federal Regulations (CFR), Title 32, Chapter 1, Subchapter M, Part 275.

7. W. Markowitz, R G. Hall, L. Essen, J.V.L. Parry, "Frequency of cesium in terms of ephemeris time," Phys. Rev. Letters, 1, 1958, p. 105.

8. W. Markowitz, "The atomic time scale," IRE Trans. Instrum. vol. I-11, December 1962.

9. G.M.R. Winkler, R. G. Hall, and D. B. Percival, "The U. S. Naval Observatory clock time reference and the performance of a sample of atomic clocks," Metrologia, vol. 6, no. 4, October 1970, pp. 126-134.

10. D. W. Allan and J. E. Gray, "Comments on the October 1970 Metrologia paper, 'The U. S. Naval Observatory clock time reference and the performance of a sample of atomic clocks'," Metrologia, vol. 7, no. 2, April 1971, pp. 79-82.

Appendix A

Official Functional Statements

Time and Frequency Division (273.00): Develops and maintains frequency and time interval standards and time scales. Conducts fundamental and applied research to establish such standards. Disseminates internationally coordinated frequency and time through radio broadcasts, portable clocks, and other advanced techniques. Engages in research and development on new dissemination techniques that improve accuracy and increase coverage. Develops improved instrumentation for dissemination of time and frequency. Coordinates time and frequency nationally and internationally. Conducts fundamental physical research in which the techniques used in time and frequency standards are of critical importance. Disseminates information through consultation and publication.

Frequency-Time Dissemination Research Section (273.01): Conducts research and development on new and improved methods of dissemination of frequency and time standards including satellites, very low frequency (VLF), portable clocks, and other advanced techniques; investigates propagation errors of time signals, provides consultation on methods of frequency and time dissemination; compares and evaluates methods of frequency and time dissemination; and makes recommendations for improvements in monitoring techniques and other mission components.

Frequency-Time Broadcast Services Section (273.02): Provides wide dissemination of frequency and time standards primarily by radio broadcasts; investigates and develops techniques for improving the accuracy with which frequency and time can be distributed by broadcasting electromagnetic signals; measures distortion involved in the radio broadcast of time and frequency standards, particularly with regard to electronic transmitting and receiving equipment; provides consultation relative to the frequency and time broadcast services; evaluates the effectiveness of the frequency and time broadcast services; recommends improvement or modification of existing services or additions of new services; and monitors frequency and time broadcasts from various sources.

Atomic Frequency and Time Standards Section (273.04): Provides atomic frequency standards for the United States and develops and improves such standards. Provides, develops, and improves atomic time scales based on the frequency standards, and evaluates such time scales for consideration as a standard. Pursues fundamental research where needed to execute the foregoing. Furnishes time and frequency signals to other sections of the division. Performs frequency and time calibration services for science, industry, commerce, and government users who require reference to the national standards.

Appendix B

Time Service Publications (Available Upon Request)

Series

1. *List of Worldwide VLF and HF Transmissions* suitable for Precise Time Measurements. Includes: Call sign, geographic location, frequencies, radiated power, etc. (Time Signal Transmissions)

2. Schedule of U.S. Navy Time Signal Transmissions in VLF and HF bands. Includes: Times of broadcast, frequencies, etc.

3. Schedule of U.S. Navy VLF Transmissions including Omega system. Includes: Location, frequencies, power radiated, maintenance periods, type of transmission, etc.

4. Daily Relative Phase Values (Issued weekly). Includes: Observed phase and time differences between VLF, LF, Omega, Television, Portable Clock measurements, and Loran-C stations and the UTC(USNO Master Clock). Propagation disturbances are also given.

5. Daily Teletype Messages (sent every working day). Includes: Daily relative phase and time differences between UTC(USNO MC) and VLF, LF, Omega, Loran-C stations. Propagation disturbances and notices of immediate concern for precision timekeeping.

6. USNO A.1 - UT1 Data. Preliminary daily values distributed monthly with final data issued as available.

7. Preliminary Times and Coordinates of the Pole (issued weekly). Includes: General time scale information; UT1 - UTC predicted 2 weeks in advance; time differences between A.1, UT1, UT2, UTC(BIH) and UTC(USNO) provisional coordinates of the pole; DUT1 value; and satellite information.

8. Time Service Announcements pertaining to synchronization by television. Includes: times of coincidence (NULL) ephemeris tables.

9. <u>Time Service Announcements Pertaining to Loran-C</u>. Includes: Change in transmissions and repetition rates, times of coincidence (NULL) ephemeris tables, coordinates and emission delays, general information, etc.

10. <u>Astronomical Programs</u> (issued when available). Includes: Information pertaining to results, catalogs, papers, etc., of the Photographic Zenith Tube (PZT), Danjon Astrolabe, and Dual-Rate Moon Position Camera.

11. <u>Time Service Bulletins</u>. Includes: Time differences between coordinated stations and the UTC Time Scale; earth's seasonal and polar variations (as observed at Washington and Florida); Provisional coordinates of the pole; adopted UT2 - A.1, etc.

12. Time Service Internal Mailing.

13. Time Service Internal Mailing.

14. <u>Time Service General Announcements</u>. Includes: General information pertaining to time determination, measurement, and dissemination. Should be of interest to all Time Service Addressees.

15. <u>Bureau International de l'Heure (BIH) Circular D</u>: Heure Définitive et Coordonnées du Pôle a 0^hTU. Includes: Coordinates of the pole; UT2 - UTC, UT1 - UTC, and TA(AT) - UTC; UTC - Signal. NOTE: USNO Time Service will distribute Circular D of the BIH to U.S. addressees only.

16. <u>Communication Satellite Reports</u> giving the differences UTC(USNO) - SATCOM Clock for each of the available SATCOM stations.

17. <u>Transit Satellite Reports</u>. Includes Satellite Clock - UTC(USNO) and the frequency offset for each of the operational satellites.

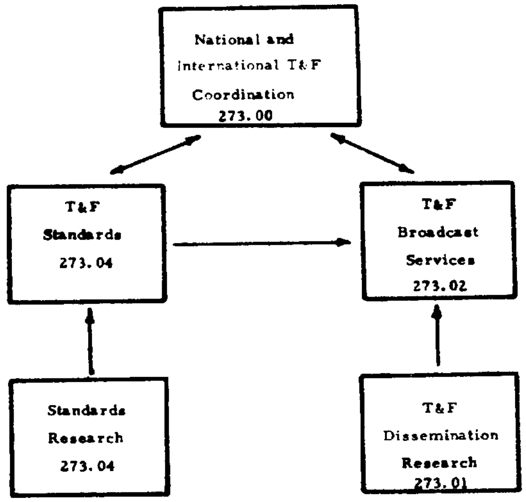

Fig. 1. The Time and Frequency Division of the NBS

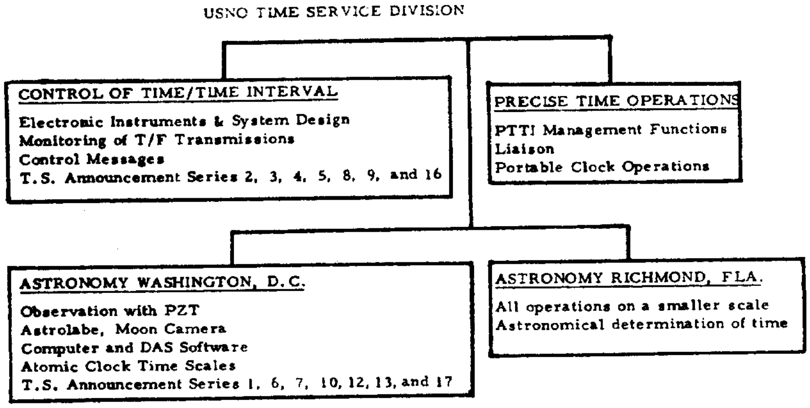

Fig. 2. The USNO Time Service Division

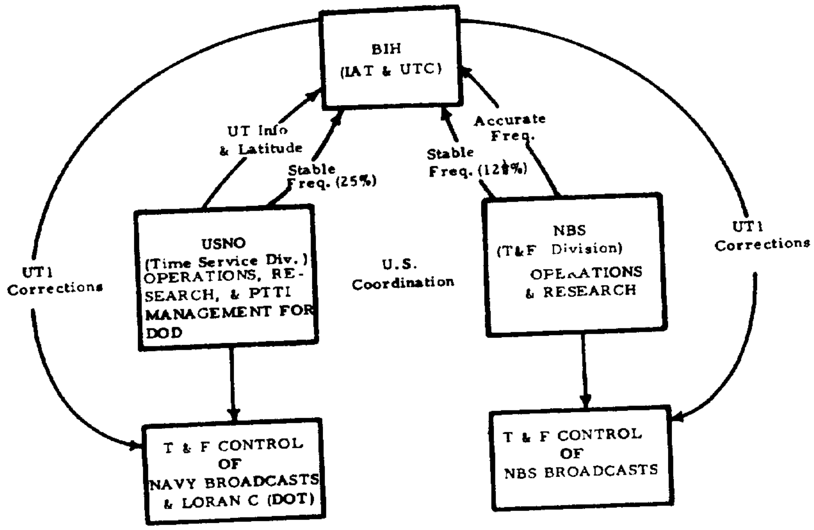

Fig. 3. NBS, USNO, and BIH Interactions

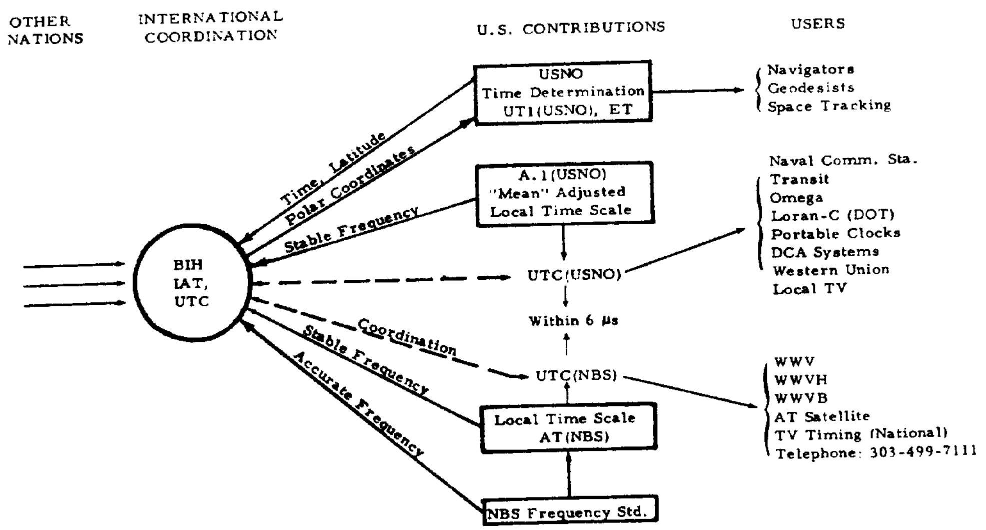

Fig. 4. Time Scales in the USA

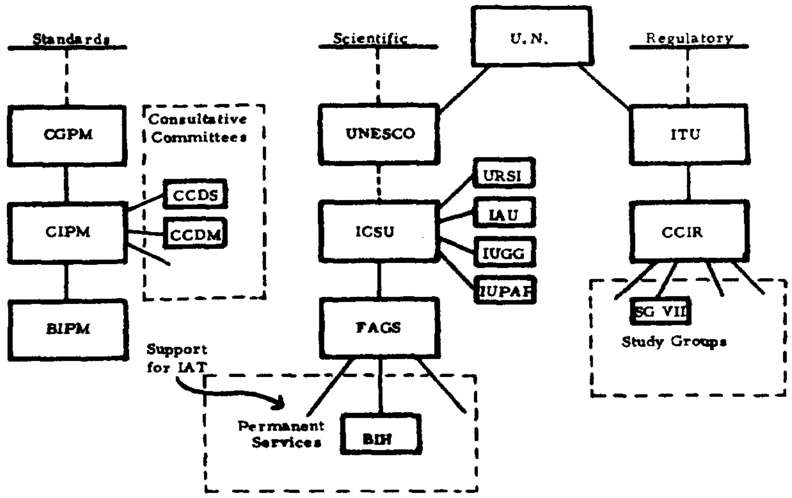

Fig. 5. International Organizations Involved with Standard Frequency and Time

NBS	USNO
National Standard of Frequency	National Standard of Time (Epoch, Date)
Standard Frequency (and Time) Broadcast	Control of Naval T&F Transmissions
Fundamental Research in T&F as related to Clock Time and Frequency Measurements, Synchronization	Applied Research in Time as related to clock applications, Astronomy, Geophysics Navigation
Consultation and Education	Consultation and Management of PTTI activities as related to DOD
USNO PTRS	

Table 1

T&F Responsibilities of NBS/USNO

UN	United Nations
CGPM	General Conference of Weights and Measures
CIPM	International Committee of Weights and Measures
CCDS	Consultative Committee for the Definition of the Second
CCDM	Consultative Committee for the Definition of the Meter
ITU	International Telecommunications Union
UNESCO	United Nations Educational, Scientific, and Cultural Organization
CCIR	International Radio Consultative Committee
ICSU	International Council of Scientific Unions
IAU	International Astronomical Union
IUPAP	International Union of Pure and Applied Physics
IUGG	International Union of Geodesy and Geophysics
URSI	International Scientific Radio Union
FAGS	Federation of Astronomical and Geophysical Services
BIH	International Bureau of Time
BIPM	International Bureau of Weights and Measures

Table 2

Abbreviations of International Organizations