

## FUTURE OPTIONS FOR CIVIL TIMEKEEPING: UTC AND THE ALTERNATIVES

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The 2012 Radiocommunication Assembly and World Radiocommunication Conference of the International Telecommunication Union recommended further studies concerning the future of UTC. Issues regarding UTC definition are not restricted to telecommunication, but have broad impacts scientifically, publicly, and legally. In response, various requirements, options, and issues are summarized, with one approach appearing to meet requirements and having consistency with current practices. This approach would officially sanction an atomic time scale with a constant offset from TAI, without leap seconds, for the users who require such a time scale, leaving the current definition of UTC unaltered. The additional scale might be realized by transmissions or services distinct from UTC, but it would be best realized as an encoded correction to UTC as currently defined. This latter approach is already recommended by ITU-R Recommendation TF.460-6.

### INTRODUCTION

*Mean solar time* is the form of astronomical time that keeps pace with solar time-of-day over the very long term. Conceptually, its rate equals the rotation rate of the Earth (one cycle per sidereal day) minus the mean motion of the Sun (once cycle per year), where cycles are measured from the vernal-equinox direction.<sup>1</sup> Because both angular rates are nearly constant, mean solar time maintains nearly uniform hours and days, which is ideally suited to the regularity of time-keeping mechanisms. Thus, time “o’clock” and “mean time” have become synonymous.

By the late 19<sup>th</sup> century, mean solar time on the meridian of Greenwich, also known as *Greenwich mean time* (GMT), was recommended internationally for many scientific and navigational purposes.<sup>2</sup> Although “GMT” still enjoys civic and navigational usage to this day, this term has been largely supplanted with *Universal Time* (UT) in astronomical circles. Starting in 1928, the recently formed International Astronomical Union (IAU) strongly endorsed the term Universal Time to describe GMT “since midnight” for astronomical purposes, because GMT had been historically used in astronomy to describe mean time since noon.<sup>3</sup>

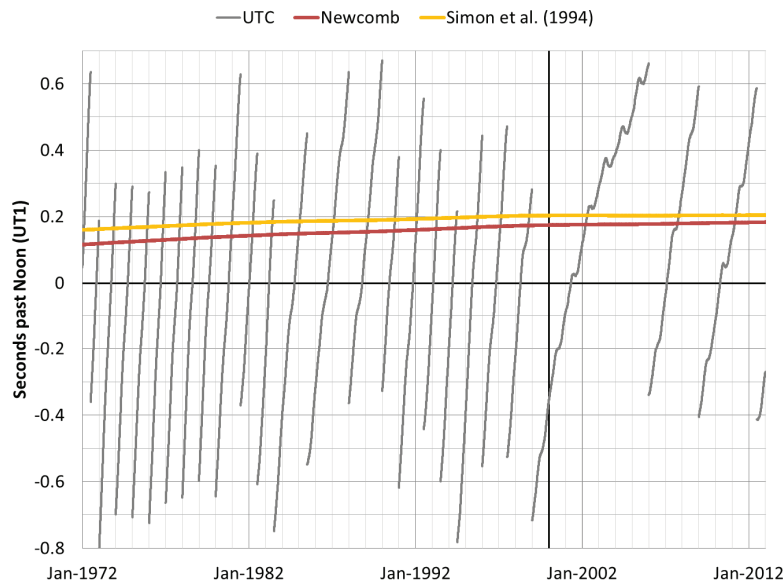
By the mid-20<sup>th</sup> century, an observed variability in Earth rotation prompted an arcane technical distinction between the original concept underlying mean solar time, and the realization which became Universal Time.<sup>4</sup> UT was the observed sidereal rotation multiplied by a scale factor,

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whereas mean solar time is a concept expressing sidereal rotation with respect to a fictitious *mean sun*. These two conventions yield slightly different results when the rotation rate of Earth is not absolutely constant. A recent study<sup>1</sup> affirmed that varying Earth rotation causes UT1 to separate from Newcomb's *c.*1895 conventional expression for the mean sun by  $1/365\frac{1}{4} \Delta T$ , or about 0.2 s since 1900.\* The supposed ephemeris error in Newcomb's mean sun is also small relative to this difference; if a more modern determination of the Earth's orbital mean motion, such as that due to Simon *et al.* (1994),<sup>5</sup> was used to re-define the mean sun, the difference would appear to be almost negligible (Figure 1).



**Figure 1. Differences between three mean solar time expressions with respect to noon UT1.**

When atomic frequency standards became available in the 1950's, slight variations in the rotation rate of Earth were precisely measured. During the 1960's, a system known as *Coordinated Universal Time* (UTC) was developed which permitted civil time to be regulated by atomic frequency standards, yet still allowed clocks to continue indicating mean time via Universal Time.<sup>6</sup> Variable broadcast frequency and fractional step adjustments were practiced globally until 1972, after which a simpler system was implemented that maintained constant frequency and used larger steps called *leap seconds*.<sup>†</sup> Over the next four decades this system was expansively adopted and employed, and endorsed by the *Conférence Générale des Poids et Mesures* (CGPM) as a basis for civil time after “considering that [...] UTC is [...] an approximation to Universal Time, (or, if one prefers, mean solar time).”<sup>7</sup> Thus, UTC has become the basis of civil time for most of the world as the atomic realization of Greenwich mean solar time.

\*  $\Delta T$  is the observed difference between UT1 and Terrestrial Time (TT), a theoretically uniform dynamical time scale having a rate of progression that is close to TAI.

<sup>†</sup> The intercalary adjustment is analogous to the introduction of February 29<sup>th</sup> into the calendar year, hence the name.

Because the wireless transmission of time signals facilitated early international coordination, responsibility for the definition of UTC fell to the Radiocommunication Sector of the International Telecommunication Union (ITU-R). Around 1999, a cause arose within ITU-R Study Group 7—the study group initially responsible for defining UTC with leap seconds—to recommend decoupling UTC from Earth rotation by ceasing future leap seconds.<sup>8</sup> This led to a formal ITU-R Study Question and the appointment of Special Rapporteur to address that Question.<sup>9,10</sup> After a dozen years, ITU-R Study Question 236/7 still remains “open” (in force), with no consensus having been reached after exhaustive debate at study-group levels.

### **WRC-12 RESOLUTION 653**

Study efforts up to 2011 are summarized in various other papers.<sup>11,12,13</sup> Since 2011, a Recommendation to suppress leap seconds advanced out of Study Group 7 without unanimity and onto the agenda of the 2012 ITU Radiocommunication Assembly (RA-12). The Assembly, representing about 190 nations, debated the matter before it deferred further consideration until 2015.\* An ITU-R press release explained that this decision had “been reached to ensure that all the technical options have been fully addressed in further studies related to the issue,” acknowledging that “suppression of the leap second [...] may have social and legal consequences.”†

#### **Calls for Additional Study**

The 2012 World Radiocommunication Conference (WRC-12) subsequently adopted Resolution 653, which drafted Agenda Item 1.14 for 2015.<sup>14</sup> This Resolution recognized “that a change in the reference time scale may have operational and therefore economic consequences,” and invited WRC-15 to “consider the feasibility of achieving a continuous reference time-scale, whether by the modification of UTC or some other method, and take appropriate action, taking into account ITU-R studies.”<sup>15</sup> The Agenda Item further invited the ITU-R “to conduct the necessary studies on the feasibility of achieving a continuous reference time scale for dissemination by radiocommunication systems” and “to study issues related to the possible implementation of a continuous reference time scale (including technical and operational factors).”

To fulfill the obligations of Agenda Item 1.14, ten international organizations were to be notified (a list which did not include any stakeholder organizations devoted to software development or the transmission of atomic time by means other than radio). Subsequently, the Russian Federation drafted a study outline requesting, among other things, that Study Group 7 consider and provide relevant information on the societal implications of keeping or removing the leap second, the organizational issues resulting from the introduction of a continuous reference time scale, the possibility and implications of using other technical options (such as a leap-minute adjustment), and the time table required for bringing a new reference time-scale into use.<sup>16</sup>

#### **A ‘Continuous’ Reference Time-Scale**

Resolution 653 specifically calls for study on achieving or implementing a “continuous” reference time scale. Unfortunately, use of the descriptor “continuous” within the context of Resolution 653 is imprecise, other than to suggest something different than UTC as currently defined. Outside of Resolution 653, the adjective *continuous* has been used to imply “without leap seconds” in literature as far back as 1999.<sup>8,17</sup> Notably, Nelson *et al.* (2001)<sup>18</sup> use “continuous” to suggest both an uninterrupted scale (*e.g.*, “...once continuous atomic time became estab-

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\* <http://www.youtube.com/watch?v=C-2UqYW9SEs>

† [http://www.itu.int/net/pressoffice/press\\_releases/2012/03.aspx](http://www.itu.int/net/pressoffice/press_releases/2012/03.aspx)

lished...”, and “...disruptions to continuous service...”), and a scale without intercalary adjustments (e.g., “continuous, atomic time scale without steps”). Lately, this latter use has been declared to imply *mathematical continuity*,<sup>19</sup> however, such continuity cannot apply to a representation of time of day which rolls over at midnight—just as the conventional representation of angle is not continuous when it exceeds  $2\pi$  by  $\varepsilon$  and returns to  $\varepsilon$  instead of  $2\pi + \varepsilon$ .

Guinot (2011) uses “discontinuous” to refer to the duplication of time stamps:<sup>20</sup>

...we mention one fact (not a judgment): UTC is not a time scale on account of its discontinuities. In particular, [...] two different events separated by one second receive the same date when a positive leap second occurs.

However, UTC as defined by ITU-R TF.460 does not employ or advocate duplicate time stamping, and it does not have “steps” *per se*, so the application of the word “discontinuous” in these senses seemingly applies only to non-standard realizations which are, arguably, not UTC. Furthermore, because UTC as defined via TF.460 is a continuous progression of seconds of equal length, the primary dictionary definition of the word *continuous* (e.g., “parts in immediate connection; uninterrupted”) seems appropriate.

Hence, the terms “discontinuous” and “continuous” invite confusion by failing to adequately describe the problem space and the requirements to be addressed by a reference time-scale from which constant frequency is desired. From the context of historical use and recent use within WRC-12 Resolution 653, the terms “discontinuous” and “continuous” are better replaced by the terms “intercalated” and “unintercalated”, respectively.

## EXPLORATION OF CIVIL TIMEKEEPING REQUIREMENTS

The term “requirement” has different meanings to different audiences,<sup>21</sup> but at the very least, a “requirement” is something *required*, e.g., it is a rudimentary characteristic that, once discovered, must be addressed.<sup>22</sup>

Historically, new time scales have been employed as new timekeeping requirements were discovered. For example, there is now a family of dynamical time scales (TCB, TCG, TT, and TDB) compatible with general relativity to meet the needs of precision ephemerides.<sup>23</sup> International Atomic Time (TAI) is an unintercalated scale estimated from the global output of atomic clocks to serve as a precise background reference. There are also time scales based on the rotation of the Earth: UT0, UT1, and UT2 have varying degrees of uniformity and correction which differ at the level of milliseconds, while UTC is based on TAI and adjusted as necessary to stay within  $\pm 0.9$  s of UT1.

### Availability of Constant Frequency and Time Interval

UTC with leap seconds was spawned from an apparent requirement to provide constant frequency and convenient access to the unit of duration of the *Système international* (SI). Communication systems with bandwidth restrictions and air-traffic collision avoidance systems of the 1970’s needed an unwavering frequency spectrum.<sup>24</sup> Before this, variable (“rubber” or “elastic”) broadcast seconds were convertible to a more uniform scale only through small frequency scale factors and step corrections, a process that was inconvenient and opaque.

### Synchronization with Mean Solar Time

The duration of the second (SI) was closely calibrated against the mean solar second determined from astronomical observations of the 18<sup>th</sup> and 19<sup>th</sup> centuries;<sup>25</sup> thus, the second (SI) emulates the mean-solar second both in its name and in its duration. To a degree, this emulation masks a requirement for the synchronization of clock time with the solar day.

To prove that synchronization with mean solar time is a fundamental requirement of timekeeping, one only needs to imagine if the second (SI) was *not* accurately calibrated against the mean solar second.<sup>22</sup> If a mere 0.002% difference\* existed in the specification of the second (SI), 86400 s (SI) would be about 1.7 s different from the mean solar day. To then keep clocks correlated with mean solar time, a leap minute would be needed about once per month, or a leap hour about every 5 ½ years. No responsible timekeeping professional would argue that such a rate difference from solar time is acceptable. Thus, clock synchronization with mean solar time is an unquestionable requirement; the debatable aspect is the level of tolerance between the two.

Technical applications deriving astronomical time from civil clocks have historically driven the designated tolerance between UTC and Universal Time, such that, if the current tolerance was to change, the extent of adverse operational impact is unclear, and it is also unclear where a new threshold should be established.<sup>12</sup> Restricting long-standing global access to Earth orientation via clock time would seemingly penalize applications that are already technologically disadvantaged, and no single organization is well positioned to gauge their current extent and scope—particularly the ITU-R.

### Access to Earth Rotation

While the practice of celestial navigation has diminished substantially in recent years due to the general availability of Global Navigation Satellite Systems (GNSS), astronomical methods are still required as a backup to GNSS and other navigational aids. For example, U.S. Navy regulations require daily checking of directional gyrocompass errors by celestial means when navigating across open ocean.<sup>†</sup> Historically, systems have been able to maintain Universal Time by consulting time signals, or have otherwise assumed that data were tagged according to Universal Time from well-maintained clocks. Some systems have operational features designed around the long-standing UTC standard and the bounded nature of  $|UT1-UTC|$ , to accommodate situations where separate Earth-orientation parameters (EoPs) may not be available. This includes systems that may be network-isolated for security reasons.<sup>26</sup> Regardless of the fate of UTC and civil timekeeping, a requirement exists to globally distribute Universal Time as a measure of the rotation of the Earth for the purposes of celestial navigation, spacecraft tracking, and the astronomical pointing of telescopes, star-trackers, solar panels, antennae, *etc.*

Proposals regarding UTC redefinition have not clearly addressed passive UT1 accessibility, deferring that responsibility to the International Earth Rotation and Reference System Service (IERS). IERS methods for predicting UT1, and hence the timing of intercalary adjustments, are improving, such that leap seconds can be predicted a year or more in advance to a high level of probability.<sup>27</sup> However, while the IERS is responsible for estimating, publishing, and forecasting UT1 and leap seconds, the IERS is not a global telecommunication entity liable for the passive broadcast of timing corrections. If UTC no longer sufficed as an operational proxy for UT1, there may be greater demand for distribution of UT1 by means other than text files shared over computer networks, as is the common practice today.<sup>28</sup>

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\* Consider that Gregorian-calendar reform changed the mean length of the calendar year by 0.002%, from 365.25 days to 365.2425 days.

† U.S. Department of Defense, Navy (2010), “Surface Ship Navigation Department Organization and Regulations Manual.” p. 3-16 (URL: [https://www.netc.navy.mil/cen-ters/swos/\\_documents/NAVY+NAVDORM.pdf](https://www.netc.navy.mil/cen-ters/swos/_documents/NAVY+NAVDORM.pdf))

## Software and Hardware Support for Existing and Future Systems

If ITU-R usage of the word “continuous” can be accurately interpreted as “unintercalated”, then it clarifies that the ITU-R requires the distribution of an international reference time scale for which there are no intercalary adjustments. This specification is most likely justified by some lack of support or compatibility with existing hardware or software, such as an inability to represent and/or receive notice of an adjustment. The implicit requirement is that the time scale must be representable on pre-existing equipment.

However, any general requirement to operate on existing systems both supports, and argues against, the abandonment of an intercalated reference scale. Almost all applications which do not support intercalary adjustments came into existence after 1972; hence, these systems were developed out of ignorance of leap seconds, or by lacking a need to conform to ITU-R Recommendation TF.460. There also exists software and hardware that dutifully conform to TF.460, which might require reprogramming or replacement if UTC is redefined; such dependencies may not be apparent to users in some cases.

On the other hand, there is software and hardware that does not consider the existence of leap seconds, and special effort is sometimes required to introduce a leap second into the indicated time. For determining time of day (*hh:mm:ss*) from a continuous sequence of seconds (SI), the dates where leap seconds exist, both in the past and near future, must be known. The display of a leap second as “60” according to TF.460 is not traditional, yet some standards stipulate the use of UTC without allowing more than sixty seconds per minute (*e.g.*, POSIX).<sup>29</sup>

Regarding future hardware and software support, one must ask whether changes to the definition of an existing time scale is expected to simplify or complicate time-scale usage. Altering definitions now may simplify some applications, while complicating others now and in the future. Because past intercalary adjustments cannot be undone, they must be supported by software and hardware indefinitely regardless of when and how future adjustments happen.

### Accessibility

Time signals must be accessible from national time services to sufficient accuracy, where sufficiency will be dictated by the application. Continuing developments in precise frequency standards will make much more accurate time scales possible, resulting in a more precise definition of the second (SI) and the potential need for new protocols to accurately distribute atomic time of the future. Thus, emerging requirements may force future reconsideration of transmission specifications such as Recommendation TF.460 regardless. Short-wave and long-wave radio broadcasts, regulated by TF.460-6, already lack sufficient accuracy for many critical endeavors. Higher accuracies may be obtained from GPS time servers, but GPS maintains its own internal system time and, thus, redefinition or supplementation of UTC offers few benefits to precision time received via GPS.

### Terminological Integrity

The historical promotion of the term “UT” over “GMT” for astronomical purposes evidences the requirement for the terminological integrity of time scales. If Coordinated Universal Time was redefined to no longer track Universal Time, a new name would be required to avoid the confusion caused by having two fundamentally different time scales—one intercalated, and one unintercalated—sharing the same name.<sup>30</sup> Likewise, the term TAI should probably be reserved for the continuation of the historical background scale of the International Bureau of Weights and Measures (BIPM), although there is already some movement to retire the label “TAI” if the label “UTC” is retained for an unintercalated scale. Specifically, the Consultative Committee for Time and Frequency (CCTF), which advises the BIPM and CGPM, announced that it “would consider

discussing the possibility of suppressing TAI,” if UTC was redefined without leap seconds, “as it would remain parallel to the continuous [unintercalated] UTC.”<sup>31</sup>

### **Conformity to Public Perceptions**

A long-standing rationalization exists amongst specialists that an “everyday user” must have limited concern over the degree to which a clock should correspond with the orientation of the Earth and sky.<sup>32</sup> This is because static offsets caused by zone times and summer-time adjustments, and the *equation of time* (the cyclic difference between mean solar time and apparent solar time), already introduce noticeable deviations between 12:00 o’clock and apparent solar noon. Such rationalizations fail to acknowledge that time zones, daylight-saving time, *etc.*, do not deviate secularly from solar time, and are employed because a single, global time is inadequate for local purposes. Locals seek to correlate local clock time with daylight hours, and otherwise resist methods of timekeeping which are perceived as “artificial” or foreign. China is sometimes exemplified of human tolerance and indifference to large deviations in the indicated time, because the mean solar time of China’s isolated western border is three (3) hours earlier than Beijing Time (UTC + 8<sup>h</sup>) nationally decreed for official use. Yet, “Ürümqi Time” (named for the largest city in western China), also known as “Xinjiang Time” (UTC + 6<sup>h</sup>), is culturally maintained to within an hour of mean solar time by the Uighur inhabitants of western China.<sup>33,34</sup>

If intercalary adjustments were eliminated from the reference scale, it has been suggested that local regions might instead alter their time-zone offsets as a summer-time adjustment “according to the wishes of citizens.”<sup>20</sup> However, the Chinese example already demonstrates that distant seats of government can thwart the local exercise of timekeeping.\* The method of implementation also appears problematic considering that a majority of people and nations do not practice daylight-saving time.<sup>35</sup> Furthermore, legislated zone re-definitions complicate maintenance of the International Dateline and would move what is now a common solar-standard for international timekeeping into far-flung decisions across different nations, states, and provinces. This would promote historical chaos as local time stamps become harder to accurately interpret over the long term.<sup>36</sup>

Thus, the decoupling of civil timekeeping and Earth rotation is not likely to go unnoticed by the “public sphere”—the sociological concept of “general public”, where individuals freely discuss and identify societal problems. A 2011 BIPM press release acknowledged there “is also the feeling that a break in the present system of synchronization of UTC to the Earth rotation will decorelate the human activities from solar time. [...] Although this is a small difference increasing very slowly we recognize that it is an important matter of principle.”<sup>37</sup> Satisfaction of public concerns over the synchronization of time-of-day and clock time is therefore a requirement in need of redress, even if this requirement for “astronomical conformity” is mainly symbolic.<sup>38</sup>

### **International Consensus and Commonality**

The definition of UTC is also a legal issue as it relates to the standard time of nations. UTC is the *de facto* basis for zone times around the world,<sup>39</sup> even though many users do not understand or appreciate the details of UTC’s basis and definition. ITU-R study groups recommended continuing with the term “UTC” for an unintercalated atomic scale, partly because UTC is a named legal standard for some nations. However, other countries specify legal time as being based on mean solar time, “world time”, or Universal Time; because unintercalated UTC would no longer be related to those named legal standards, the legal impacts of a change in definition are uncertain.<sup>35</sup>

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\* China enjoyed five official time zones before a single national zone was imposed around 1950.

## **Widest Utility**

Telecommunication and time metrology are not the only technical fields affected by a redefinition of UTC: also affected are astronomy, astrodynamics, geodesy, computer sciences, engineering, meteorology, space sciences, and others. When Louis Essen introduced the idea of a leap second, he wrote:<sup>40</sup>

...time scales have always served the three quite distinct functions, of giving the time of day, the season of the year, and also a measure of time interval or duration. Any new scale must continue to serve these purposes, if it is to be of universal use and although an atomic clock can provide a very precise scale by simply counting and recording the number of seconds that have elapsed since some arbitrary zero, the time of day and the season of the year can be obtained only by astronomical measurements. It would of course be possible to use separate and independent scales of atomic and astronomical time but this possibility already seems to have been rejected, and rightly so in my view, since it would lead to confusion and duplication of effort.

Arguably, international civil time scales must then be useful over the widest possible conditions, having applicability to future users and present users of past data. Changes add penalizing complexity that must be technically supported indefinitely, because former definitions never disappear, once used.<sup>41</sup>

## **SOME NON-REQUIREMENTS**

In addition to the requirements for civil timekeeping listed above, there are long lists of desirable criteria and characteristics for scientific, business, technical, legal, and other purposes which may or may not be absolutely required.<sup>13</sup> The following highlights some characteristics which have been purported to be time-scale requirements, yet do not meet a criterion of being unquestionably necessary.

### **Single Reference Time Scale**

Although desirable, there is no true requirement for having only a single reference time scale. In practice, UTC already has many real-time national realizations and is not a single reference time scale. Indeed, definitive “TAI and UTC are not time-scales represented by clocks in real-time.”<sup>42</sup> GNSS scales are specific examples of where experts chose to broadcast an unintercalated atomic reference scale different than UTC.

Study groups initially purported the modification of UTC alone because the ITU-R recommends UTC as the sole reference time scale for radio broadcasting. However, it has not been the historic position of the ITU-R that there must be only one reference time scale. ITU-R Recommendation TF.1552 specifically recommended “that in applications requiring a uniform time scale TAI be recovered from UTC,” and TF.460-6 was amended in 2002 to include a recommendation to disseminate “DTAI” (TAI-UTC) via time signals. Only recently (2011) did ITU-R study groups suppress Recommendation TF.1552 to support a claim that “TAI is not an option for applications needing a continuous reference as it has no means of dissemination and is not physically represented by clocks.”<sup>43</sup> Resolution 653 has reaffirmed the ITU-R’s lack of a requirement for a single reference time scale by inviting consideration of “the modification of UTC or some other method,” despite professional opinions that the availability of more than one scale promotes confusion or lack of standardization.

### **Uniform Duration of Non-SI Units**

The second (SI) is the most accurate metrological unit and a basis of other standards.<sup>44</sup> However, it is not clear that non-SI units of duration used with the SI, such as the minute, hour, or day,



must always have uniform duration when used for calendrical purposes. For example, NIST Special Publication 811 notes that such non-SI units might be necessary “when time relates to calendar cycles” (which are intrinsically astronomical), and also acknowledges the *year* as a useful unit of duration with a conventional length of  $365.0 \times 86400$  seconds (SI).<sup>45</sup> However, the *tropical* (mean-solar) *year* as a natural unit is closer to 365.2424 days. Furthermore, the calendar year actually varies from 365 to 366 days. Thus, when time is specifically related to calendar cycles, there is precedent for non-SI units not maintaining fixed durations.

## EXPLORATION OF OPTIONS

The call for additional studies by WRC-12 through Resolution 653 suggests that ITU-R study efforts may have prematurely discounted a number of practical approaches. Various options related to changes in civil timekeeping on Earth have been discussed since 1999; some of these have always appeared unviable but have been maintained in discussions for completeness.<sup>17</sup> Attention to the requirements, together with the WRC-12 Resolution 653, reveals several options that should receive revived consideration. Several of these options are now reviewed.

### Retain the *Status-Quo*

This option would maintain ITU-R Recommendation TF.460-6 and its established timekeeping practices. Reasons for retaining the current definition of UTC with leap seconds include:

- A new time scale, fundamentally different than the current standard, will represent a historical discontinuity that will add operational complexity that cannot be undone, and risk confusion.
- There is an unknown amount of software and hardware based on  $|\text{UTC}-\text{UT1}|$  being less than one second. Alterations could prove difficult and expensive. For example, navigation systems operate within the current definition, and changing and testing configuration-controlled systems would be very expensive and without benefit.<sup>46</sup>
- Backup methods to GNSS will be impacted, which could result in confusion in an emergency.
- Documentation in textbooks and other literature would have to be extensively updated to recognize and explain both the old and new definitions.
- An unintercalated atomic time scale is already available via GPS.
- Public perceptions regarding the tie between civil timekeeping and celestial motions should not be ignored. The vast majority of nations, now or historically, base their national time scale on mean solar time, which UTC with leap seconds represents. If decoupled, changing back to a mean-solar-time standard would seem intolerable.
- Leap seconds gives the timekeeping community publicity it otherwise lacks.

An oft-repeated objection to the *status quo* is that the frequency of leap seconds might increase to nearly two per year in about a century; another is concern over emerging problems and thus growing dissatisfaction.<sup>47</sup> However, the established specification handles up to twelve leap seconds per year, and more frequent leap seconds would increase opportunities for testing and general awareness.<sup>12</sup>

### Increased Tolerance between UTC and UT1

Two similar options fall within this category, both of which potentially increase the duration of intercalary adjustments.

*Larger Leaps.* This option would replace leap seconds with leap minutes occurring decades apart, or leap hours separated by centuries. The reported advantage of this approach is that “it would be relatively easy to adopt”<sup>47</sup> because “it pushes the problem so far into the future that no one is worried about it.”<sup>48</sup> However, the details of how to promulgate an acceptable adjustment procedure into the distance future have never been clarified, and this ambiguity has already led to the apparent dismissal of leap hours by ITU-R study groups.<sup>49</sup> Leap minutes are also conjectured to be too infrequent to be employed successfully, addressing only aesthetics and raising more technical issues for the future than they solve now.<sup>50</sup>

*Predictable Introduction of Leap Seconds.* This option would introduce an intercalary adjustment (that is likely greater than one second) on a predictably recurring date such as February 29<sup>th</sup>. However, the possibility of introducing either zero or one second on the scheduled date still exists, just like the current practice of introducing leap seconds at the end of a month such as June and December. Thus, the primary distinction of this option from current procedures is that two or more leap seconds could be introduced and there is no existing infrastructure for this situation.

### **Cease Leaps**

This option has received the most discussion and attention to date, having been recommended from Study Group 7 without acceptance by RA-12. Entire papers are devoted to its perceived advantages and disadvantages.<sup>12</sup> Some commonly recognized reasons for redefining UTC without leap seconds include:

- Many computer systems do not correctly account for the possibility of a leap second, with software and hardware assuming that there can only be sixty (60) seconds per minute.
- The leap second may not be properly disseminated, or may not be applied on time, causing differences in the readings of timekeeping devices and the time tagging of business transactions.
- Leap seconds are generally inconvenient, as they require resources to implement and test.
- Leap seconds encourage the introduction of unintercalated scales, possibly causing confusion.

However, if leap seconds are ceased, unofficial time scales with leap seconds might be potentially established by those who need a scale like the former system aligned with UT1 for their own purposes. These scales could introduce leap seconds according to some mutually established rules for inserting future leap seconds, or they might differ in how they track UT1.

### **Cease Leaps and Rename**

This option would assign a new title to the time scale now known as UTC, and eliminate leap seconds, after a certain date, which is equivalent to retiring UTC and continuing with an unintercalated scale. This option carries the same justifications as the option to “Cease Leaps”, except that the name of the scale is altered to maintain terminological integrity. A perceived disadvantage is that a change of name would require extensive documentation changes, but a fundamental change to civil timekeeping will demand changes regardless.

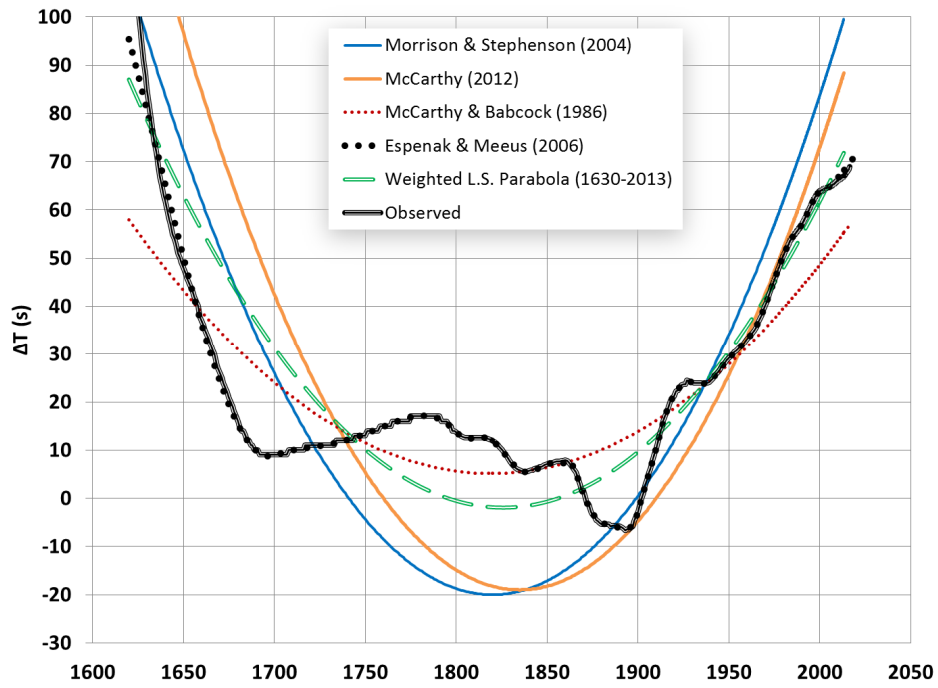


Figure 2. Past  $\Delta T$  behavior and various fits to the observations

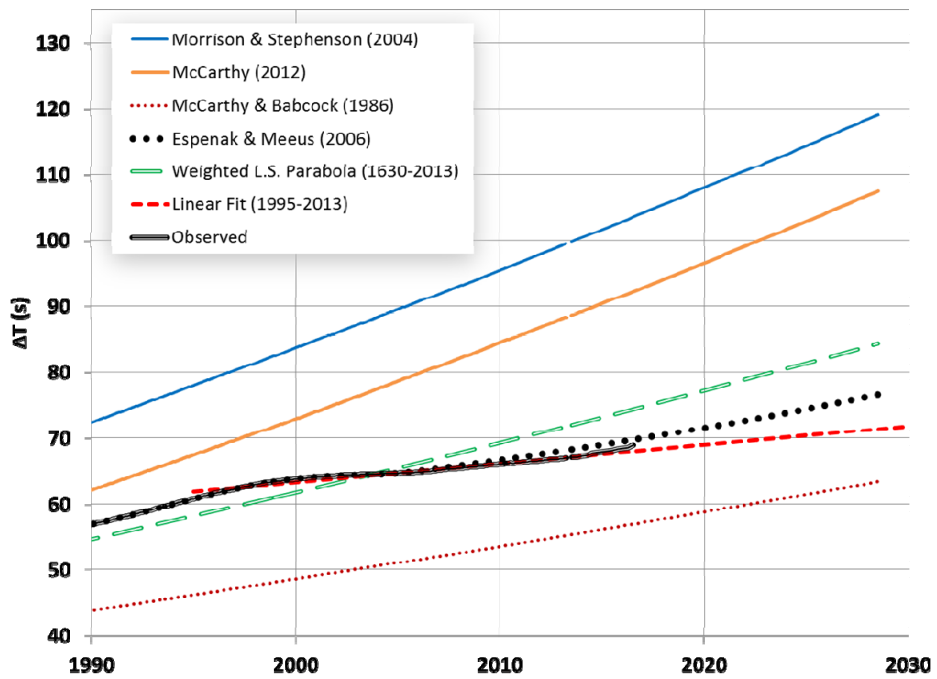


Figure 3. Projections of  $\Delta T$  into the future.

### Track Predicted Long-Term Trend

This proposal is relatively new; it would insert leap seconds into UTC according to an algorithm, rather than the observed rotation rate of Earth.<sup>51</sup> This option retains the title UTC, and employs leap seconds, to track an imaginary scale that separates parabolically from TT. However, there is some question as to what the “best” parabolic trend might be. Figure 2 recalls various fits<sup>50</sup> to historic  $\Delta T$ ; Figure 3 projects these estimates into the future, also adding a simple linear fit to  $\Delta T$  from 1995 to 2013 to emphasize the most recent trend. The wide variation of these projections indicates the significant uncertainty in predicting the frequency of intercalary adjustments.

The uncertain long term trend in Earth’s rotation rate is governed by tidal interactions between the Earth and the Moon. A trend for UT1–UTC that best fits the near term behavior should result in both large positive values and large negative values. A trend that accelerates faster has the operational advantage of keeping adjustments positive, but may result in a worse approximation of Universal Time. Perhaps of greatest technical concern is that this proposal masquerades at providing Universal Time by its name and continued use of leap seconds, but it does not represent Earth rotation at any technically useful level.

### Add Unintercalated Atomic Scale

This option would retain UTC as it is currently defined, and would officially recognize and make available an unintercalated atomic time scale additionally. This approach was recommended by the ITU-R before the campaign to cease leap seconds. However, unlike ITU-R Recommendation TF.1552 suggesting that the unintercalated scale represent TAI, the unintercalated scale could carry a different name (such as *International Time*<sup>52</sup>) and be offset from TAI by zero,  $-19$  s (the value of GNSS time\*), or some other number that avoids confusion with UTC. Reasons for adding an unintercalated atomic time scale to UTC include:

- An intercalated scale, plus an unintercalated scale, together appears to satisfy all requirements.
- It visibly establishes a recommended scale without leap seconds.
- It formalizes practices already happening, and will continue, regardless of what the ITU-R decides. For applications that do not want leap seconds, GNSS or TAI-like time scales are currently being used.

A disadvantage with the broadcast of a supplementary scale is the appearance of duplicated effort and some mild risk of confusion. Thus, for operational acceptance, it seems prudent that the unintercalated scale be accessible via a broadcast parameter that is added to (or subtracted from) UTC and which increments at each leap second, not unlike DTAI as recommended in TF.460-6.

### Clock Slewing

As a supplementary method for accommodating leap seconds in UTC, some computer scientists have suggested the controlled slowing of oscillators to add a leap second gradually over last fraction of the day.<sup>†</sup> Because this approach has already been effectually implemented (*e.g.*, by

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\* Like GPS time, the Galileo navigation system expects to maintain its time at approximately TAI–19 s, which could be referred to as the *GNSS time scale*. GPS time does not include leap seconds, but increments the difference between UTC and GPS time.

† “UTC with Smoothed Leap Seconds (UTC-SLS).” URL: <http://www.cl.cam.ac.uk/~mgk25/time/utc-sls/>

Google in 2012\*) and meets the requirement of compatibility with existing hardware and software, it probably should not be objected to, especially in low-precision applications, where the sequence of date labeling is more important than the uniformity of the scale. However, this practice does not seem viable as an international reference time scale because it does not provide invariant frequency and time interval during the slewing interval. Nevertheless, the practice would benefit from the establishment of an industry-standard slewing interval, so networked applications that expect invariant frequency could exercise caution during this interval.

### **Variable Frequency**

Variable frequency was used during the 1960's, where the rate relationship between civil time broadcasts and atomic frequency was fixed for extended periods. These slight frequency shifts could not guarantee long-term proximity to UT, such that small, fractional steps were also introduced. This approach was found to be too cumbersome for communication purposes, and is now considered obsolete.

### **Swap Scales**

This option would cease UTC and substitute another atomic time scale as the reference time scale on some date.<sup>47</sup> Unlike the option to “Cease Leaps and Rename,” this scale would not necessarily share UTC's epoch at the time of adoption. Synchronization with TAI has been proposed as a characteristic of the replacement candidate.<sup>52</sup> Nevertheless, this option is considered unviable, due to a number of practical operational disadvantages.

### **Redefine the SI Second**

This option would alter the definition of the second (SI) by increasing its duration.<sup>47</sup> This approach is unworkable considering that other physical units are now based on the second (SI); also, a redefinition would only reduce the frequency and/or size of intercalary adjustments, but not eliminate them. Natural decadal variations in the rotation rate of Earth would still cause differences in the near term, and in the long term the Earth's rotation rate is still expected to decrease.

## **OPTIONS VERSUS REQUIREMENTS**

Recognized requirements can be tabulated and compared to proposed options for time scales. Table 1 lists some of the requirements discussed, and which options appear to meet them. Of the requirements and options considered here, ceasing intercalary adjustments appears to be least satisfactory, while adding an unintercalated scale to *status-quo* UTC provides the most utility.

All potentially viable options are expected to provide general accessibility to invariant frequency. Although tracking a predicted “Long-Term Trend” promises some indication of mean solar time (less accurate than the current standard), it fails to reliably indicate Earth rotation to any technically useful level. It is also unclear to what degree the “Long-Term Trend” option will satisfy public perceptions regarding solar time or if it will meet with international consensus. Indeed, international consensus can be claimed for only two options: the *status quo*, and the *status quo* plus an unintercalated scale. This is because both options are reflected in ITU-R Recommendation TF.460-6, which is presently active. The cessation of intercalary adjustments (“Cease Leaps”) is already known to lack international consensus, per national declarations within ITU-R study groups and RA-12.

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\* “Time, technology and leaping seconds.” URL: <http://googleblog.blogspot.com/2011/09/time-technology-and-leaping-seconds.html>

**Table 1. Requirements v. Options.**

	<i>Status Quo</i>	<i>Increase  UT1-UTC </i>	<i>Cease Leaps</i>	<i>Cease Leaps &amp; Rename</i>	<i>Long-term Trend</i>	<i>Add Unintercalated Scale</i>
Constant frequency & interval	✓	✓	✓	✓	✓	✓
Synchronized w/ Mean Solar Time	✓	inaccurate			inaccurate	✓
Earth-Rotation Access	✓	inaccurate				✓
Software & Hardware Support	varies		varies	varies	limited	✓
Accessibility	✓	✓	✓	✓	✓	✓
Terminological Integrity	✓			✓		✓
Public Perceptions	✓	varies			?	✓
Int'l Consensus	✓	?			?	✓
Widest Utility						✓

Despite WRC-12 Resolution 653, consideration of the requirements and relevant options raises some question over the urgency for action. ITU-R Recommendation TF.460-6 already advocates the broadcasting of *status-quo* UTC together with the parameter  $DTAI = TAI(k) - UTC(k)$  to allow users to realize an unintercalated  $TAI(k)$ . That DTAI is not yet broadcast suggests that user demand for civil TAI-like time via radio may not be as great as Resolution 653 implies. Further evidence is the fact that the proposal for “UTC-without-leap-seconds” has languished in committee for more than a decade. In the meantime, GPS already distributes an unintercalated time scale well suited for many operational applications seeking such a scale.

**CONCLUSIONS**

Historically, new time scales have been developed as new requirements emerged. After exploring different requirements and reflecting on various options that meet those requirements, it seems logical to address WRC-12 Resolution 653 by officially recognizing a supplementary time scale without intercalary adjustments, rather than eliminating the current UTC with leap seconds. It would be appropriate for this supplementary scale to be distinctly offset from UTC to avoid confusion with UTC, just as current GNSS scales. To transmit such a scale, TF.460-6 already advocates the broadcast of a supplementary offset parameter to be added to UTC. It would also be appropriate to give this unintercalated time scale a unique name (such as *International Time*).

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## DISCUSSION CONCLUDING AAS 13-524

RUSSELL REDMAN admitted that he liked “market-based” solutions. A claim made by many people, and which probably has a substantial fraction of truth behind it, is that “a timescale without leap seconds is better than one with.” If an unadjusted atomic timescale was therefore made available as a tool to be used in parallel with UTC, and then libraries implemented them correctly—which means fixing the bugs in the current implementations of UTC— and then people were allowed to use them, we would find out which one is better because people will choose the one that works best. And then, ten years after that has been done, we will have a fair comparison: how many people used this one versus how many people used that one, and why. KEN SEIDELMANN said he would agree with that procedure and would go along with that, but SEIDELMANN also predicted during his presentation that the increased accuracies coming with clocks will require other technology changes to take place and that may well cause some unforeseen transformation to take hold ten or twenty years from now, and that is when a significant change should take place—not now.

KEVIN BIRTH said he would disagree with the logic behind REDMAN’s proposal, based on historical evidence. The town clock in Berlin in the mid-18<sup>th</sup> century had hands installed to indicate both local apparent solar time and mean time, but the residents of Berlin rebelled and insisted that the mean-time hands be removed. So, if two timekeeping options were available for ten years, BIRTH was not sure that the public would necessarily come up with the best long-term solution. SEIDELMANN suggested that we have a more sophisticated and wider audience today; BIRTH evoked jollity by rejoicing that “we are same species that we were 200 years ago.”

CHRIS TUASON wondered if navigation satellites could disseminate UT1. DENNIS MCCARTHY said that was being planned for GPS III. TUASON asked if other navigations system would disseminate UT1 as well, to which MCCARTHY replied “Yes.” However, SEIDELMANN said his point was about the case when GPS is not available in an emergency situation. JIM KIESSLING commented that it was possible to “coast through” such anomalies, providing that the appropriate timescales and tools are available. To that SEIDELMANN added that one must be appropriately prepared. KIESSLING agreed, saying that the timescale needed to maintain a tie to UT1. SEIDELMANN added that he was speaking with regard to having a backup in an emergency situation.

GEORGE KAPLAN asked about changing the name of the timescale. If leap seconds are removed from UTC and the name is changed to, say, *International Time*, that creates a situation where no country has that timescale as their legal time, and that name would not appear in interface control documents for some very complex systems. People then have to decide what timescale they are going to use, and everybody in the world is forced to make a market-based decision. Does not the possibility of mass confusion arise if one country decides to stay with UTC, or create its own version of UTC, and another one does something different? STEVE ALLEN said that is where Israel is right now, because Israel is on daylight-saving time but not *legally* on daylight-saving time, and nothing is breaking. So nothing would break in the case of a name change.

KIESSLING said that in terms of the documentation, and the legal materials, and all that work to conform to a time standard, the name change actually exposes the cost of the decision. If the name did not change, the decision cost is not exposed yet there still is a need to change the documentation to reflect a change. SEIDELMANN added that the attendees had seen lists of countries and references to their legal code; if UTC is changed then a legal question exists throughout and “lawyers could have a field day with this situation.” However, SEIDELMANN would expect countries to stay with UTC at the start, because that is available and that is what they have been doing. But if they found the alternative to be advantageous then they could initiate a legal procedure to make a change.

KAPLAN said this could result in some countries having midnight offset a different number of seconds than others, but ANDREW MAIN noted that this situation already exists at the sub-second level. SEIDELMANN said such things remain the prerogative of sovereign nations to decide, which seemed no different than managing time zones. ARNOLD ROTS noted that there are plenty of countries that do not rely on the term ‘UTC’ in their legal codes and that did not seem bothersome as a legal issue. SEIDELMANN replied that they might have ‘mean solar time’ or ‘Greenwich time’, for which UTC currently serves and is about “as close you can get.” ARNOLD ROTS added that a number of countries say ‘world time’ and that could mean anything. ALLEN thought that the time running in operational systems is the time of everyone’s concern: “as long as they keep running, it will be okay.”

BIRTH noted that there is case law and precedent for dealing with two co-existing timescales in former Commonwealth nations (British colonies). Back before the period of 1752, the New Style and Old Style calendars ran concurrently, with only the Old Style calendar being the official legal calendar. So there are nations out there that have legal precedent for dealing with this particular situation. SEIDELMANN noted the situation today for, say, China or Israel, where the Gregorian calendar is used for international purposes but cultural calendars are used internally. BIRTH agreed and acknowledged that there are actually a lot of different nations with existing case law for dealing with different ways of reckoning time, and how to reconcile them or deal with disputes having to do with time.

KAPLAN recalled that, in the United States, codified time zones were based on the mean solar time of standard meridians until 2007; with MCCARTHY’s involvement the law was changed mentioned UTC specifically. KAPLAN tried to imagine a discussion around the table within Congress about changing the legal basis to “this new timescale called *International Time*.” Then, if somebody brings up the fact that it is just an atomic scale not based on the Sun at all, the whole discussion comes back again. And then, multiply that discussion by almost every country around the world...

BIRTH thought that courts would settle the issue first, because that is what happened at the turn of the 20<sup>th</sup> century with regard to zone time versus local time. The Standard Time Act of 1918 actually came after a series of court cases that set precedents which actually defined what that law would be. So in the United States, BIRTH thought that Congress would “get to it late in the game.”

MCCARTHY did not think the issue would much involve Congress, because the United States has provisions for technical issues such as this. He could not “remember the official name of the publication but these things are published as guidance for lawyers and take precedence over any other law. And it is meant specifically for technical issues such as this which does not require an Act of Congress to handle. It can say something as simple as ‘for all intents and purposes for legal cases, courts should recognize *this* as equivalent to *that*,’ which would be the case here.” KAPLAN replied “That is fine, but who makes that decision and on what basis?” MCCARTHY thought it might be the U.S. Department of Commerce because that department deals with physi-

cal standards, and someone from NIST would be able to tell MCCARTHY the name of the document.\* Regardless, MCCARTHY had been “assured that this sort of thing exists specifically for technical issues which do not require all the lawyers in the world to be involved.”

REDMAN said that basically the same kind of system exists in Canada. The government can issue an *order in council* that instructs lawyers on how to interpret for legal purposes terms like “time on the Greenwich meridian”, GMT, and Universal Time. It does not go before Parliament, it does not require debate, it is based on the best technical advice available and it becomes the law of the land.† They do not even have to go back and revise the laws, but they can if they want. (TUASON wondered lightheartedly if this was coming from a country that does not have a written constitution; REDMAN affirmed in jest that actually Canada has a written constitution, although it is a “wimpy one”.) BIRTH said there may be nations where it is an issue but many nations have existing precedent and policies and procedures for dealing with it. This is largely because nations have gone through major time changes before. Going from local time to zone time was a *major* change for much of the world, and it was dealt with.

Considering some of the potential options raised by SEIDELMANN, KIESSLING wondered if it was “possible to think about deprecating UTC” by promulgating something like TAI and generating UTC on demand for those applications that need it. REDMAN thought it was not necessary to deprecate UTC; however, if software is going to be fixed properly, he supposed a TAI-like atomic timescale would need to be distributed. REDMAN said that most of the mess with the coding right now was due to workarounds from an early bug that was never fixed. MAIN said “there is a tendency to screw it up because most programmers are not experts on time.” Software developers are working from pre-existing programs and existing APIs that did not account for this, so it is a mess.

KIESSLING had seen a human tendency even by the expert programming community to do weird base-60 computations on something that should be a continuous counting scale, and then “they act like they have to do weird things about smoothing.” Because there was international expertise on the other side of the table on time APIs, KIESSLING posed the question: “why are you guys messing around with this base-60 stuff? Generate it on demand, but there is no reason to calculate by that.” JOHN SEAGO asked if the answer to KIESSLING’s question could be held until the general roundtable discussion to follow, so that discussion specific to SEIDELMANN’s presentation might conclude first.

MAIN noted that SEIDELMANN had raised a point about whether UTC qualifies as being ‘continuous’. MAIN thought that MCCARTHY’s presentation had “made a fairly good point by looking at mathematical definitions” but MCCARTHY’s definitions really applied to a single scalar variable and UTC timestamps are not adequately described in terms of a single scalar variable. Thus, MAIN thought that the mathematical concept of ‘continuous’ did not really apply. MAIN construed SEIDELMANN as making the point that one can get a continuous scale out of UTC by labeling the seconds differently, but that amounts to a translation to TAI. To MAIN’s comment, SEAGO interpreted SEIDELMANN as suggesting that there is more than one definition of ‘continuous’. SEAGO said a mathematical definition might lead to questions about whether calendar representations of time are continuous, or whether clock representations of time are continuous because

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\* *Editors’ Note:* MCCARTHY afterwards affirmed that the document was the *Federal Register*, the daily journal of the United States Government.

† *Editors’ Note:* The discussion concluding AAS 13-505 also contributes to the subject of Canadian orders in council in relation to UTC.

time of day rolls over from 23:59:59 to 00:00:00, and so on. But SEAGO understood SEIDELMANN as talking about the *primary* definition of ‘continuous’, namely, whether a sequence (of seconds, days, *etc.*) is interrupted or not interrupted.

TUASON said the discontinuity comes in the wave-form issue when one is constrained to use a certain set of labels and one does not have a 61<sup>st</sup> second and it becomes discontinuous. KIESSLING remarked that there were handling issues at the 61<sup>st</sup> second simply because of the choices made. SEAGO noted that behavior “would not be UTC as it is currently defined.” KIESSLING added “...but that is not UTC’s problem. The problem is how people are choosing to interpret it. The definition of UTC explicitly states the handling for the leap second and the software people choose not to deal with it literally.”

MAIN said that is not the issue being dealt with here. The problem here is if one takes the sexagesimal notation and a timescale such as TAI or UT1, one can take the sexagesimal parts and put them together mathematically into a single real value that increases in a continuous manner at an essentially constant rate. (SEIDELMANN clarified that technically, UT1 does not have a constant rate, to which MAIN agreed and apologized.) Continuing, MAIN said that with UTC, if one has these sexagesimal parts which are put together by any such mathematical expression, one gets a scalar variable that is discontinuous. Thus, to interpret UTC as continuous, essentially SEIDELMANN must not be treating the labels the way UTC does.

SEIDELMANN replied that if one goes to a dictionary and looks up the word ‘continuous’ as he did, then one will find the concept of ‘continuous’ as he presented it—the *dictionary* definition. MCCARTHY had brought up a *mathematical* definition for differential equations, which SEIDELMANN guessed was not continuous. However, SEIDELMANN’s actual point was that neither ‘continuous’ nor ‘discontinuous’ seemed to be the right word for the situation. MAIN thought it was absolutely right to say that ‘continuous’ was not necessarily the right word; a much more useful word would be ‘uniform’, because it is fairly clear that UTC is *not* uniform. TUASON added that UTC is “not uniform in terms of the *label*,” to which MAIN agreed. BIRTH further suggested that UTC is uniform at the level of seconds, but at the level of minutes UTC ceases to be uniform because of the leap seconds. And thus there are hours that are not uniform, and days that are not uniform, and so on, and this is part of the problem of meeting expectations of scalability discussed earlier (AAS 13-523). ROB SEAMAN said it seemed to him that days are not uniform because of the effects that DANIEL GAMBIS showed in his presentation (AAS 13-522), and not “because of the leap second.”

KIESSLING thought that “the internal definition of how they come up with leap seconds is not discontinuous, how people nominally interpret that assuming that we are talking about base-60—effectively you are not; you have some alphanumeric labels which people are choosing to interpret in a conventional fashion that is base 60.” KIESSLING again suggested “deprecating UTC” by distributing TAI and generating UTC on demand from TAI as needed. MAIN thought that the recommendation to generate UTC locally “does not sound much like deprecation,” with REDMAN affirming that “‘deprecate’ is not the right word.” At most, MAIN thought, KIESSLING’s proposal deprecated the direct use of UTC for clock synchronization. KIESSLING clarified that the use of UTC in mathematical operations, where one has to kludge around things because of the way the definitions are being treating, is something to be grossly avoided. SEIDELMANN preferred the option of keeping what people have and to recognize what people might already be using to support a uniform capability. KIESSLING said he was not arguing against SEIDELMANN’s solution, but wanted to emphasize that there were software problems tied to an inflexible understanding of what developers think the time code means.