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History of the Bureau International de l'Heure

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Abstract. At the beginning of the 20th century, the development of radio time signals offered the possibility of unifying the measurements of Universal Time (UT). A new service, the Bureau International de l'Heure, hosted by the Paris Observatory, was entrusted with this task. The BIH began its operation in 1912, although its statutes were officially settled only in 1919. This paper recalls the activities of the BIH on time determination and various connected fields: Earth rotation, reference frames, atomic time. With the importance of atomic time and the emergence of new techniques for the measurement of Earth rotation, a new organization was required. It was prepared by the MERIT and COTES programs (1978) and by the bodies of the Metre Convention, with the active participation of the BIH. The BIH was dissolved at the end of 1987, its work being shared between the Bureau International des Poids et Mesures and the new International Earth Rotation Service.

1. Introduction

The creation of the Bureau International de l'Heure (BIH) is a consequence of the progress of radio-electricity. Towards 1910, the exchange of radio time-signals at long distance showed that these signals may disagree by 1 to 2 seconds and that a much better synchronization might be achieved, on the basis of the universal time (UT) recommended by the *Conférence internationale pour l'adoption d'un méridien unique et d'une heure universelle*, held in 1884 in Washington.

Schematically, radio time-signals provided comparisons of distant clocks with the unprecedented inaccuracy of some 0.01 s, later reduced to about 1 ms. Within these limits, it became possible to refer all measurements of UT to a single clock, to average them in order to form a unique time scale, here denoted UT(BIH), which could be conventionally taken as the basis of unification of time. The dissemination of UT(BIH) could be ensured by publication of UT(BIH) – TS, where TS represents the nominal time of emission of time signals. It is precisely the scheme adopted nowadays for atomic time and it may appear as straightforward. However it involved research in many domains: technical improvements of clocks and signals, propagation, unification of longitudes and star catalogues, techniques of observations, need of pole coordinates, *etc.* These research had to be pursued during the whole existence of the BIH: this would

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make the chronological exposition of the BIH activities exceedingly confused. I prefer to consider the historical development of some major themes at the BIH.

2. Creation and administration of the BIH

After hearing a report by G. Ferrié, the Bureau des Longitudes (Paris) took the initiative to organize a *Conférence internationale de l'heure radiotélégraphique*, held in October 1912 at the Paris Observatory, where 16 countries were represented. A permanent commission, the Commission Internationale de l'Heure, and an executive body, the Bureau International de l'Heure, were created. On the proposal of a delegate, the Bureau was provisionally installed at the Paris Observatory. Next year (20–27 October 1913), a diplomatic conference was held in Paris, with plenipotentiaries of 32 countries, which prepared an international convention for creating an International Association for Time, with a Committee, a Permanent Council and the BIH. The Director of the Paris Observatory was invited to organize immediately the Bureau, although the convention was not yet ratified by the member countries. Unfortunately, the international community had to face more vital problems and the convention was never ratified. In 1919, it was found simpler to insert an International Commission of Time (Commission 31), with its executive BIH at the Paris Observatory, in the newly created IAU. [Acronyms are given in Annex 1]. The authority of Commission 31 on the BIH was effective until 1939, but, after the war, this authority progressively lessened. In 1956, when the FAGS was created, the BIH became a service of this federation and in 1965, in conformity with the statutes of FAGS, the BIH received a directing board whose expert advice contributed greatly to the development of the Bureau.

One can observe that the initial organization prepared for time was quite similar to that of the Metre Convention (1875). With its failure, the BIH had lost the opportunity of becoming an intergovernmental body with a truly international founding. The grant from the IAU, with later a contribution from IUGG, was becoming more and more insufficient. It was then replaced by grants from the ICSU (FAGS) and UNESCO which, although essential for the freedom they offered, covered only a few percent of the total expenditures. The BIH could survive thanks to some contracts, to loans of equipment from cooperating observatories, to the help (starting in 1973) of the BIPM, and to the contribution of French organizations, the CNRS and the Paris Observatory. The generous support of the Paris Observatory never failed and towards 1980, it covered the quasi-totality of the cost of the Bureau. However, this situation was not fully satisfactory, the apparent lack of independence from national authorities being often criticized. This was aggravated by the fact that, from 1928 to 1965, the Director of the BIH was *ex officio* the Director of the Paris Observatory and that a clear distinction between what belonged to the BIH and to the observatory was not always possible.

3. The *Demi-Definitive* and *Definitive* times (1920–1967)

The BIH established its own time service at the Paris Observatory and its first activities were in a large part devoted to the technical aspects of time keeping: construction and improvement of receivers and transmitters of time signals, and studies of pendulum clocks. Although it is not said explicitly, the first publications give the impression that the BIH considered its own time signals as an international reference: this required the best quality. Progressively, a distinction between the BIH and the time service of the Paris Observatory was established and formally completed in 1976, with the creation of the Laboratoire Primaire du Temps et des Fréquences (LPTF).

Until 1929, the BIH used only the astronomical determinations of UT (or Greenwich mean sidereal time) made by the Paris Observatory. This realization of UT was called *heure demi-définitive.* It was disseminated by publication in a Bulletin Horaire of corrections to the nominal time of the BIH time signals and from a few signals of foreign stations at their reception at the BIH. It was thus unnecessary to apply corrections for propagation, poorly known at this epoch; but the user had, in principle, to apply its own corrections. In spite of this inconvenience, the publication of the *heure demi-définitive* of receptions at Paris continued until 1966, for an increasing number of signals, because the *heure définitive* based on all astronomical determinations through the world required much longer delays (6 months to one year).

The *heure définitive* appeared in the Bulletin Horaire in 1929. There were initially 6 contributing observatories; in 1963 their number reached 37. Large (and varying) systematic differences between data of the observatories and their irregular flow forbade a direct average of UT determinations. To overcome this difficulty, the BIH introduced the concept of the *Mean Observatory.* Each contributing observatory i established its own UT(i) scale on the basis of its own observations, then the BIH averaged these UT(i) for a fixed number of observatories, with fixed weights, defining the Mean Observatory. Thus, systematic differences were averaged and did not introduce short-term irregularities. The composition of the Mean Observatory was modified several times, but the difference of results for the various mean observatories has always been given.

In 1931, the publication of the *heure définitive* by the Bulletin Horaire took the form which was kept until 1966: daily lists of values of UT — nominal time of time signals, at their emission.

How well does the *heure d'efinitive* represent UT1, apart from a constant offset? I would say that the Allan standard uncertainty lies between 5 and 10 ms for one month averaging time at the height of the system, towards 1960.

The computation of the *heure définitive*, as simple as it may look, required an enormous amount of work. For example, in 1953, 27 000 time signals were received by the BIH. The corrections to more than 200 signals were published daily. Only in the 60s did it become possible to reduce this number of corrections, some signals being steered by clocks stable enough to allow for interpolation.

During the war 1939–1945, the *heure demi-définitive* was regularly published. During the first months of war, all data, including those of Germany, reached the BIH. Then, the computation of the *heure définitive* was interrupted in February 1940 and was resumed in 1947. The gap was filled later.

4. The BIH as a global Earth rotation service (1967–1987)

The *heure définitive* of the BIH was computed without applying a correction for the motion of the pole and did not truly represent the rotation of the Earth. However the corrections based on provisional coordinates of the pole communicated by the ILS were published in the Bulletin Horaire since 1939 and provided what has been called later UT1. In 1955, in order to shorten the delay of publication of UT1, the IAU recommended that the ILS establishes a Rapid Service for the Polar Motion (SIR), based on the free cooperation of stations equipped with zenith tubes and astrolabes sending their latitude measurements. After a period of irregular functioning of the SIR, the BIH took over the activity of this service. In 1965, the SIR became officially part of the BIH.

However, at the same epoch, the BIH undertook a major reorganization to reduce drastically the delay of publication of UT1(BIH), which was especially required by the development of space research, and to improve its quality. The leading ideas were:

- to use all determinations of UT0 and latitude, or polar motion, by any technique in a single set of equations giving the Earth rotation parameters (ERP), *i.e.* UT1 and the coordinates of the pole;

- to eliminate pre-smoothing inherent to the method of averaging *demi-definitive* times;

- to provide raw results with a resolution of 5 days, in order to study short-term effects which were known (tides) or suspected (atmosphere).

The BIH new algorithm could be called in modern language a stability algorithm. It was attempted to keep as small as possible fictitious drifts of the origin of longitudes, of the mean pole and of the amplitude of the annual components in UT1 and polar motion. For the coordinates of the pole, this is in contrast with the ILS method, which aimed to accuracy by rigorous planning of the observations, but suffered from the small number of participating stations. A characteristic of the BIH algorithm was the use of a complex weighting to reduce the noise in two regions of its spectrum, towards Fourier frequencies of one cycle per year and one cycle per ten days. In the long term, the BIH results should have required calibration against accurate methods. This could have been left to comparisons with the ILS data over decades, but it was already clear that new techniques would replace classical astrometry with much more precise and accurate results.

After approval by the IAU and the IUGG in 1967, the series of Bulletin Horaire was replaced by a monthly circular (Circular D), providing the results (raw and smoothed) for month m at the beginning of month m + 2 and by an Annual Report. In 1967, the Allan standard uncertainties for 5 days were $0''.015$ on the pole coordinates x and y, 0.0012 s for UT1. At the height of classical astrometry, in 1972, 80 stations entered in the BIH solution, and the uncertainties were somewhat reduced. The BIH technique gave the possibility to organize, under a contract to the Jet Propulsion Laboratory, a weekly service giving the ERP with a delay of a few days, for the needs of space navigation. At some critical periods a daily service could even be run. Starting its operation in

1970, this service used data of selected observatories (including in USSR), sent by teletype.

In 1973, the pole coordinates provided by the Dahlgren Polar Monitoring Service, obtained from tracking of TRANSIT satellites, entered in the BIH evaluations with a heavy weight. The development of other new techniques, stimulated by the working groups MERIT (1978) and COTES (1980) to which the BIH actively participated as coordinating center, led the BIH to base entirely its current evaluation of the ERP on these techniques in 1984, although a solution for classical astrometry was computed for some time.

Thus, the BIH has ensured a smooth transition to the modern methods for measuring the ERP. But this was far from its initial mandate: time was measured by atomic clocks. Clearly, a reorganization of the services dealing with time and the ERP was required. It took place in 1988, when the IERS was founded.

5. Terrestrial and celestial reference frames

During its whole history, the BIH gave much attention to the definition of its reference systems in space and for the Earth.

Until 1984, classical observations used the plumb line as terrestrial reference and thus led to astronomical latitude and longitude. The unification of longitudes was a major concern of the BIH since the very beginning of its activities, shared with IAU Commission 18 on Longitudes (1922–1952). It required that a common reference in space be used: this was first the Eichelberger catalogue of stars (1925), then the FK3 (1940), and the FK4 (1962). In 1983, one year before the official date, the BIH adopted the IAU (1976) System of astronomical constants, the 1980 IAU Theory of nutation and the equinox of the FK5.

The BIH participated in the campaigns of determination of longitudes in 1926, 1933 and 1958 (International Geophysical Year). But, it was already remarked in 1935 that the BIH was making daily determinations of 20 longitude differences. The longitudes (and, since 1967, the latitudes defining a realization of the Conventional International Origin, CIO), were regularly published until 1983.

Unfortunately, these astronomical coordinates have little geodetic value and they were affected by systematic errors. A radical change appeared with the emerging techniques of measurements of the ERP, which truly refer to the figure of the Earth. During their development, coordinated by MERIT and COTES, it was recognized that the services which permanently monitor the ERP could provide and maintain the best realization of a terrestrial reference system. Without waiting for an official mandate from the IAU and the IUGG, the BIH published in its Annual Report for 1984 a homogeneous set of coordinates of 34 sites, which formed a realization of the so-called BTS84 (BIH Terrestrial System). Soon afterwards, the reference system WGS84 of the Global Positioning System (GPS) was aligned on the BTS84, a decision which contributed largely to the unification of terrestrial references.

The orientation of the BTS84 was fixed by the condition that the ERP be continuous at the changeover from the old to the new techniques. Its accuracy (uncertainties in the range 1 to 10 cm) was improved and the number of sites was increased in yearly versions, until 1987, which provided the coordinates for 1984.0, using the AM0-model for plate motion. These versions were submitted to the condition that there be no global rotation at epoch. When, in 1988, the IERS took over the responsibility for the terrestrial frame, named ITRF, it maintained the continuity with the BTS.

In the past, it was sometimes objected that the concept of mean observatory led to a variable longitude of Greenwich, differing from zero by a few 0.001 s. Now it is much worse, the prime meridian of ITRF is away from the reference point in Greenwich by some 100 meters. This is a consequence of the continuity condition on UT1. This could have been avoided by different means, but nobody considered the question in due time.

The BIH found also useful to describe explicitly the reference frame in space which was coherent with the BTS and the published values of the ERP. To this end, in its last Annual Report, that of 1987, the BIH published the coordinates of 228 extra-galactic sources. This frame, a forerunner of the ICRF, was labelled RSC(IERS)88 C 01.

6. Atomic time

The first operational cesium clock appeared in 1955. It was followed in 1956 by other cesium clocks constructed by several laboratories, then by the industry. In a few laboratories, including the BIH, researchers began to establish atomic time scales in order to improve the averaging of determinations of UT1, to study its irregularities and to extrapolate the emission of time signals. However, in the mid 60s, the opinion prevailed among the astronomers that atomic standards could provide the unit of time, but not the continuous time scale that they needed. On the contrary, the BIH and its Directing Board were convinced that an atomic time scale will become the best reference in time. An important part of the BIH resources, human and financial, was then devoted to atomic time. Two periods can be distinguished in the BIH activity. From 1955 to 1966, over intercontinental distances, only accurate frequency comparisons were possible: the scale of atomic time was obtained by integration. Then, accurate time comparisons became available, and atomic time took its modern form, leading to the International Atomic Time, TAI.

6.1. Integrated atomic time

The relative inaccuracy of the first cesium standard was of about 10^{-9}. Using classical radio time signals, more than two weeks of averaging would have been required to disseminate its frequency without loss of accuracy. Fortunately, there already existed VLF emissions whose carrier was stabilized by quartz crystal clocks. The common reception of these emissions was an excellent means to compare frequencies at distance. It was thus possible to compare the frequencies of several standards with that of a reference local clock, used as an integrator, and to average these frequencies. The integrated atomic time was available locally by corrections to the local clock, but its dissemination had to be made by the usual time signals, with uncertainty of about 1 ms.

The first report on atomic time in the BIH publications appears in the Bulletin Horaire, Series G, No 8, March–April 1960. It provides the differences between UT2 and atomic times integrated by the BIH, for individual standards and for the mean, when it became possible.

From July 1955 to July 1956 there was only one cesium standard at the NPL [The acronyms are given in Annex 1]. The scale was called AT. When other laboratories were included, NRL (1956), ON (1957), NBS (1958), CNET (1958), the name became AM. In 1961, other participants joined the club and the BIH mean scales were denoted An where n is the number of standards. In 1964, AM represented the mean scale based on all standards, while A3 was the scale based on the three best of them. Then A3 was kept for the best scale whatever be the number of standards. These complexities are mentioned to show the hesitations in this pioneer work. But we can retain that in the series of An, there is a continuous scale with A3, which later became the International Atomic Time TAI.

By convention, all integrated atomic times, at BIH and elsewhere, were set so that an event at 1958 January 1, 0 h UT2, receive the same date in UT2 and atomic time scales. However the observatories used their own values of UT2: that explains that longitude errors of a few 0.01 s appear in the local independent time scales, as they are presently realized.

6.2. Time comparisons and International Atomic Time

The expansion of atomic time is, of course, a consequence of the progress in accuracy of frequency standards and of the production of high quality industrial cesium clocks. But it could not have taken place without accurate means of time comparisons. These means appeared in August 1968 with the synchronization of the Atlantic LORAN-C chains, later extended to the Pacific area. The reception of LORAN-C signals, associated to local time comparisons using television and to cesium clock transportation by air, reduced the uncertainties of clock comparisons between North America, East Asia and Europe to 1 microsecond, or even better.

At 1969 January 1, the BIH scale was redefined as a mean of 3 national atomic time scales TA(i): for PTB, USNO and F, with a time offset in order to ensure the continuity with A3 at the changeover, but without attempting to avoid a frequency step. Later in 1969, RGO, NRC, NBS, ON joined the first participants, their time scales being included with a method avoiding time and frequency steps. The BIH scale, named AT or TA, was thus keeping the memory of the mean frequency of the 3 initial TA(i). The scale TA was disseminated by publication of the values of UTC − UTC(i), at 10-day intervals, in the monthly Circular D, the differences UTC − TA and UTC(i) − TA(i) being available.

With this progress in atomic time keeping, a much wider use of atomic time could be envisaged and the need to adopt conventionally a scale for world-wide unification of time was becoming stringent. Already in 1967 the IAU had recommended the use of the BIH scale. It was followed by the URSI in 1969, the CCIR in 1970. The ultimate recognition was that of the bodies of the Metre Convention in 1971 (14e Conférence Générale des Poids et Mesures), which gave the official name of TAI. The next technical step was to derive TAI directly from the data of individual clocks. It was motivated by the desire of a uniform treatment of all clocks aiming to ensure very long-term stability (a criterion which may not be that for the TA(i)). The BIH also had the opinion that the greatest possible

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number of nations should be involved in the construction of TAI. A stability algorithm, ALGOS, has been devised and a system of data transmission was prepared and kindly accepted by participants. This new method became operational in 1973, with 68 clocks in 10 laboratories of 8 countries (in 1987, these numbers were 223, 36 and 24). In the following years, the progress of primary standards revealed that the scale unit of TAI was substantially different from its nominal value (the second at sea level). On 1977 January 1, 0 h TAI, the TAI frequency was lowered by 1×10^{-12} and a procedure of frequency steering was initiated in order to avoid departure from the frequency of the primary standards. (Note that this explains why the scientific coordinate time scales TCG, TT, TCB, TDB had their origins fixed by reference to TAI in 1977). The access to TAI remained the publication of UTC − UTC(i) at 10-day intervals, for 21 laboratories in 1973, a number which reached 40 in 1987.

The ALGOS algorithm and the organization settled in 1973 and 1977 are still operational at the BIPM, after adaptation to the evolution of the accuracy of clocks, frequency standards, comparison means (the GPS started to be used in 1983) and communication methods.

The activities on TAI were developed in close cooperation with international bodies, especially with the CCIR, and the CCDS. It was clear, at the BIH, that the responsibility for TAI should join that for other base physical quantities at BIPM, where the activities would benefit from an intergovernmental support. This transfer was prepared since the end of the 60s. A physicist of the BIPM was attached to the BIH in 1973. In March 1985, the direction and the time section of the BIH were moved to the BIPM, while the section on the rotation of the Earth remained at the Paris Observatory. In January 1988, the BIPM took the entire responsibility of TAI and associated activities on time.

Many researches at the BIH accompanied the development of atomic time, especially in the domain of statistics, relativity, frequency and time comparisons.

6.3. Coordinated Universal Time, UTC

The initiative of coordinating the emission of time signals disseminating UT1 was taken by the UK and the USA in 1959. The basic idea was to link these signals to an atomic time scale with an agreed frequency offset, and to further adjust the signals to UT1 by small time steps at agreed dates. At first, this system was not favoured by the BIH. But it was adopted by several countries and, at the request of the URSI, the BIH accepted its coordination in 1960.

Until 1965, the more or less common scale for emission of signals, which had received spontaneously the name of Coordinated Universal Time (UTC), had not been strictly defined. For example, the BIH considered UTC as a mean of the time of emission of signals. An important step was the decision taken by the BIH in 1965 to define UTC by a mathematical relation with its own atomic time scale. The new UTC being in continuity with the previous one, this decision was practically unnoticed at the epoch. Nevertheless, the coordination of time signal with this theoretical UTC was progressively improved. The link between TAI and UTC was thus born in 1965. Let us recall that the IERS has now the responsibility of fixing the date of occurrence of leap seconds of UTC, while the fraction of the second, which is that of TAI, is under the responsibility of the BIPM.

Acknowledgments. After hesitation, I decided not to give the names of persons who worked at the BIH. The reason is that, in such a short paper, it would have involved a selection which would have not been fair. Moreover, the history of the BIH is that of a collective adventure to which hundreds of persons participated: physicists, astronomers, observers, computers, technicians of many laboratories and observatories, members of commissions, of the BIH Directing Board. The contributions of all these persons took several forms: communication of data, loan of equipment, official and personal advice. In the last years of the existence of the BIH, the cooperation with the Bureau was complete: any organization in the world which could cooperate did it. The community owes much to all these persons whose names should have been mentioned also. We should keep the memory of their hard work, often with little personal return, and express our gratitude.

ANNEX 1. Acronyms

BIPM	Bureau International des Poids et Mesures
CCDS	Comité Consultatif pour la Définition de la Seconde
CCIR	International Radio Consultative Committee
CNET	Centre National d'Etudes des Télécommunications, France
CNRS	Centre National de la Recherche Scientifique, France
COTES	Conventional Terrestrial System
F	Commission Nationale de l'Heure (France)
FAGS	Federation of Astronomical and Geophysical Services
IAU	International Astronomical Union
IERS	International Earth Rotation Service
ILS	International Latitude Service
ICRF	International Celestial Reference Frame
ICSU	International Council of Scientific Unions
ITRF	International Terrestrial Reference Frame
IUGG	International Union of Geodesy and Geophysics
MERIT	Monitoring Earth Rotation and Intercomparing Techniques
NBS	National Bureau of Standards (USA)
NRC	National Research Council (Canada)
ON	Observatoire de Neuchâtel (Switzerland)
PTB	Physikalisch-Technische Bundesanstalt (Germany)
RGO	Royal Greenwich Observatory (UK)
URSI	International Union of Radio Science
USNO	US Naval Observatory (USA)

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