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UTCr: a rapid realization of UTC

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Abstract

Considering the evolving needs of time metrology and the convenience of allowing the contributing laboratories access to a realization of UTC more frequently than through the monthly *Circular T*, the BIPM Time Department started in 2012 to implement the computation of UTCr, a rapid realization of UTC published every week and based on daily data. After 18 months of pilot experiment, this new product has been declared operational and is now an official publication of the BIPM. This paper presents the main characteristics and properties of UTCr.

Keywords: timescale

(Some figures may appear in colour only in the online journal)

1. Introduction

Since 1988, the Coordinated Universal Time UTC has been calculated with one-month data batches, and has been available monthly in the BIPM *Circular T* [1] under the form of [UTC − UTC(k)], where UTC(k) is a local realization of UTC by participating laboratory k, at five-day intervals. Extrapolation of values over 10 to 45 days based on prediction models is necessary to many applications. UTC, as published today, is not adapted for real and quasi-real time applications and it was recognized that a more rapid realization would benefit, e.g., the following:

- UTC contributing laboratories would have more frequent assessing of the UTC(k) steering, and consequently better stability and accuracy of UTC(k) and enhanced traceability to UTC;
- Users of UTC(k) would have access to a better 'local' reference, and indirectly, better traceability to the UTC 'global' reference;
- Users of Global Navigation Satellite Systems (GNSS) would get a better synchronization of GNSS times to UTC, through improved UTC and UTC(k) predictions: this is the case for UTC(USNO) for GPS, UTC(SU) for GLONASS, and for the UTC(k) to be used in the generation of Galileo, BeiDou and IRNSS/Gagan system times.

For these reasons, the BIPM proposed in 2011 to provide UTCr, a new realization of UTC available with a reduced delay. After a phase of pilot experiment started in 2012, and with the approval of the Consultative Committee for Time and Frequency (CCTF), UTCr has become a regular product of the BIPM. This paper presents the main characteristics and the main phases of implementation of UTCr in section 2, and more details on the data and algorithm in section 3. Section 4 presents the time comparisons of UTCr with UTC and discusses various technical aspects of UTCr. Section 5 deals with the use of UTCr as a prediction of UTC from the viewpoint of participating laboratories. The paper concludes with some considerations on the BIPM time scales.

2. Main characteristics and implementation of UTCr

The general features of UTCr were designed at its inception in 2011: UTCr was defined as a weekly solution based on daily data reported daily by contributing laboratories. It is disseminated through daily values of [UTCr − UTC(k)] published at one-week intervals on the Wednesday afternoon, providing access to results up to the preceding Sunday.

The stability of UTCr was expected to be about comparable to that of UTC, albeit slightly worse because the number of participating clocks would necessarily be smaller and because, in general, a deferred solution (here UTC) is expected to be better than a rapid solution (UTCr). In order to achieve a similar performance, it was decided to use the same algorithm (frequency prediction, weighting scheme) and to apply it in a similar manner with a calculation interval covering approximately one month.

Finally, UTCr was designed to be a realization of UTC, i.e. in practice the goal is to minimize the time difference |UTCr − UTC|. For this purpose a steering algorithm has to be implemented.

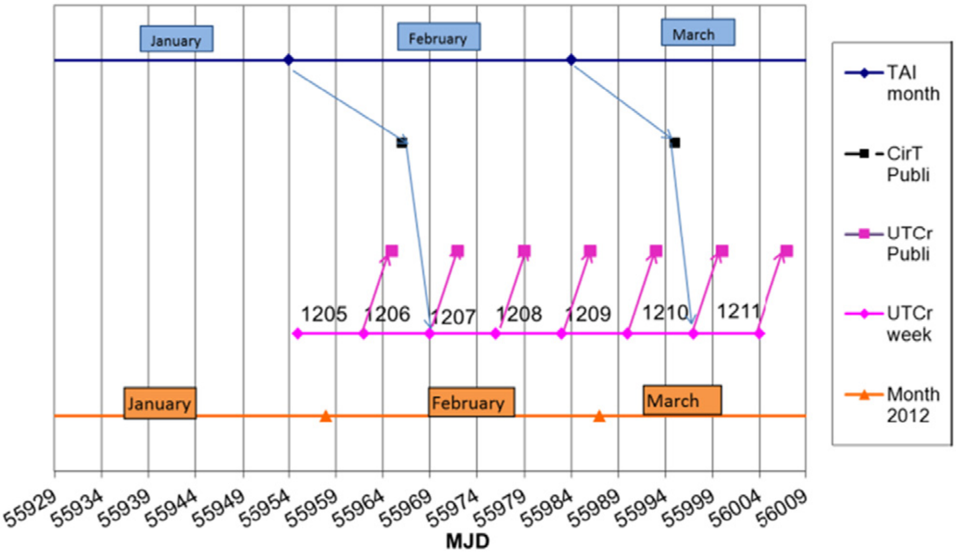

Figure 1. Sequence of events for the computation of UTC and UTCr. The second line from bottom indicates the week numbers for UTCr computation and their date of publication. The top line shows the TAI months in 2012 where the standard dates are indicated in the vertical grid. The line below indicates the date of publication of the corresponding *Circular T*, e.g. showing that the January *Circular* is available for the 1206 UTCr computation, and the February *Circular* for the 1210 UTCr computation.

Although the main characteristics have not changed, details in the realization have evolved over the early period of UTCr production. Section 3 will provide more insight into these issues and the changes that occurred.

The announcement of a pilot experiment for UTCr was sent to all UTC contributing laboratories in September 2011. By the end of November 2011, 48 laboratories representing 86% of the clock weight in UTC indicated their intention to participate by sending daily clock and time transfer files.

The regular data reports started on 1 January 2012, and the first weekly computation was carried out for the fifth week of 2012, labelled 1205 (the label YYWW identifies the WWth week of year 20YY), and was published on 27 February 2012. ‘Operational’ publication started with week 1208, published the next Wednesday on 29 February 2012, and has continued since that time. The results are published every Wednesday before 18:00 UTC on the web page ftp://tai.bipm.org/UTCr/Results/.

Interim results of the UTCr pilot experiment were presented at the 19th meeting of the CCTF in September 2012 [2]. It was decided to pursue this experimental phase until a few remaining problems had been solved. In June 2013, the CCTF working group on TAI authorized the Time Department to end the pilot experiment and UTCr was declared a BIPM official product on 1 July 2013. Starting with the first such publication for week 1326 published on 3 July 2013, UTCr has also been available on the Time Department ftp server [1].

3. Input data and algorithm

The calendar of publication of UTC is monthly and follows the list of standard dates, i.e. Modified Julian Day (MJD) ending in 4 or 9, while that of UTCr is weekly and follows the civil week. This has some implications on UTCr, e.g. the definition of the computation interval and the process of steering UTCr, which must be based on an extrapolation of the observed past differences between UTC and UTCr. An illustration of the sequence of dates for UTC and UTCr may be seen in figure 1.

The elaboration of UTCr can be split into four steps, which are briefly described in the following sections.

3.1. Data reporting and checking

UTCr is based on daily data. Clock data at 0 h UTC and a complete day of time transfer data must be reported daily by contributing laboratories; in practice the data of day D must be uploaded before day D+2, 12:00 UTC. Each laboratory uses an individual account on the FTP server and should indicate to the BIPM its intention to participate in UTCr before posting data.

Due to the short delay in publication, procedures have been developed to allow the automatic treatment of data and calculation of the solution. In operational use, it is expected that no interaction should happen with laboratories for data correction.

The automatic processing is based on the name of the files and the FTP directories. Standard file naming conventions must be respected, see ftp://tai.bipm.org/UTCr/Documents/ for guidelines.

Manual handling is required only to allow the inclusion of new data in the data set. With this exception, a number of tasks are automatically carried out in the following steps:

- continuous detection of incoming files;
- automatic report of unknown file names;
- automatic checking of the data format for the known file names;
- automatic report on recognized data files (see an example in figure 2);
- automatic data reminders sent to laboratories on Tuesday 12:00 UTC.

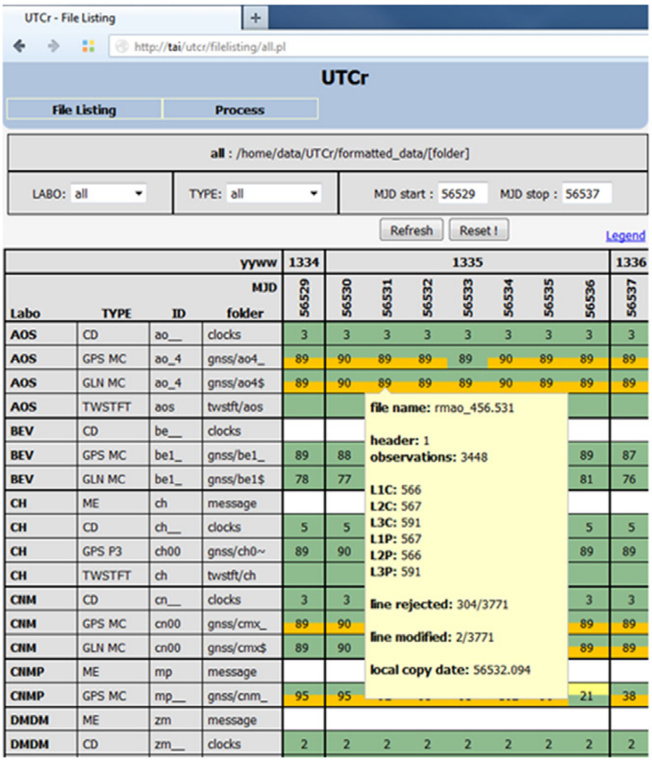

Figure 2. Example of automatic report showing the status of the recognized data files of UTCr week 1335. A pop-up window shows details on the content of one of the files.

3.2. Computation of the time links

Initially, all UTCr time links were based only on GNSS code data provided in the CGGTTS format [3]. GNSS code data are processed using the Rapid Precise Orbits and clocks products of the International GNSS Service (IGS) for GPS and of the Information-analytical Center of the Federal Space Agency (IAC) for GLONASS, and the rapid ionosphere products from the Center for Orbit Determination in Europe (CODE), all of which are available in less than one day. Procedures have been developed to allow automatic treatment, particularly where the detection and correction of possible time steps to avoid interpolation errors are concerned.

Following the CCTF meeting, in order to use a closer set of links in UTCr and UTC, we have started introducing some two-way satellite time and frequency transfer (TWSTFT) links in UTCr: starting with week 1245, two TWSTFT links were introduced in the UTCr calculation and new ones are gradually introduced to match the links used for *Circular T*, e.g. on week 1336 seven TWSTFT links are used. Comparing the time links used in UTCr and UTC (see section 6 of the *Circular T* [1] for acronyms and more details on the different types of time links), the situation is the following:

- If the UTC link is 'GPS P3', 'GPS MC', 'GPS SC' or 'GPSGLN', the UTCr link is the same as the UTC link.
- If the UTC link is 'GPSPPP', the corresponding 'GPS P3' link is used for UTCr. This should cause at most a small additional noise because the statistical uncertainty is estimated at 0.7 ns for a 'GPS P3' versus 0.3 ns for a 'GPSPPP' link. However, no systematic difference is expected because the PPP results use the P3 code as a reference.
- If the UTC link is 'TWSTFT' or 'TWGPPP', then either the TWSTFT or the corresponding 'GPS P3' link is used for UTCr. In the latter case, when large systematic differences exist between the two types, corrections are applied to maintain the differences between UTC and UTCr links below the declared u_B uncertainty reported in section 6 of *Circular T*.

A preliminary automatic calculation of UTCr links is carried out on Tuesday at 13:00 UTC in order to check possible main processing troubles and the final automatic calculation is performed on Wednesday afternoon.

Plots of computed time links are automatically generated, and for laboratories providing several techniques comparisons between the different techniques are produced, see an example in figure 3. In the case of gaps in the data, extrapolation for the standard dates at 0 h UTC is automatically calculated up to 12 h.

3.3. Stability algorithm

The stability algorithm is similar to ALGOS [4–6] used for TAI. It consists of two parts: the clock frequency prediction algorithm and the clock weighting algorithm.

The computation interval $[T, T + \tau]$ has a duration τ between 27 days and 31 days, as it starts with a 'TAI standard date' (i.e. a MJD ending in 4 or 9) and it ends with the last day of the week under computation.

The ensemble scale UTCr is

$$\mathrm{UTCr} - h_j(t) = \sum_{i=1}^{N} w_i \left[h_i'(t) - x_{i,j}(t) \right] \qquad (1)$$

where N is the number of participating clocks, w_i the relative weight of clock H_i, $h_j(t)$ is the reading of clock H_j at time t, $x_{ij} = h_j - h_i$, and $h_i'(t)$ is the prediction of the reading of clock H_i that serves to guarantee the continuity of the timescale.

The prediction algorithm is used to avoid time and frequency jumps due to different clock ensembles being used in consecutive calculation periods; in ALGOS, since August 2011, a quadratic model [7] has been used to describe the atomic clocks' behaviour so that the frequency drift of the clocks is taken into account. In UTCr, until week 1244, only a linear prediction had been implemented, which represented a marked difference with ALGOS. The quadratic prediction model has been implemented starting with week 1245, published on 14 November 2012. In this, the frequency drift of a clock is taken to be the drift value obtained for that clock in the most recently available monthly UTC computation. As specified in [7], the frequency drift is evaluated in ALGOS by using 4 months of the difference in frequency between the BIPM realization of the Terrestrial Time (TT(BIPM)) [8] and the clocks.

The goal of the weighting algorithm is to obtain a weighted average that is more stable in the long term than any of the contributing elements [9, 10]. In UTCr as in ALGOS, the weight attributed to a clock reflects its long-term stability

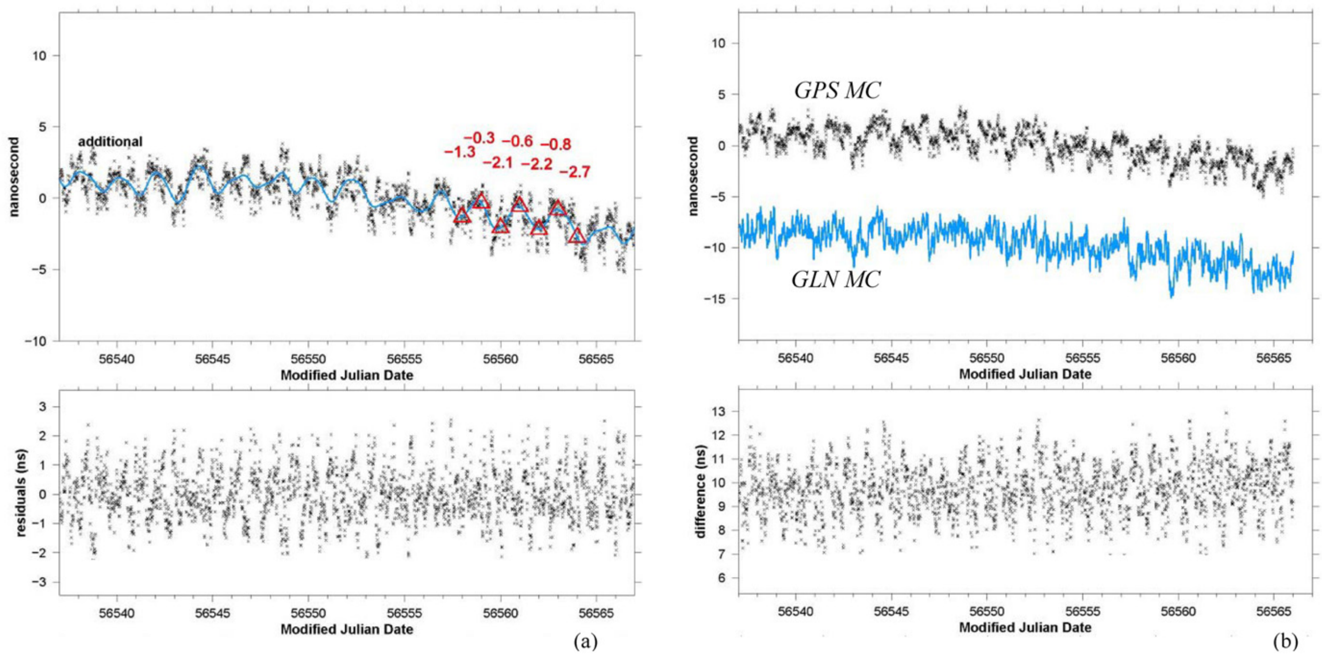

Figure 3. Example of a UTCr time link computation (a) and time link comparison (b). The top plots display the link results (a) and the two compared links (b) while the bottom plots display the residuals to a smoothing (a) and the difference of the two compared links (b), with all units in nanoseconds.

and a maximum weight is fixed to avoid clocks having a predominant role in the resulting time scale. Similar to the ALGOS algorithm, the weight attributed to a clock in UTCr is the reciprocal of the individual classical variance computed from the frequencies of the clock over the computation interval and (up to) eleven 30-day intervals preceding it. Three other rules are applied, which modify the weights obtained from the computed instability:

- if less than four past intervals are available, an *a priori* null weight is attributed to the clock;
- the maximum weight of a clock is set at $2.5/N$; where N is the number of clocks with a non-null *a priori* weight;
- a test for 'abnormal behaviour' is implemented, similar to the one in ALGOS, i.e. if the rate over the computation interval deviates from the rate over the preceding past interval by more than three times a threshold limit. This threshold is equal to the standard deviation of the available past rates of either the considered clock, or the worst clock at maximum weight, whichever is larger.

After these rules have been applied, the weights are renormalized and the procedure is iterated until convergence.

3.4. Steering to UTC

The steering of UTCr to UTC is done by replacing the past values of [UTCr − Clock] by the values [UTC − Clock] when they become available after each monthly UTC computation. This ensures that the past values of the clock data, used to compute the predictions $h_i'(t)$ in (1), never diverge between UTCr and UTC. Depending on the position of the computation interval of UTCr with respect to the last available monthly UTC computation (see figure 1), the last date t for which a value $[\mathrm{UTC} - h_i](t)$ is available may be slightly before, at or slightly after the start of the UTCr computation interval (date T). When $[\mathrm{UTC} - h_i](T)$ is not available, the value $[\mathrm{UTCr} - h_i](T)$ is used instead. In any case, this technique ensures an automatic steering in time of UTCr to UTC and has been shown to be efficient; see the next section for the quality of the realization of UTC by UTCr. The effect of this monthly steering may be seen in figure 4(b) where, each month, for the first point following the publication of the *Circular T* (these points are shown as filled squares in figure 4(b)) the value of [UTCr−UTC] is closer to zero than for the previous point.

4. Validation of UTCr and comparison with UTC

In the following sections, we report data aiming at the validation of UTCr and its comparison to UTC.

4.1. Comparison of UTCr to UTC

Our direct comparison of UTCr with UTC is a weighted average of the individual differences between UTC and UTCr for each laboratory k, computed at the date t_j as

$$D(t_j) = \sum_{k=1}^{N} W_{kj} \big([\mathrm{UTCr} - \mathrm{UTC}(k)]\,(t_j) - [\mathrm{UTC} - \mathrm{UTC}(k)]\,(t_j)\big) \quad (2)$$

where N is the total number of laboratories and W_{kj} is the total weight of the laboratory k in the UTCr calculation at the publication date t_j.

Figure 4 shows this direct comparison for 19 months (February 2012 to August 2013). In figure 4(a), two periods can be clearly distinguished, before and after November 2012

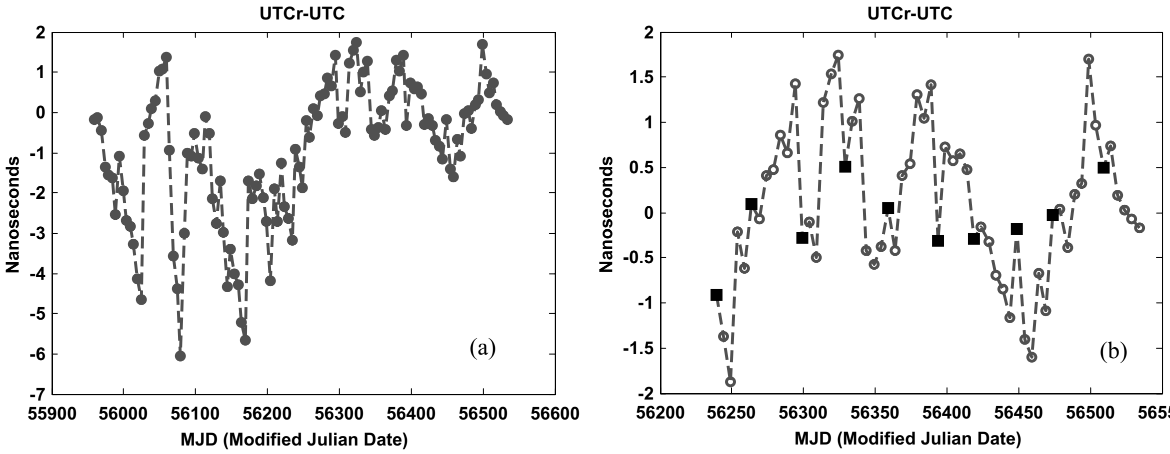

Figure 4. Comparison of UTCr to UTC: (*a*) from the beginning of the pilot experiment in February 2012 until August 2013 (19 months); (*b*) from the finalization of the procedure in November 2012 until August 2013 (10 months); in (*b*) filled squares indicate the first UTCr values immediately following a monthly UTC computation, i.e. following a steering of UTCr to UTC. See sections 3.4 and 4.1 for details.

(MJD 56239). In the first months of the pilot experiment until November 2012, a number of events happened that caused significant excursions in UTCr: the steering strategy was changed several times in the first months until the adoption in November 2012 (week 1245) of the strategy described in section 3.4; wrong data were reported for some clocks, until this eventually was discovered by comparing the clock data submitted for UTCr with those reported for UTC; however, the main cause of instability in UTCr is probably the use of a linear clock frequency prediction until week 1244. Starting November 2012, after introducing in UTCr the same quadratic prediction model as in UTC and ensuring the consistency of all clock data, the agreement between UTCr and UTC is at a level below 1 ns root mean square (RMS), see figure 4(*b*). Over the interval 56239 to 56534 UTCr−UTC remains in the interval [−1.88 ns; 1.75 ns], with a mean of 0.09 ns and a RMS of 0.83 ns.

In their goal to provide an accurate realization of UTC, several time laboratories have devised special algorithms to ensure that their UTC(k) remain close to UTC. For example, the USNO relies on a set of more than 80 clocks including four Rb fountains [11] that typically make up 25% of the total weight of UTC. In another approach, since February 2010 UTC(PTB) has been realized by steering in frequency an active hydrogen maser to a combination of the primary and commercial caesium clocks of PTB [12]. Such an approach is also pursued at the LNE-SYRTE [13] and in other laboratories. We now compare the performances achieved by the USNO and PTB in the difference [UTC − UTC(k)] with that observed for [UTC−UTCr]: over the interval 56239 to 56534, [UTC−UTC(USNO)] has a mean of 0.0 ns and an RMS of 1.8 ns and [UTC−UTC(PTB)] has a mean of 0.1 ns and an RMS of 1.7 ns. We see that, over the same interval, [UTCr−UTC] has an RMS value which is about half the RMS values of [UTC−UTC(PTB)] or [UTC−UTC(USNO)]. Therefore, the realization of UTC by UTCr is about 50% more accurate than the realizations provided by the major participating laboratories. This result is not unexpected but shows that UTCr fulfils its stated goal well.

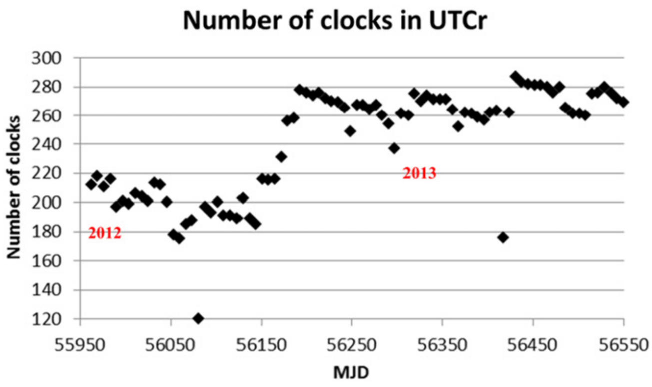

Figure 5. Number of clocks considered for weighting in UTCr for all weeks between February 2012 and August 2013.

4.2. Comparison of statistical data

The main statistical data readily available for all weeks of UTCr computation is the number of clocks considered for weighting (figure 5). It can be seen that, after the initial seven months of operation and the CCTF meeting in September 2012, the number of clocks sharply increased and has remained more or less constant since that time, to represent about 70% of the number of clocks in UTC. It may also be seen that the number of clocks can sharply vary from week to week, due to the automatic processing enforcing strict deadlines for submission. More detailed statistical data based on two different months are presented: the first set considers four weeks in February 2012, i.e. the first UTCr results. The second set considers four weeks in July 2013, i.e. the first operation of UTCr as an official product.

In February 2012 (weeks 1205 to 1208) some 32 to 36 laboratories participated in UTCr, of which 26 to 30 provided clock data (versus 69 in UTC, with 62 providing clock data) and 27 laboratories had some weight in UTCr at least once (versus 49 in UTC). In July 2013 (weeks 1327 to 1330) some 37 to 39 laboratories participated in UTCr of which 34 provided clock data (versus 72 in UTC, with 62 providing clock data) and 26 laboratories had some weight in UTCr at least once

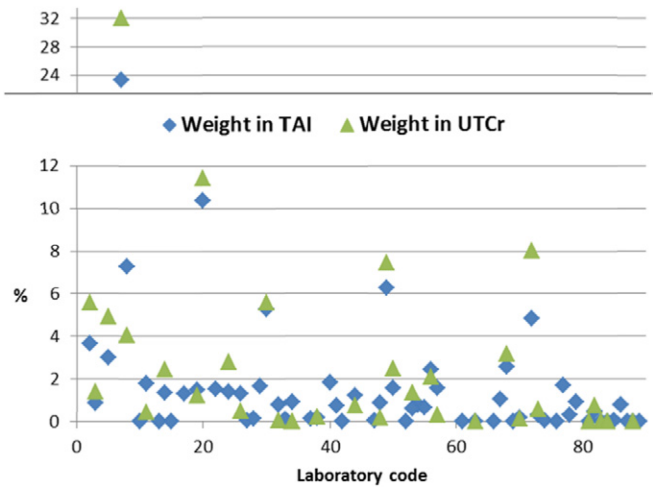

Figure 6. Average weights of the laboratories participating in the four UTCr computations in February 2012 (triangles) compared with their weight in the February 2012 UTC computation (diamonds).

(versus 48 in UTC). We see that the population of participating laboratories and clocks has been quite stable since the start of the pilot experiment with only a handful of new laboratories getting involved after the initial call for participation.

Some more detailed comparisons of the clock populations have been carried out for February 2012. We note the following:

- 32 UTC laboratories, the clocks of which represent 86% of the total UTC weight in February, participated in the four UTCr computations;
- some 60% of the total number of UTC clocks contributed data to UTCr (their total weight in the February UTC computation is lower than the 86% mentioned above, because not all UTC clocks are reported for UTCr);
- the maximum weight $w_{\max}$, which is computed with the same formula as $2.5/N$, is therefore higher in UTCr than in UTC;
- the proportion of clocks reaching $w_{\max}$ is slightly lower in UTCr than in UTC.

Looking at the weights gained by the clocks and laboratories, we see (figure 6) that many of the laboratories, which have a significant weight in both UTC and UTCr, have a larger relative weight in UTCr. This is expected because each clock has a larger weight due to the reduced number of clocks in UTCr compared with UTC. However, the variability of the weights gained by laboratories is larger in UTCr because, due to the tight schedule of computation, no effort is made to recover late or missing data. On the other hand, due to the overlapping structure of the computation, clocks which happen to miss one week in UTCr fully regain their weight as soon as the missing data are completed.

Table 1 presents some characteristics related to the weights in UTCr and in UTC over the two months considered above. We see that the one-month stability of clocks at maximum weight is quite constant and similar in UTCr and UTC. This confirms that the structure of the UTCr clock ensemble does not change significantly and is comparable to that of the UTC ensemble. The main evolution is with the number of participating clocks which then drives the number of clocks at maximum weight and correspondingly improves the stability of the timescale.

4.3. Conclusions of the comparisons

The number of clocks eligible for weighting in UTCr strongly increased until the end of September 2012, and has been maintained more or less between 260 and 280 since that time (see figure 3). We can infer that UTCr is about 20% less stable than UTC, considering that it is based on 60% to 70% of the clocks with similar characteristics. Following the procedure in [14], we estimate the one-month instability of UTC to be of order 3.5×10^{-16} over 2012 to 2013, so that the one-month instability of UTCr is of order 4.0×10^{-16}.

Considering the direct time comparison between UTCr and UTC, we have seen that the RMS difference has been well below 1 ns since November 2012. However, this conclusion does not necessarily apply when a given laboratory tries to use UTCr as a prediction of UTC; see more developments in the next section.

5. Use of UTCr as a prediction of UTC

It is to be noted that there is not a unique method to compute the difference UTCr−UTC. In section 4.1, we have used the weighted difference $D(t)$ as defined in (2). However, each laboratory k will tend to use the difference obtained through its UTC(k) as $[\mathrm{UTCr} - \mathrm{UTC}(k)](t) - [\mathrm{UTC} - \mathrm{UTC}(k)](t)$. In the case where the same link is used for laboratory k in UTCr and UTC, the two estimates should be close. But if the links are different, the two estimates may be somewhat different and users should be aware of this fact when using [UTCr−UTC(k)] as a prediction of [UTC − UTC(k)]. Obviously, there is no means to ensure that the link used for a given UTCr computation is the same as will be used for the whole month of the next UTC computation.

For most laboratories, UTCr can directly provide a realization of UTC because the average value of [UTCr − UTC(k)] − [UTC − UTC(k)], which would represent an apparent bias between UTCr and UTC, is considerably smaller than typical instabilities due to other sources. For example, over the interval of MJD 56239 to 56504, [UTCr − UTC(k)] − [UTC − UTC(k)] has an average of 0.6 ns and a standard deviation of 0.9 ns for PTB, and an average of 0.5 ns and a standard deviation of 0.9 ns for USNO. In other cases, the statistics may be different but the conclusion remains valid for the vast majority of laboratories participating in UTCr.

However, for a few laboratories, a statistically significant bias does exist and needs to be taken into account when using UTCr as a prediction of UTC. For example figure 7 displays the differences UTC−UTC(SP) (full grey line) and UTCr−UTC(SP) (dashed black line) over the interval 56239 to 56534 MJD. In this case a shift of about 4 ns is present because the time links used in UTC (TWSTFT) and in UTCr (GPSP3) are different over the period shown. This particular case has been corrected using the TWSTFT link starting with the UTCr week 1336 computation. However, with UTCr now

Table 1. Some characteristics of the clocks forming UTCr and UTC in February 2012 and July 2013.

	UTCr 1202	UTC 1202	UTCr 1307	UTC 1307
N clocks with weight	206–214	355	243–262	360
Max weight w_{max}	1.15%–1.18%	0.704%	0.89%–0.96%	0.694%
One-month stability at w_{max}	$(4.5–4.7) \times 10^{-15}$	4.8×10^{-15}	$(4.6–4.7) \times 10^{-15}$	4.8×10^{-15}
Total weight at w_{max}	31%–37%	41%	38%–44%	42%

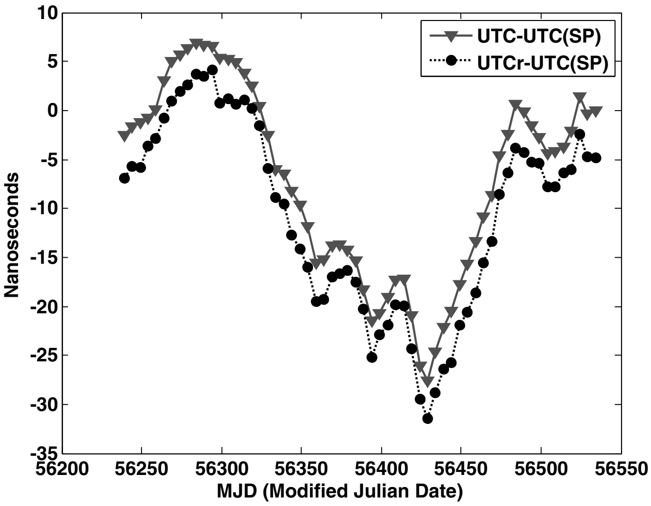

Figure 7. UTC−UTC(SP) (full grey line) and UTCr−UTC(SP) (dashed black line) over the interval 56239 to 56534 MJD.

in operational mode, such remaining differences are the most significant features that need to be addressed.

6. Conclusions

UTC contributing laboratories have been invited to participate on a voluntary basis to a pilot experiment to generate a rapid realization of UTC named UTCr. The pilot experiment started in January 2012, and produced an interim report for the 19th meeting of the Consultative Committee for Time and Frequency in September 2012. After a final report in April 2013, UTCr became an official product of the BIPM in July 2013. With UTCr, the delay of availability of the realization, and therefore the need for extrapolation, is between 3 and 9 days, a large reduction with respect to UTC for which the delay is between about 10 and 45 days.

After a period of development and experimentation in the pilot experiment, results since November 2012 have shown that it is possible to perform an automatic computation and a rapid publication of UTCr, while maintaining the metrological quality of the rapid realization, which has an RMS difference to the final UTC of less than 1 ns.

It is to be noted that UTCr is not a timescale that exists independently of UTC and might eventually replace it. Rather, in its present form, it relies on UTC in several ways, e.g. through the values of past clock rates and drift used for the stability algorithm (see section 3). Therefore, UTC continues to be calculated and published as before the advent of UTCr. However, UTC also benefits from UTCr through a shorter latency of publication due to anticipated data checking and pre-processing and possibly through a better quality of data and an early detection of problems from the contributing laboratories. It is therefore expected that UTCr enhances the benefits brought to time laboratories by the UTC international cooperation.

Acknowledgments

We thank the time laboratories for their participation in UTCr, particularly those who initiated the phase of pilot experiment in January 2012. We are grateful to the IGS, the IAC and the CODE for timely providing rapid GNSS products.

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