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1. INTRODUCTION

The mission of IAU Commission 31 is to facilitate the astronomical use of the techniques, data, and equipment produced by workers in the field of time and frequency, and to ensure that a uniform and logical nomenclature is used by workers in all related fields. Since theories of general relativity require that coordinates of space and time be treated logically as components of a four-space metric tensor, the task of Commission 31 integrates closely with those of the Commissions responsible for the definition, creation, and maintenance of astronomical coordinate systems, and specifically Commissions 4 (Ephemerides), 7 (Celestial Mechanics), 8 (Positional Astronomy), and 19 (Rotation of the Earth).

The following report is abstracted from the many papers and communications shared by the members.

2. BUREAU INTERNATIONAL DES POIDS ET MESURES (BIPM)

The BIPM was charged by its parent body, the Comité International des Poids et Mesures (CIPM), with the task of maintaining International Atomic Time (TAI) and Universal Time Coordinated (UTC). According to the

I. Appenzeller (ed.), Reports on Astronomy, Vol. XXIIIA, 109–116.

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Comptes Rendus of the 18e Conférence Générale des Poids et Mesures (1987): "The purpose of the BIPM [in the field of time] is to provide the physical basis necessary to insure worldwide uniformity of measurements. Therefore, [among] its principal tasks are... to establish and disseminate the International Atomic Time, and in collaboration with the appropriate astronomical organizations, Coordinated Universal Time...". The definition of TAI was approved by the CIPM in 1970, and recognized by the CGPM in 1971, as follows: "International Atomic Time (TAI) is the time reference coordinate established by the Bureau International de l'Heure on the basis of the readings of atomic clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of units". Subsequent resolutions clarified this definition in terms of general Einsteinian relativity: the TAI second is realized in the reference frame of the Earth standard geoid. UTC is defined by the International Telecommunications Union (ITU) Radiocommunications Working Group 7A (on Time and Frequency). UTC is offset from TAI by an integral number of seconds to approximate the variable time appropriate to the Earth's rotation. The work of determining when this offset should be incremented by leap seconds falls under IAU Commission 19. The responsibility for maintaining TAI was formally transferred to the Time Section of the BIPM in 1988, in Sèvres, France, from the Bureau International de l'Heure (BIH) at Paris Observatory in France. Therefore, the work of the various national timing laboratories thruout the world is realized by the creation of TAI and UTC, and comes under the BIPM.

TAI is created in two steps. First, a free atomic time scale, EAL (= échelle atomique libre) is calculated as a weighted average of the large number of free running and independent clocks in the various contributing timing laboratories. In 1994, 230 clocks contributed to EAL/TAI, in 46 national timing centers spread world wide, but not all these clocks were available at any one time. The weighted average is formed by an algorithm, ALGOS, that is optimized for long term stability, and postprocesses measurements in data blocks T = 60 days long. Second, TAI is obtained from EAL by comparing the EAL frequency against primary cesium standards, and steering EAL to conform as closely as possible to the ideal Standard International (SI) second. Since the computation requires 60-day blocks of timing data, and since there is also a slight delay in communicating this data from the contributing laboratories to the BIPM, neither TAI nor its offset quantity, UTC, is available in real time. For example, the definitive UTC updates for September and October 1995 were released to users on 17 November 1995, or 20 days after the end of the standard data block on 28 October. However, in this case, one of the laboratories was exceptionally late in reporting data; and normally the interval between data collection and publication can be shortened. Provisional values of TAI/ UTC are published each month in BIPM Circular T; thus, values for September 1995 appeared on 17 October.

Three primary developments, improving the stability of TAI, have been reported during the period 1994-1996: (1) installation of many improved commercial cesium atomic clocks, the Hewlett-Packard (HP) 5071A's, as intermediate frequency standards at the contributing laboratories; (2) improvements in the TAI steering algorithm, especially in response to (1) above; and (3) improvements in techniques of time transfer from these laboratories to the BIPM.

The HP 5071A clocks have improved the stability of commercial frequency standards by about an order of magnitude over the previous HP 5061's, largely by self-correcting algorithms that yield great environmental insensitivity. Reinforcing the excellent intermediate and short term stability of the several contributing hydrogen masers with cavity tuning, these clocks provide TAI stability of a few parts in 1×10^{15}. But, by a seeming paradox, the improvement in the stability of the contributing clocks poses a problem in the creation of a stable weighted average. If the statistics of the clock ensemble were stationary, then the optimal weight for an individual clock would be proportional to the inverse of the square of its standard deviation from the ensemble average, and any departure from inverse sigma square weighting would be non-optimal. However, the statistics are strongly nonstationary – in fact, a clock may simply fail. This fact strongly restricts the BIPM (or any timing laboratory) as it forms a time scale. One must impose a maximum limit on the weights, to prevent a small group of clocks from dominating the weighted average, since if a very high-weighted clock were to fail, the average would be strongly perturbed. The ALGOS algorithm imposes an upper limit P_{max} to the weight for any clock, such that the square of the standard deviation of the maximum weighted clock in nanoseconds (ns)/day = $10{,}000/P_{max}$. On 2 May 1995, P_{max} was increased from 1000 to 2500. Even so, in May - June 1995, 93 of the 172 clocks contributing to TAI had reached the limit. Improved weighting systems are being studied.

As distinguished from stability, the accuracy with which the SI second is realized depended until recently on the primary cesium standards CS1 and CS2 of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany. The replacement of CS1 by CS3, and the addition of three new primary standards – NIST-7 of the US National Institute of Science and Technology (NIST), the LPTF-F01 in France, and the SU-MCsR-102 in Russia – should, when the CCDS Recommendation S2 is implemented (see below), improve the accuracy of TAI to a few parts in 10^{15}.

3. CONSULTATIVE COMMITTEE FOR THE DEFINITION OF THE SECOND (CCDS)

Further improvements to the maintenance of the TAI time scale were proposed by the CCDS in its 13th Session, 12-13 March 1996. A comprehensive report on this meeting contains four recommendations: S1 (on primary frequency standards); S2, on correcting the black-body frequency shift in primary (cesium) frequency standards; S3, correlations among the clocks contributing to TAI; and S4, coordination of satellite systems used for timing. A separate volume concerning the 13 th session, containing reports on the CCDS Working Group (WG) on TAI, and the WG on the Application of General Relativity to Metrology (an interim paper), the WG on Time Transfer Standards, and the WG on two-way satellite time transfer, together with the working documents submitted in advance of the 13th Session, has been issued by the BIPM. Of the Recommendations, S2 entails a rate change of about 1.8×10^{-14} over the years 1996-1998, implemented in small steps of 1×10^{-15} at 60 day intervals, well below the perception of the users. Recommendation S4 is to keep the reference time of both the US Global Positioning System (GPS) and the Russian GLONASS as close as possible to UTC, except for the effect of accumulated leap seconds since January 1980, when the GPS time scale was established. (Ideally, TAI-GPS = 19 s, always.) In fact, GPS time is currently (1995-1996) being steered to UTC to within about plus or minus 20 ns, minus the accumulated leap second offset. However, on 21 December 1994, because of faulty procedure in a US Air Force training exercise to replace the Colorado Springs monitor station clock, GPS time rate jumped discontinuously by about -22 ns/ day, and GPS time reached a maximum offset of -257 ns on 17 January 1995. To satisfy the CCDS recommendations will require improved integrity monitoring, and better capability to handle frequency jumps.

Since the Global Positioning System of navigational satellites (GPS) is widely used for international time transfer, the CCDS Group on GPS Time Transfer Standards (CGGTTS), a subgroup of the permanent CCDS WG on TAI (see above), hosted an open forum in San Diego, on 28 November 1995. This Group had published an International Report entitled Technical Directives for Standardization of GPS Timing Receiver Software... (D. W. Allan and C. Thomas, Metrologia, 31, pp 69-79, 1994). At San Diego, the Group reviewed the status of the firmware (EPROM's) programmed by the US National Institute of Science and Technology (NIST) to implement the Directives, and the special problems encountered with GPS timing receivers which are not of the NIST design.

4. INTERNATIONAL TIME TRANSFER

As stated above, intercomparison of clocks kept by timing laboratories in all parts of the world is essential to the formation of TAI/ UTC. Of the 46 laboratories, all but two were compared using the GPS common view method (see above). Also used, at least on an experimental basis, were two-way time transfer using geosynchronous communication satellites, and the Russian navigational satellite system GLONASS, and LASSO, and PRARE. LASSO (Laser Synchronization from Stationary Orbits) is a satellite laser technique for intercomparison of remote atomic clocks. Altho the basic technique should readily permit sub-ns time transfer, it is not suited for routine operation because of its expense and liability to weather. Nevertheless, the BIPM reports that it is potentially an excellent tool for assessing the accuracy of other techniques. Preliminary experiments have been conducted between the Observatoire de la Cote d'Azur in Grasse, France, and the McDonald Observatory in west Texas, USA, an 8000 km distance. An intercalibration demonstration to remove the large (about 140 ns) bias in the laser ranging equipment proved difficult, but successful. However, the bias is not constant in time, and the technique as presently implemented would require frequent recalibration. PRARE (Precision Range and Range Rate Experiment) is a two-way satellite based tracking system, of which the time transfer modification is called PRARETIME. LASSO and PRARE/PRARETIME are strictly experimental. More nearly operational is international two-way time transfer using commercial communications satellites. Field trials using the INTELSAT V-A (F13) satellite were conducted three sessions a week each five minutes long, and various estimates for the achievable accuracy range from 25 ns to 1 ns, showing that significant systematic errors affect the results – for example, the unknown, unsymmetric time delays in the satellite circuitry.

The principal burden of time transfer is carried by GPS. Strict use of the common view method, by which two receivers track the same satellites over the same time periods, eliminates completely, by differencing, the effects of Selective Availability (SA), the artificial error superposed for military reasons on the uncoded GPS satellite time. However, if data are not strictly synchronous – if, for example, one receiver uses UTC time while the other uses GPS time – the difference (11 seconds in 1996) introduces an appreciable SA error in the result (in this case, about 2 ns). The BIPM issues international common view schedules twice a year, and future tracking schedules will conform to the new CCDS Technical Directives (see above), so as to remove SA error completely. Other important sources of error are due to the satellite ephemerides, poorly determined ionospheric and tropospheric path delay, multipath effects at each local antenna, and errors in the antenna geodetic coordinates. Altho sub-ns time transfer is achievable using multi-channel, two frequency P-code GPS timing receivers, almost all timing laboratories still use single frequency, single channel CA receivers. Ionosphere is a major problem. General availability of two-frequency receivers that eliminate ionosphere, and use of precise International GPS Service (IGS) ephemerides, should reduce typical GPS time transfer errors from 4 to 1 ns by the year 2000. Also, implementation of US President Clinton's Presidential Decision Directive (PDD), announced on 28 March 1996, according to which SA should be eliminated over the next four to ten years, should greatly simplify the task of international time comparisons.

5. TIME DISSEMINATION

Once TAI/UTC has been formed by the BIPM (see above), it must be disseminated to users. GPS is not satisfactory for users needing time synchronization better than several hundred ns, because of SA. However, GPS disciplined oscillators which steer quartz or rubidium clocks to agree with averaged GPS time over hours or days have found wide use in the last few years – for example,in European calibration laboratories. It has been observed that the decorrelation time of the SA corrupted GPS broadcast time is about 200 seconds to 300 seconds, and that white phase noise predominates for longer observation times, which can be averaged out. To provide traceability back to TAI, several nations have established laboratories providing what are called Calibration Services. For example, the Italian Calibration Service is managed by the three primary national metrological institutes, including the Istituto Elettrotecnico Nazionale (IEN), which generates the Italian time standard UTC(IEN) via an independent atomic time scale TA(IEN). Since May 1995, the IEN data are reported to the BIPM. This national standard is provided to the local calibration services by the passive television method, by time signals on the Italian National Radio (RAI), and by GPS. To establish traceability for frequency and time, each calibration laboratory must perform daily an agreed number of time interval measurements, and periodically report the results to the IEN. Every three months, the accredited laboratory is supplied with a calibration certificate, reporting the reference oscillator parameters, the relative frequency offset from UTC(IEN), and (in the case of television and GPS synchronization) the frequency drift. The accuracy with which the calibration centers are referred to the national primary centers has been determined to be about 7×10^{-13} for averaging times of one day.

6. TIME KEEPING AND TRANSFER IN CHINA

Generation and dissemination of precise time in Asia poses special problems, because of the very wide area to be covered and great diversity of the users. Three local time scales, maintained in the Institute of National Metrology (NIM), Shaanxi Observatory (CSAO), and Shanghai Observatory (SO), contribute to BIPM's TAI. To meet the needs of many different frequency standards users, Shanghai Observatory has developed three types of hydrogen masers, which are called laboratory, engineering, and mini-engineering clocks. Up to early 1996, ten engineering hydrogen masers have been manufactured and deployed in different institutes, including the Australia Telescope National Facility (ATNF) in Canberra, Australia. Broadcast time signals are BPM, XSG (shortwave), and BPL (LF groundwave). For precise time transfer, Shanghai Observatory uses GPS primarily, supplemented by television and Loran-C. Extensive experiments have shown the best way to remove the effects of GPS SA by data averaging. Standard time dissemination by satellite TV channel has achieved precisions better than 1 microsecond. The satellite position is determined to about 100 m accuracy, and a technique has been developed by which to broadcast the orbital parameters via Chinese Central Television (CCTV). Two way satellite time transfer has been proposed (July 1993) using one voice channel in a Single-Channel per Carrier (SCPC) satellite digital communication ground station with bandwidth of 45 kHz. The system is to consist of one master station and up to 62 secondary stations, and an accuracy of better than 2 microseconds is anticipated.

7. (US) NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)

NASA has six groundbased timing systems currently in use. Four of these rely on commercial cesium beam standards: the NASA Satellite Laser Ranging Network (NSLR); Network Mission Operations Support (NMOS); NASA Kennedy Space Center (KSC); and the Tracking Data Relay Satellite (TDRS) Ground Terminal Network. Two use hydrogen masers: the Very Long Baseline Interferometry (VLBI) stations of the Space Geodesy Program; and the Deep Space Network (DSN). Three of these six use triply redundant clocks: NMOS, KSC, which achieves redundancy via a LORAN-C timing receiver and a GPS disciplined quartz crystal clock; and the DSN. All use GPS; and the DSN uses GPS in the common view mode.

The US NASA Jet Propulsion Laboratory (NASA/JPL) near Pasadena, California, which operates the DSN, is experimenting with several new techniques to improve improve timing accuracy. Several mercury Linear Ion Trap devices have been constructed, one of which is operating at the US

Naval Observatory (USNO). Also under development for use in the DSN are ytterbium trapped ion standards, cryogenic sapphire resonator oscillators, and electro-optical oscillators. Since the stations within each DSN complex are often widely separated – e.g., over 26 km. at the Goldstone complex – fiber optic links have been developed to distribute time from the primary station clock(s). JPL operates an environmental stability test facility for measuring the performance of frequency standards, synthesizers, distribution systems, local oscillators, and exciters. The laboratory reference time is maintained by an ensemble of hydrogen masers and commercial cesium clocks using GPS in the common mode to synchronize to UTC(NIST).

8. IAU COMMISSION 31 WORKING GROUP ON PULSAR TIMING

IAU Commission 31 renewed two Working Groups at the 1994 General Assembly at The Hague: the WG on Time Transfer, and the WG on Pulsar Timing. The work of the WG on Time Transfer is subsumed under the general work on international time transfer (see above). The WG on Pulsar Timing, chaired by M. Gerard Petit of BIPM, has focussed on increasing the availability of pulsar timing data files to workers in the field of international time. The most comprehensive such file is that maintained at Princeton University (USA) which is accessible by Internet. The IAU WG recommends that such data be reduced using the Princeton TEMPO, or the TIMAPR software available from O. Doroshenko at Internet address "http://www.mpifr-bonn.mpg.de/pulsar/olegd/"

9. REFERENCES

The work of Commission 31 is represented by a very large body of published research. There are three primary symposia where this work has appeared: (1) the annual IEEE International Frequency Control Symposia; (2) the more recently organized annual European Frequency and Time Forums; and (3) the (United States) Annual Precise Time and Time Interval (PTTI) Applications and Planning Meetings, organized jointly by the Department of Defense and NASA. Important journals for research in time and frequency are the Proceedings of the IEEE, and Metrologia. Two important papers have appeared that are formally outside the work of Commission 31, but have strong relevance to it:

International Vocabulary of Basic and General Terms in Metrology (VIM) International Organization for Standardization (ISO), Geneva, Switzerland [1993].

V. Kose, "Dissemination of Units in Europe: Traceability and Its Assurance in a National and Regional Context", Metrologia 31, pp457-466 [1995].