THE DETERMINATION OF UT1 BY THE BUREAU INTERNATIONAL DE L'HEURE (BIH)

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ABSTRACT

The determination of UT1-UTC is obtained at the Bureau International de l'Heure from a world centralization of the astronomical measurements made in 60 stations.

The combination of the data, involving analysis and prediction of the individual behaviour of the stations, is described. The stability of the results made available to different kinds of users under various time delay/accuracy conditions is characterized.

INTRODUCTION

The rotation of the Earth is computed from ground optical measurements of star directions. An observation, at station i, gives a local value of the instantaneous angular position of the Earth: UT0(i) - UTC. UT1-UTC is obtained at the BIH by combining the local UT0(i) - UTC after they are corrected for the motion of the pole on the Earth. In 1976, 60 astronomical instruments are transmitting their observations of UT0 to the BIH.

In the future, new methods are envisioned to measure the Earth rotation: Lunar Laser Ranging [1] (operation expected to start in 1977) and VLBI. These methods are expected to provide results with a greater precision and a better time-resolution than the classical astronomical method, but the latter is still improving, as shown by the following numbers for 1967 and 1975:

	1967	1975	ratio $\frac{1975}{1967}$
number of visual instruments	34	36	1.06
number of photographic / photoelectric instruments	16	24	1.50
number of observing nights per year	4 225	6 233	1.48
number of observed stars per year	93 882	187 831	2.00
Allan variance of the BIH 5-day raw values $\langle \sigma^2 (2,\ T = \tau = 5d) \rangle$	$(0^s.0022)^2$	$(0^s.0011)^2$	0.25

The above first four lines show the increasing effort of the observatories, which use photographic or photoelectric instruments rather than visual ones; moreover, the number of observing nights grows faster than the number of instruments, and the number of observed stars grows even faster. During the same time, our studies of the individual time series of UT1(i) - UTC led us to an improved prediction of their behaviour. These studies and their application to the current computations in order to get consistent values of UT1 will be outlined. Then the precision of the values of UT1-UTC as published by the BIH with time delays ranging from one week to one year will be estimated.

OPTIMAL FILTERING OF THE INDIVIDUAL TIME SERIES OF UT

The astronomical measurements of UT supply the instantaneous position of the Earth in its rotation by linking a network of stations which represent the Earth crust to a set of stars which provide an inertial reference system. These measurements may suffer from the influence of instrumental errors, tectonic motions, refraction irregularities, star catalog effects, etc. In addition, the time series of UT1(i), i. e., UT0(i) corrected for the longitude effect of polar motion, have a large individual annual component (see Figure 1). On the other hand, the BIH has to publish consistent values of UT1 with a time delay largely shorter than one year. We must then be able to predict the individual errors, according to an appropriate modeling of their statistical and deterministic features.

Determining the Power Density Spectrum of Errors

Assuming constancy of errors, we analysed the noise spectral density as a function of the frequency, $S(f) = h_\alpha f^\alpha$, for time intervals longer than one year. The Allan variance criterion $\sigma^2(n, T = \tau = 1y)$ [2] was used in order to determine α. The deterministic part of the errors is represented by a time independent term, an annual term and a semi annual term. The study of the yearly values (1962 to 1973) of these parameters indicate that in the mean the type of noise is significantly different for the three components:

- the time independent term shows a preponderant flicker noise ($\alpha = -1.0$). This is the consequence of all the accidental local and instrumental changes.

- the amplitude of the semi annual term has white noise ($\alpha = -0.1$): it suffers only from measurement errors.

- the amplitude of the annual term has an intermediate noise density spectrum ($\alpha = -0.6$): it is also affected by instrumental errors, but in a lesser proportion than the time independent term.

Predicting the Systematic Deviations

The monitoring of UT1 with a short time delay, providing homogeneous results in spite of the various sources, with irregular data acquisition rates, the starting and ending of operating stations, makes it necessary to predict the behaviour of each station. In the BIH computations, this prediction is repeated annually.

The optimum filter adapted to the types of noise of the three systematic components has been theoretically derived but its implementation is practically impossible on account of a poor knowledge of the noise levels of individual instruments and to the lack of constancy of their statistical properties. In practice, a white noise prediction, limiting the past to four years, which was adopted after a previous study [3], doesn't give rise to such difficulties and has shown to be satisfactory. The individual series of UT1(i) are corrected for their predicted time independent, annual and semi annual terms before being combined to give UT1.

CORRECTION OF SHORT TERM VARIATIONS AND SMOOTHING

Short-Term Variations

The astronomical measurements have short-term local variations due to diurnal nutation and earth tides: all known corrections are applied to the UT1(i) before combination. There are also some other variations in the Earth's rotation due to the zonal earth tides; they are not corrected. The components of period shorter than one month are thus present in the published raw values of UT1 (Table 6 of the BIH Annual Reports) but they vanish in the usual smoothing (circular D).

Smoothing

The raw values of UT1 in Table 6C of the BIH Annual Report are freed from all known or estimated systematic variations; they are the relevant data for studies of the Earth's rotation. As they indeed still have noise spectral density, an appropriate smoothing will provide the users of UT1 with better current values.

At the BIH, we use Vondrak's smoothing method [4], which is an extension of Whittaker-Robinson's one for the case of unequally spaced and weighted data. A parameter ϵ allows one to choose the roughness of the smoothed curve; the usual smoothing of the 5-day raw values of UT1 is made with $\epsilon = 10^{-11}$, which attenuates the amplitude of waves of different frequencies according to Figure 2. This filtering is strong enough to remove the waves due to zonal tides (13.7 and 27.7 d) and weak enough to leave in the smoothing the semi annual variation which is also present in the Earth's rotation. The spectral analysis of the residuals of raw data with respect to this smoothing (Figure 2) shows the two zonal tide lines, noise outside the lines and a low frequency cutoff near 0.02 c/d: for time intervals longer than approximately 50 days, the time series of 5-day raw and smoothed values of UT1 are statistically equivalent.

PUBLICATION OF THE RESULTS - TIME DELAY AND PRECISION

The preceding sections dealt with the way in which the BIH insures the consistency and accuracy of its results: all the published values of UT1 are in the same system, which is linked to the conventional origin of longitudes. However, the various needs of the different users of its data lead the BIH to issue different publication series, with different time delays after the last observation date, which implies a varying precision according to the time delay of publication.

To characterize these precisions we shall take the usual Vondrak's smoothing ($\epsilon = 10^{-11}$) of raw values of Table 6C as a reference. The residuals of this smoothing since 1974 are shown on Figure 3. Over the time interval 1972.0 - 1976.5, their r.m.s. value is $0^s.0014$, while their mean standard error is $0^s.0009$. This indicates that some correlations still exist between the raw values independently computed. Astronomical time series are known to have sometimes transient systematic errors during intervals ranging from a few days to several months. These apparent steps can hardly be corrected and thus generate flicker noise in the global combination for UT1 [5], as shown by the Allan variance $\langle \sigma^2 (2, T = \tau) \rangle$ of the residuals from a strong smoothing ($\epsilon = 10^{-15}$) for varying sampling intervals (Figure 4).

Publication Delay: One Week

Since April 1971, we have operated a Rapid Service, under a contract with the Jet Propulsion Laboratory. Our data are used for the navigation of deep space probes. The calculations for this weekly service are made with the astronomical data transmitted to us by teletype by 34 stations, three days after the last observation date; 16 soviet observatories recently joined this group. Every Thursday, 14 h UT, we are able to teletype smoothed daily values of UT1 and the pole coordinates for the preceding week. The r.m.s. deviation of these UT1 values (taken every 5 days) from the usual Vondrak's smoothing is $0^s.0021$ (see Figure 3).

Publication Delay: One and a Half Months

The monthly Circular D is published at the beginning of month m; it provides the users with 5-day smoothed and raw values of UT1 and the pole coordinates for month m-2. The smoothed values are obtained by the usual Vondrak's smoothing, with only very few values available after the date of the last published point. This smoothing may then slightly differ from the final one. The measured r.m.s. deviation from Vondrak's usual smoothing is $0^s.0008$ (see Figure 3).

Publication Delay: One Year - Definitive Values

The Annual Report of the BIH which is published every year in June gives definitive values for the preceding year. The values of UT1 in Table 6C are essentially the raw values of the monthly Circular D, with all improvements made possible by the passing of time: individual weighting of the data according to the actual (and no longer predicted) dispersion, taking into account all known data amendments, and, more generally, the correction of any anomalies in the received data, which can only be detected after a while.

REFERENCES

[1] STOLZ, P. L. et al. 1976. Earth Rotation measured by Lunar Laser Ranging, Science, 193, 997.

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[4] VONDRAK, J. 1969. A contribution to the problem of smoothing observational data, Bull. of the Astron. inst. of Czechoslovaquia, 20.

[5] BARNES, J. A. 1969. The generation and recognition of flicker noise. Frequency and Time Stability seminar, NBS.

The description of the BIH methods for deriving UT1 and the pole coordinates is given in the Annual Report for 1969 (in French) and for 1970 (in English).

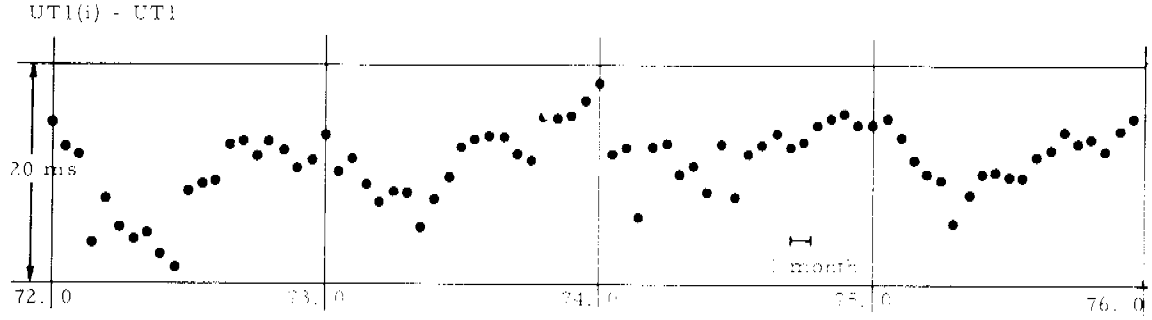
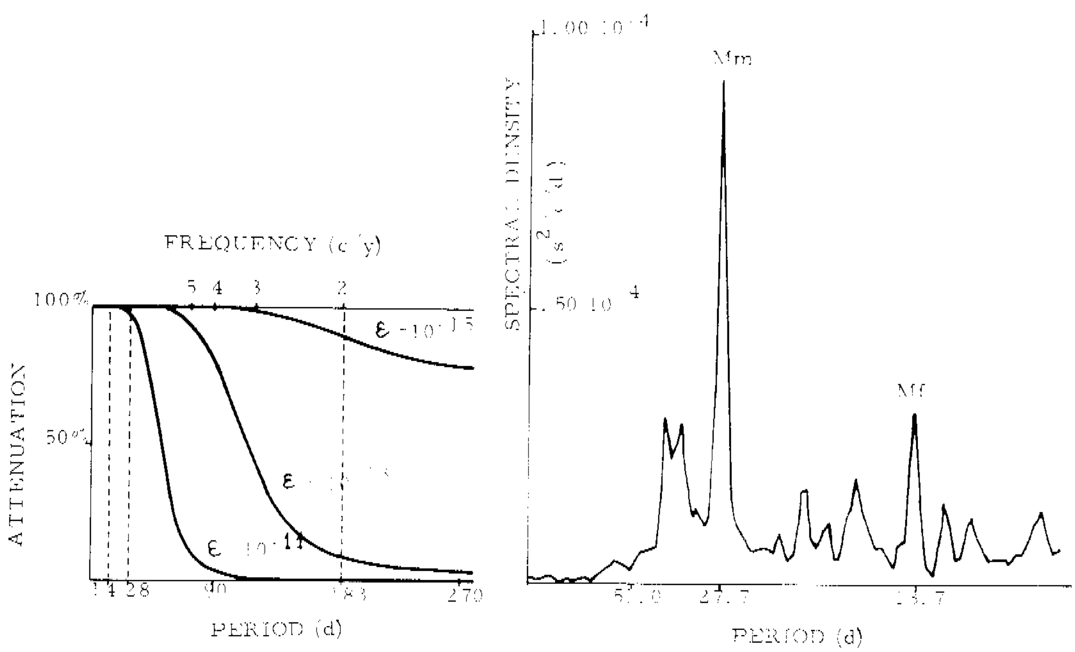


Fig. 1 A typical example of station residuals (means over 0.05 y).



a. Attenuation of waves according to ε

b. Spectral density of residuals from the smoothing (ε = 10^{-11})

Fig. 2 Vondrak's smoothing of 5-day raw values of UT1-UTC.

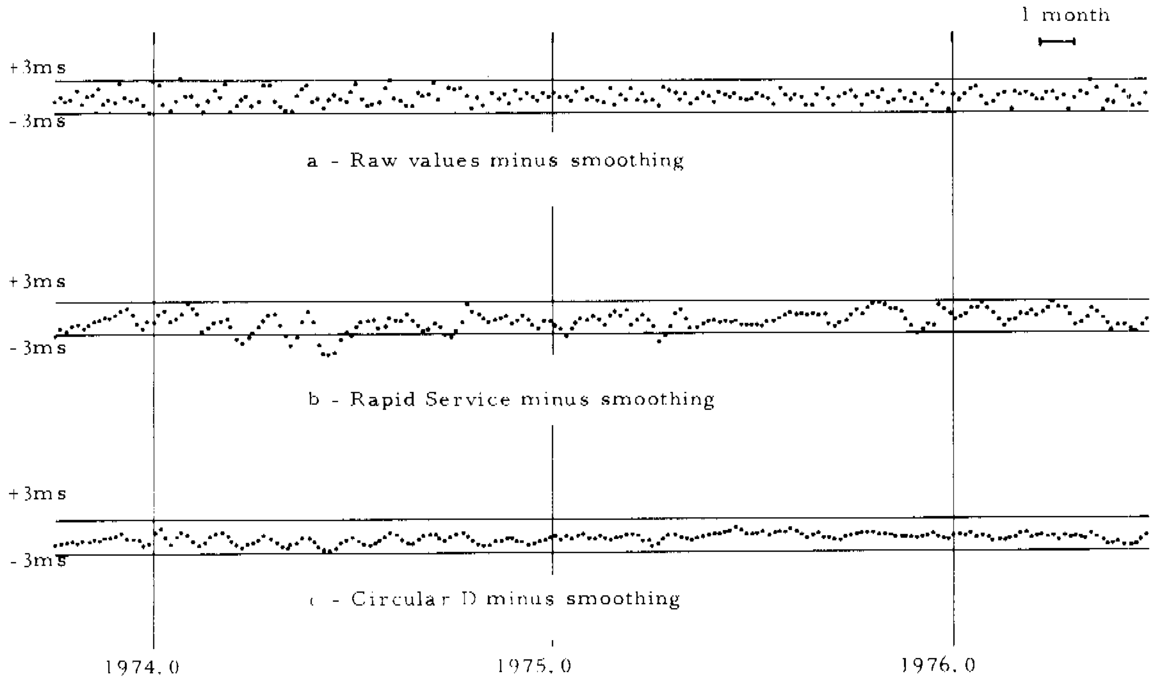


Fig. 3 Residuals of UT1 5-day values from Vondrak's smoothing($\varepsilon = 10^{-11}$).

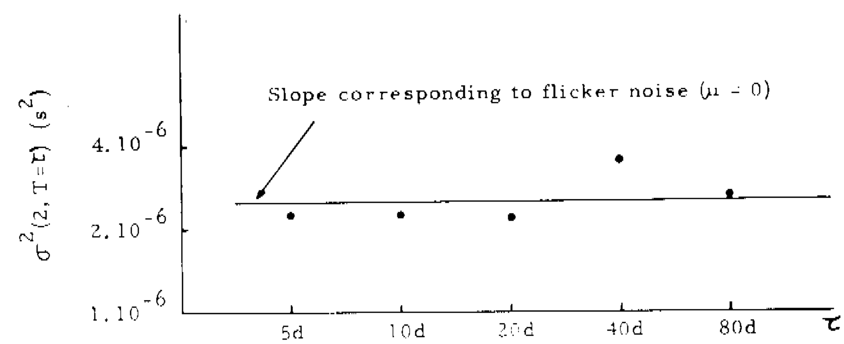


Fig. 4 Allan variance of UT1 as a function of measuring interval.