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Reply

Reply to Comment On: A proposal to change the leap-second adjustment to UTC

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Abstract

A previous paper by Judah Levine in Metrologia (61 055002) proposed a change to the method of maintaining the link between Coordinated Universal Time and UT1 by introducing an algorithmic adjustment process that would replace the current method that uses leap seconds. In addition to presenting the algorithmic method, the paper included a discussion of how the algorithmic adjustments could be computed and realized, and illustrated its advantages over other possible schemes. Petit and Tagliaferro submitted a comment to that paper in which they raised a number of objections to the proposal and discussed an alternate method for computing the magnitude of the periodic adjustments. This contribution replies to the issues that were raised in the comment. It raises a number of technical questions about the analysis in the comment and notes that this analysis included ad hoc assumptions and details that were not clearly justified and whose impact on the results was not clear. The reply also considers the other implications that were raised in the comment, and the reply concludes that the advantages of the algorithmic method outweigh the disadvantages and difficulties raised in the comment.

Keywords: leap seconds, UTC, UT1-UTC tolerance

1. Introduction

Coordinated Universal Time (UTC) is computed by the International Bureau of Weights and Measures (BIPM) by using data from cesium standards and hydrogen masers that are located at a world-wide network of National Metrology Institutes and Timing Laboratories. The computation of UTC involves a number of intermediate steps including the computation of International Atomic Time (TAI) and other products. The internal details of the computation are well known and are not relevant to the current discussion.

Since 1972, the UTC time scale is derived from TAI by adding integer-second time steps on an irregular basis, and the UTC time scale inherits the characteristics of TAI apart from the impact of the leap-second adjustments. These time steps, or 'leap seconds,' are inserted into UTC so that the magnitude of the difference between UTC and UT1, a time scale based on the rotation of Earth, does not exceed 0.9 s. (The link between UTC and UT1 was also maintained before 1972, but was realized by a different method before that time.)

The discontinuities in UTC that result from the insertion of leap seconds are fundamental to the leap-second process. The irregular insertion of leap seconds adds to these difficulties, since it is difficult to predict when a future leap second will be needed, and it is not easy to recognize previous leap events or to compensate for the discontinuities they produced.

Although these difficulties have been present since 1972, they have become more serious in recent times because the applications of UTC increasingly depend on a smoothly varying time scale with a well-defined frequency, while the link between UTC and UT1 is less important than it was when the leap-second system was defined. Discussions to change the method of linking UTC to UT1 have been ongoing since 1999 [1].

These difficulties were recognized by the General Conference on Weights and Measures (CGPM). The CGPM adopted Resolution 4 in 2022 [2], which states, 'that the maximum value for the difference UT1-UTC will be increased in or before 2035.' The resolution of the CGPM also requested, 'that the International Committee of Weights and Measures (CIPM) [3] consult with the International Telecommunication Union (ITU) and other organizations that may be affected by the decision in order to propose a new maximum value for the difference UT1-UTC that will ensure the continuity of UTC for at least a century.' At the meeting of the World Radiocommunication Conference in 2023, WRC-23 resolved that the Radiocommunication sector of ITU (ITU-R) collaborate with the BIPM to define a new maximum value for the difference between UT1 and UTC, and that the maximum value should not be less than 100 s [4]. Both of these resolutions implicitly assume that a link between UTC and UT1 should be maintained in some form, and implicitly reject a solution that would completely remove such a link. Neither resolution addresses the questions of what will happen when new maximum tolerance is reached and how (or if) a link will be maintained between UT1 and UTC after a century has elapsed.

A previous paper by the author [5] ('The Paper') proposed an algorithmic method to realize the decision of the CGPM. The Paper also discussed an example for how the algorithm could be realized. It evaluated the strengths and limitations of the algorithm by applying it to a prediction of the evolution of UT1-UTC in cases where the actual evolution was known from other data. Petit and Tagliaferro [6] commented on The Paper, and this is a reply to that comment.

2. The proposal

There are three components to the method proposed in The Paper, and the following text provides a reply to the corresponding text in the comment.

a. The algorithmic adjustment process

The Paper proposes that the irregular adjustment process currently used for maintaining the link between UT1 and UTC be replaced by an algorithmic process. The algorithmic process would make fixed adjustments at fixed times. The magnitude of the adjustment and the times at which it would be applied would be pre-defined and would remain constant for a century.

The magnitude of the total adjustment for the next century would be evaluated every 100 years based on the actual evolution of UT1-UTC over the previous century and could be adjusted to amortize the value of UT1-UTC remaining from previous adjustments. The predicted evolution of UT1 would be realized by periodic adjustments of a fraction of the total prediction. For example, 10% of the estimated evolution would be applied every 10 years. The adjustment magnitude also might be modified to incorporate an improvement in the understanding of the geophysical effects that drive the evolution of UT1-UTC. Although the magnitude of the periodic adjustments might be changed once per century, the basic principle of periodic adjustments would not be modified. The time of the periodic adjustments would be chosen to minimize the impact on the user community as much as possible.

The maximum tolerance of UT1-UTC would be chosen to be large enough to absorb the irregular and unpredictable deviations of the evolution of UT1-UTC from the value used in the algorithm, and the decision might include insights from simulations. The exact value of maximum tolerance would not be important, and it would not have any direct influence on the parameters of the algorithm.

The algorithmic adjustment process is the central proposal in The Paper. The rest of the text explains how the algorithm could be realized in practice, but the details of the implementation are significant only if the algorithmic adjustment process is accepted *in principle*.

The authors of the comment raise a number of objections to the proposal. They suggest that users who need accurate values of UT1-UTC would not be satisfied by this proposal, and it is not clear to the authors of the comment that the proposal would benefit anyone. The first part of this comment is true now and is likely to be true no matter what adjustment process is adopted. This class of users currently get the accurate values of UT1-UTC from Bulletin A, which is published by the International Earth Rotation and Reference Systems Service [7] or from another equivalent source. The second part of the comment is more problematic. The problems that would affect users of UTC by any change in the method of linking UTC to UT1 have been at the center of the discussions for 25+ years, and it is largely because of these problems that the link between UTC and UT1 has not been modified during this period. Given that a link between UTC and UT1 is to be maintained in some form, the algorithmic adjustment proposal is designed to ameliorate the inevitable difficulties with maintaining the link. Asserting that these difficulties are not important or are small enough to be ignored is too narrow and ignores the complexity of 25+ years of discussions. There are strong advocates for changing the leap-second system, but there have been and continue to be equally strong and continuing opposition. The algorithmic proposal could be considered a compromise between these two opposing positions.

A second objection notes if the maximum tolerance between UT1 and UTC were set to 100 s then it is likely that the magnitude of the difference UT1-UTC would remain less than this maximum tolerance for at least one century even if no further adjustments were made to UTC. The authors then invoke Occam's razor to argue that no adjustment is preferred because it is simpler than the algorithmic adjustment or any other adjustment method. A more complete invocation of Occam's razor would be to compare the algorithmic-adjustment proposal with the alternative, which would be of the form, 'Do nothing until the magnitude of the difference between UT1 and UTC reaches some maximum tolerance, *X* seconds, **and then apply an adjustment to UTC of type *Y*.'** Furthermore, do not consider the impact of the magnitudes of

X or *Y* on the user community. This comparison is very difficult because the alternative proposal has not been completely specified and because it is not clear how to evaluate the impact of an adjustment that may happen many years from now.

The impact of the adjustment might be minimized by increasing the maximum tolerance, *X*. The need for an adjustment could be pushed arbitrarily far into the future, and there is no clear distinction between a very large tolerance and completely removing the link between UTC and UT1. Although increasing the maximum tolerance increases the interval between adjustments, it also increases the impact of an adjustment when it eventually became necessary. It would also increase the impact on the user community of the increase in UT1-UTC before the maximum tolerance was reached. It is not necessarily a better solution. There is an advantage to discussing the problem now when there is no pressure to reach a solution in a short time. It is not appropriate to ignore these problems because they are difficult to quantify. The lengthy and ongoing contemporary discussions on how to modify the link between UTC and UT1 are a direct result of the decision in 1972 not to consider the obvious problems with the leap second adjustment process. The current lengthy discussions might not be needed now if a more appropriate method of linking UTC to UT1 had been devised in 1972, and it would be better not to make this mistake again.

The authors of the comment are concerned that the algorithmic adjustment process is too complicated and will discourage the user community from using UTC. The concern over the decreasing use of UTC is important, but this outcome is largely driven by the widespread use of timing data derived from the system timescale of Global Navigation Satellites. There is no easily available alternative source of accurate time and frequency data for many users. The system-time data transmitted by these satellites is often considered adequate for many purposes and for satisfying many regulatory requirements [8, 9]. The proposed algorithmic adjustment to UTC certainly adds complication, but it is not the dominant reason for the decreasing use of UTC, which is driven by the widespread availability of GNSS signals, and would probably continue no matter what changes were made to UTC or even if the link to UT1 were completely removed. See section 3 in [1].

The algorithmic adjustment process also addresses the problem that leap seconds are inserted at irregular and unpredictable times, so that it is impossible to design clocks to include future events, and that the process of inserting leap seconds is prone to errors even after the method has been in use for 50+ years. Increasing the interval between adjustments could make this problem worse. If the adjustment process were applied only once every 100 years, the adjustment process would almost never be tested in the professional life of a clock designer. This problem is at the root of the current concern about the possible need for a negative leap second.

b. The method of adjusting UTC

The Paper proposes a periodic, digitally-defined frequency adjustment to UTC to realize the predicted evolution of UT1 over 100 years. Each periodic adjustment would be a fixed fraction of the total prediction. (For example, 10% of the total every 10 years.) The rate of advance of UTC is adjusted by exactly a factor of 2, and the adjustment is always scheduled to begin at the same time. The Paper suggests starting the periodic adjustments at 12 UTC on 1 January, which is chosen to minimize the impact of the adjustments because it is closest to a universal holiday in all time zones. The duration of the periodic adjustment will be determined based on the predicted evolution of UT1-UTC, and will remain constant for a century. The exact duration of the adjustment is always a frequency adjustment and never a time step. A typical adjustment might take about 10 s. It is similar in concept to the 'frequency smear' technique [10] used by Google; many other similar, but mutually incompatible, adjustments are used by others [11, 12].

The proposal in The Paper recognizes the short-term advantage (in the immediate vicinity of the adjustment) of using a frequency adjustment compared to the current method (or any other proposal) that would realize the adjustment by the use of a time step, which is an instantaneous or nearly instantaneous change to the time with no change to the frequency. (All adjustment processes will look the same when viewed with sufficiently low resolution or over a sufficiently long time-span.) It proposes to replace the incompatible frequency smears with a universal adjustment that is digitally defined and can be removed if necessary. It always occurs at the same time with a duration that is constant for a century so that it would not be difficult to remove the adjustment from historical data without the need for look-up tables or other external data.

c. Determining the magnitude of the adjustment process

The largest part of the comment is devoted to this discussion. The significant difference between the estimate in the comment and the estimate in The Paper is that the comment makes extensive use of simulations while the paper does not. The results of the simulation are interesting, but the relevance to the proposal in The Paper is more difficult to evaluate.

A simulation of the evolution of UT1 over 2700 years might be interesting and useful, although it cannot include the irregular and unpredictable variations in the evolution that can persist for decades. It has no connection to the proposal in The Paper, which is based on a prediction only a century into the future. The method proposed in The Paper is based on a re-evaluation of the magnitude of the adjustment every century, and this re-evaluation would predict the evolution of UT1 for the century in the future based on the *actual* evolution (**not the simulated evolution**) over the previous period. If necessary, the adjustment for the next century would include an additional contribution to amortize the difference between the predicted evolution over the previous period and the actual evolution.

The *actual* evolution of UT1 for the century after the algorithmic method is adopted will not be known for 100 years, so that the algorithmic proposal cannot and does not make any attempt to predict what will happen when the magnitude of the adjustment is reconsidered after the process has been operating for 100 years. This re-consideration would also recognize any improvements in our understanding of the processes that drive the variation in the length of the day. The periodic re-evaluation of the magnitude of the adjustment provides a natural framework for incorporating an increase in the accuracy of the predictions of the evolution of UT1. This is a fundamental difference between the discussion in The Paper and the method in the comment.

The results of a simulation can be no better than the input parameters that it is based on. The authors model the evolution between 1820 and 2024 as a 'clear' random walk of frequency, but note that, '… at longer time span such noise would yield variations significantly larger than those observed ….' The authors of the comment remedy this divergence at longer periods by introducing an ad hoc statistical model that treats the data as a combination of flicker and random-walk processes for different averaging times. This solution is introduced without any quantitative justification, and it is difficult to estimate the dependence of the results on this assumption. The confidence of the reader in the usefulness of this assumption might have been increased if the authors had included a study of the sensitivity of the solution to the details of the chosen statistical model. This study is lacking so that it is difficult to evaluate the accuracy of the simulations.

In spite of these issues, the results of the simulation displayed in figure 5 in the comment are useful in providing estimates of the simulated prediction only one century in the future. The median of the prediction error over one century in figure 5 is about 100 (+100 −50) s, and the limits in the parentheses are maximum and not RMS values. Although the method of analysis in The Paper is very different, the conclusions are similar: 'The differences in the different predictions of the evolution of UT1-UTC over a century are of order tens of seconds,' and, 'In the two centuries from 1820 to 2020, the algorithmic method would have made a total adjustment of 100 s, about 31 s more than the actual evolution of the difference between UT1 and UTC ….'

Instead of using simulations, The Paper evaluated the proposed adjustment algorithm by applying the same algorithm that is proposed for estimating the future evolution of UT1 to previous intervals where the value of UT1 at the end-points was known from other sources. This is a significant advantage over the method of simulations, which can provide estimates of stability or reproducibility, but not accuracy. The accuracy of a simulation depends on the assumption that the model used in the simulation is stationary, and this is not the case for the evolution of UT1-UTC, which exhibits unmodeled departures from the long-term variation that persist for decades. On the other hand, the algorithmic method proposed in The Paper can be tested over only a relatively small number of intervals where the evolution of UT1 is even approximately known from an independent source.

A difficulty with the method used in The Paper is that there is a wide variation in the estimates of the evolution of the length of the day, and the evolution of UT1 is driven by the square of this parameter. As was mentioned in the previous paragraph, the differences among the different predictions of the evolution of UT1 are of order tens of seconds over a century, and this dispersion is small compared to a maximum tolerance of order 100 s.

The authors of the comment attempt to reproduce the algorithmic method in The Paper, but there are differences in the two implementations, and it is difficult to estimate the importance of these differences.

The method described in The Paper is based on a quadratic evolution of UT1—UTC from an origin year that is fixed and is chosen because the length of the day was 86 400 s at that point. The linear evolution in the length of the day produces a quadratic evolution in UT1. The authors of the comment also use a quadratic evolution in the UT1 time scale, but they re-define the vertex of the parabola at the start of each prediction. The accuracy of this new vertex depends on an extrapolation from the origin year, and the uncertainty in this extrapolation affects the future evolution. The decision to re-define the vertex of the parabola is not obviously better than the method in The Paper and could be worse.

The Paper proposes adjustments at times T + 10 years, T + 20 years, …, T + 100 years. The authors of the comment use T + 5 years, T + 15 years, …, T + 95 years. Both of these methods use an adjustment every 10 years, but the method The Paper has an adjustment at T + 100 years which would provide information on the change in the magnitude of the adjustment after one century. The adjustment process in the comment does not have this coincidence, which is a fundamental aspect of the adjustment proposal.

3. Discussion

The most important contribution of The Paper is the proposal to maintain the link between UT1 and UTC by using a periodic, algorithmic process that will remain unchanged for a century. Discussions to change the method of linking UT1 to UTC have been ongoing for about 25 years, and no broad consensus on the way forward has developed in that time. This is not surprising. Contrary to the opinion expressed by the authors of the comment, there are many applications that depend directly or indirectly on maintaining a relatively close link between UT1 and UTC, and there is continuing opposition to a significant change in the method of realizing this link [13]. These considerations were too extensive to present in The Paper, and are certainly too extensive to address in this response to the comment.

Although there will certainly be some opposition to any change, there is a general consensus that the maximum tolerance between UT1 and UTC must be increased, and that a new maximum tolerance on the order of 100 s would be acceptable. A conservative extrapolation of the contemporary variation in the length of the day predicts that this maximum tolerance would not be reached for a century.

Increasing the maximum tolerance increases the interval between adjustments, but it does not address the question of what will happen when the tolerance is reached. It would be possible to delay this question to some future time about

100 years from now, but it would be better to consider the question now rather than wait until the question must be considered under time pressure. To emphasize this point, the problems with the leap-second solution of 1972 resulted from the irregular and unpredictable interval between adjustments and from the decision to define the time of a leap second as 23:59:60, which could not be represented by most clocks. These deficiencies were fundamental to the adjustment process from the very beginning, and they did not vanish in 1972 just because they were not addressed at that time. A more careful definition of the method of adjusting UTC in 1972 could have saved a lot of time and effort now. We should not repeat this mistake.

It is difficult to conceive of a 'painless' process that would adjust UTC by 100 s, and the very long interval between adjustments would make the process prone to errors because almost no one would have an opportunity to develop and test the adjustment process in a professional lifetime. (The concern about a possible negative leap second is an example of this problem.) The periodic algorithmic adjustment proposal addresses this concern.

4. Conclusion

The resolutions of the CGPM and the World Radio communications Conference to increase the maximum tolerance between UT1 and UTC does not include any discussion of the adjustment process that will be required when the tolerance is reached. The impact of this question is attenuated by the increase in the maximum tolerance, which increases the interval between adjustments. Unless the link between UT1 and UTC is removed completely, some adjustment of UTC will be needed eventually, and the advantage of increasing the interval between adjustments or by delaying an adjustment to a time arbitrarily far into the future must be balanced by the difficulty of making the large adjustment when it is finally needed. In addition, increasing the interval between adjustments increases the probability that the infrequent adjustments will not be tested and validated and will not be done correctly.

If the maximum tolerance were increased to 1 h or longer, the next adjustment would not be needed for several centuries, and this is so far in the future that postponing a decision on how to implement the adjustment is not unreasonable. This decision would push the problem from the method of making the adjustment to the impact that this large tolerance would have on the general user community. A position to completely discount this impact does not recognize the lengthy discussions over the last 25 years.

The algorithmic method proposed in The Paper maintains a link between UT1 and UTC and realizes the resolutions of the CGPM and the WRC. It completes these resolutions by defining how adjustments to UTC are to be implemented to maintain the link between the two timescales that is implicit in the recommendations. It defines a process that would replace the irregular and unpredictable method that is currently used for inserting leap seconds by a predictable periodic adjustment that can be tested and validated. It provides a natural framework for incorporating advances in our understanding of the effects that drive the variation in the length of the day.

The method of adjusting UTC would not use time steps or other time discontinuities that might eventually be needed to apply a very large adjustment. It is designed to replace the arbitrary and incompatible third-party 'smear' methods with a single method that is digitally defined and realized with the intent of making UTC a universal time scale for all applications. It is unfortunate that the authors of the comment do not take a wider view of the question and the proposed solution.

Important publisher's note

In the original paper [Reference; https://iopscience.iop.org/article/10.1088/1681-7575/ad6266], the author proposes a method of frequency steering—a topic not addressed in the accompanying Comment and Reply exchange. During the review process, the Editorial Office became aware of a Liaison Statement issued by the IEEE Precise Network Clock Synchronization (1588) Working Group, available on their public website. The link below is offered to our readers for a broader perspective on the organizational and technical challenges related to changes of implementing UTC.

Editorial disclaimer

This Liaison Statement reflects the views of the IEEE 1588 Working Group. The journal and publisher remain neutral with respect to its content.

Reference: IEEE Precise Network Clock Synchronization working group Liaison Letter to BIPM, 2 April 2025 IEEE 1588 Working Group Documents, (available at: https://sagroups.ieee.org/1588/public-documents/, accessed 8 May 2025).

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