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by

Constance A. McDaniel Wyman

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The Leap Second Debate

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The Leap Second Debate

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Report

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This work is

dedicated to my family.

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The Leap Second Debate

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The University of Texas at Austin, 2013

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Coordinated Universal Time (UTC) is the standard civil time scale available via time signals in use in most parts of the world today. Leap seconds are the means to keep civil time, or UTC, aligned with adjusted Universal Time (UT1), a time based on Earth rotation corrected for polar variation. They are intentional adjustments to UTC that are instituted to prevent the difference between UT1 and UTC from exceeding +/- 0.9 seconds, based upon international agreement. Over a decade ago various technical communities for whom a continuous time scale would be more suitable than UTC, as disseminated in real-time, currently provides began making a case that the definition of UTC should be changed to eliminate leap seconds as a way to specify time unambiguously. This issue was discussed at the 2012 World Radiocommunications Conference (WRC), but consensus for elimination of the leap second was not achieved and a decision was postponed until the 2015 WRC.

This report examines the leap second debate by summarizing general concepts of time and basic aspects of the leap second, followed by a discussion of non-technical considerations, technical aspects, and possible solutions.

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Chapter One: Introduction

Throughout human history astronomy has been used to define and determine time. This has included dividing each solar day into useful parts, determining the correct day for specific celebrations or religious rites, and establishing standard time scales that enable the coordination of events. Seidelmann and Seago (2013) make the argument that maintaining, "clock synchronization with mean solar time is an unquestionable requirement" (Seidelmann and Seago, 2013) of timekeeping because most civil activities are linked to solar time. Much of the current debate is about the best means to do that, and at what tolerance to maintain it (Seidelmann and Seago, 2013).

Coordinated Universal Time (UTC) is a standard atomic civil time scale available via time signals (USNO, 2013a) in use in the United States. UTC was accepted by the forerunner of the International Telecommunication Union (ITU) and is maintained by the Radiocommunication Sector of the ITU, know as ITU-R. Universal Time (UT) is time based on Earth rotation and UT1 is a partially corrected version of UT (ITU-R, 2002). Leap seconds are the means to keep civil time, or UTC, aligned with UT. They are intentional adjustments to UTC that are instituted to prevent the difference between UT1 and UTC from exceeding +/- 0.9 seconds (USNO, 2013a).

The leap second can be more clearly described for implementation as, "…[a]n intentional change in the number of seconds per minute, to extend a designated minute by one extra second (a positive leap second) or to finish the minute early by one second (a negative leap second). The leap second is used to adjust…[UTC]… to ensure approximate agreement with UT1 when both are expressed in days/hours/minutes/seconds" (Redman, 2013). Leap seconds allow UTC to be used as a close approximation of UT1 and maintain the relationship between civil time and Earth rotation.

By established protocols the insertion or deletion of leap seconds are announced six months prior to the event (IERS, 2013). While theoretically leap seconds can be positive or negative, i.e. inserted or deleted, the trend of the Earth to slowly decelerate (in angular rate) over time has resulted only in leap second insertion since the institution of leap seconds in 1972 (Seago, 2013). For this reason leap second insertion will be discussed; however deletion also could occur in the event that the difference between UT1 and UTC changes sign (USNO, 2013a).

Over a decade ago various technical communities who require sub-second precision timing and/or those for whom a continuous time scale would be more suitable than UTC, as disseminated in real-time, currently provides began making a case that the definition of UTC should be changed to eliminate leap seconds as a way to specify time unambiguously (Gambis, 2013). This issue was discussed at the ITU Radiocommunications Assembly and the subsequent 2012 World Radiocommunications Conference (WRC) (Finkleman and Warburton, 2013). Consensus was not achieved and the ITU-R passed Resolution 653, which postponed a decision on the matter owing to the need for continued study of the issue and placed the subject of UTC re-definition onto the agenda for the 2015 WRC (ITU-R, 2012a).

The ITU-R has tasked one of its working groups, Working Group 7, with exploring the implications of a change in the definition of UTC and specifically with the consideration of whether it is feasible to achieve a continuous standard time scale via the modification of UTC or another means (ITU-R, 2012a). Other entities are exploring the issue within their own context. In fact, the initial discussion of the issues surrounding changes in the requirements of UTC and this report began with an exploration of the *Requirements for UTC and Civil Timekeeping on Earth – A Colloquium Addressing a Continuous Time Standard* held in Virginia in May 2013

(Seaman et al., 2013) and incorporates many of the ideas contributed to that discussion herein.

Much of the drive to discontinue the practice of inserting leap seconds was generated by individuals and groups within the computing, telecommunication, and electronic navigation industries for whom the discontinuities introduced by leap seconds can be a problem (McCarthy, 2013), particularly with the proper implementation of leap seconds in software. On the other hand, other software systems exist that incorporate insertion of leap seconds without issues (Seidelmann and Seago, 2013).

There are other aspects of the debate. An ITU-R press release issued after the passage of Resolution 653 acknowledged that the, "suppression of the leap second...may have social and legal consequences"(Seidelmann and Seago, 2013). As Stenn (2013) put it,

"Perhaps uncharitably, people may be quick to understand the severity of the problems they see with the issues around UTC while being less tolerant of the severity of the different problems others have" (Stenn, 2013).

In the following discussion, general concepts of time will be summarized and the basic aspects of the leap second will be examined followed by a discussion of non-technical considerations, progressing to examination of more technical aspects and possible solutions.

Chapter Two: General Concepts of Time

Historically timing devices were based on using the Earth and its rotation to measure time (Duncombe and Seidelmann, c.1977). For example, by astronomical methods the second is obtained by dividing the day into 24 hours of 60 minutes per hour and 60 seconds per minute to arrive at what will be referred to as a solar second, representing 1/86400 of a day (Seidelmann and Seago, 2013). This definition of the solar second is derived from the length of the day based on Earth rotation at a specific epoch, approximately 1820. This corresponds to the median date that Newcombe used in determining his *Tables of the Sun* (USNO, 2012b).

2.1 Clock Time and Earth Rotation

To date, civil time has been tied to the position of the Sun in the sky throughout the day. UTC maintains this link with the apparent motion of the Sun, or more correctly the Earth's rotation, by inserting leap seconds so as to stay within 0.9s of mean solar time obtained from direct observation of the Sun (Gambis, 2013).

Universal Time (UT), time based on Earth rotation, encompasses time obtained from several successive adjustments to specific measurements. UT0 refers to "mean solar time of the prime meridian obtained from direct astronomical observation" (ITU-R, 2002). UT1 is UT0 corrected for polar variation, and UT2 is UT1 corrected for smaller fluctuations in the Earth's rotation rate (ITU-R, 2002). The difference of UTC and UT1, DUT1, is projected and made available to allow more accurate determination of the UT's for users requiring a higher level of precision than the assumption that UTC = UT1 (Seago, 2013). DUT1 is broadcast to the decimeter second level (Duncombe and Seidelmann, c.1977).

The Earth's motion is perturbed causing deviations in the length of a day, such that the duration of each day is not exactly 86,400 seconds in length. Length of Day (LOD) is the time derivative of UT1 and represents the excess length of time in one astronomically determined day greater than 86400 seconds. Fluctuations in the Earth's rotation cause variations in LOD and thus in its integrated value, UT1, and, "are an important factor in driving UT1 apart from UTC." (Gambis, 2013).

Phenomena that perturb Earth rotation, which cause these fluctuations, include (Gambis, 2013):

Surface:

- sea-level loading
- melting of ice
- atmospheric loading
- groundwater
- ocean currents
- plate tectonics
- gravitational attraction
- lunar and solar tides
- earthquakes
- winds

Internal:

- viscous torques
- core phrenology
- electromagnetic coupling (Gambis, 2013)

As can be seen in Figure 2.1 LOD has been decreasing because the Earth's rotation has been decelerating over time. This deceleration is due to tidal braking (USNO, 2012b).

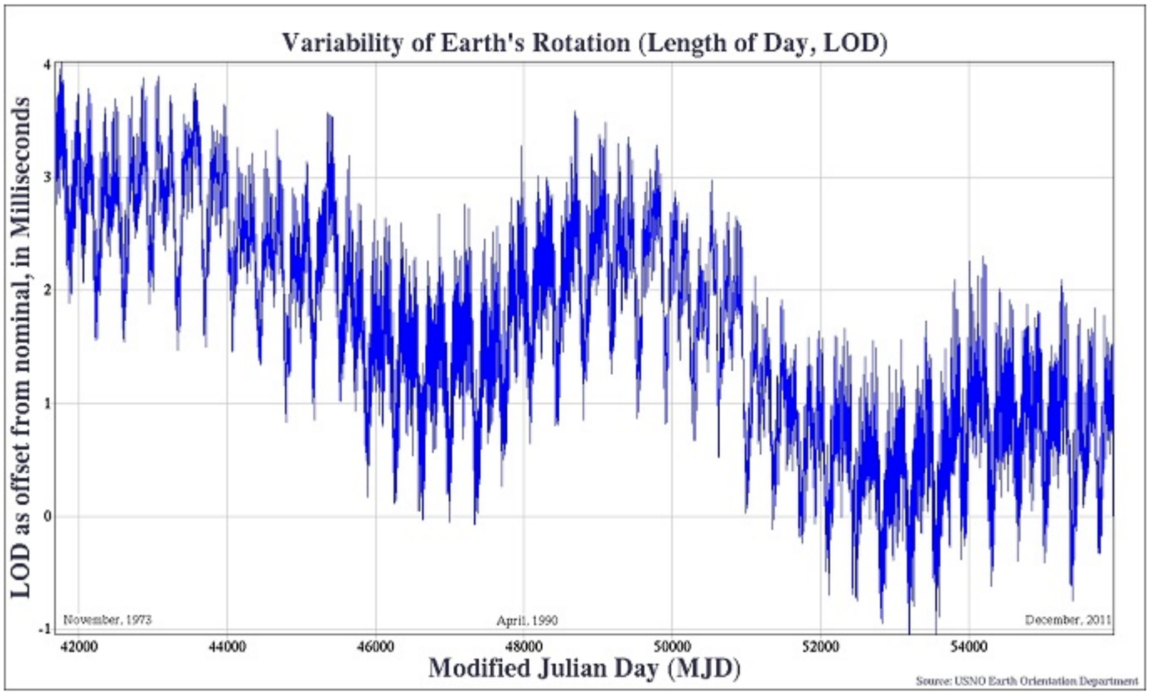

Figure 2.1: LOD vs. Modified Julian Day (UNSO, 2012)

So far in the 21st century the Earth is decelerating at a slower pace than in the 20th century, causing more time to pass between the insertions of leap seconds. The cause of this change is uncertain.

2.2 The Atomic Time Standard

The atomic second is defined, "as the duration of 9,192,631,770 cycles of microwave light absorbed or emitted by the hyperfine transition of cesium-133 atoms in their ground state undisturbed by external fields." (USNO, 2013d) The atomic cesium-based second is the System Internationale (SI) second and was chosen because it could be calibrated to match very closely with the solar second. However, the atomic second does not match *exactly*; it is slightly shorter (USNO, 2012c).

According to the United States Naval Observatory (USNO) the accuracy of atomic time measurement is 2 ns/day (UNSO, 2013d) which equals 730.5 ns/year. At this rate it would take almost 1.4 million years to amass 1 second of accumulated drift (USNO, 2013d). In 1967 owing to the greater stability of atomic clocks, the atomic second replaced the solar second as the basic unit of time. As a result of precise atomic clocks and the adoption of the atomic second, "Variations in the length of the day over the course of a year are now hundreds of thousands of times larger than the precision with which the start of each second is known using state of the art atomic clocks" (Seidelmann and Seago, 2013).

Astronomical observations traditionally were used to determine time because the Earth was a suitable clock, but due to the fluctuations listed above and the development of atomic clocks the Earth is no longer considered to be a good clock. That is to say that it is not a suitable clock for the level of timing precision needed in modern society. While the determination of UT is based on the current rotation of the Earth, UTC is a measurement of time based on the atomic second. The choice to change to an atomic time standard is another factor that causes the values of UT1 and UTC to diverge, although this component of the divergence is much smaller than the portion due to Earth rotation.

It is worthwhile to note that although UTC has as its basic unit the second which is based on oscillation of the cesium atom, it is used in conjunction with the Gregorian calendar, a calendar based upon the Earth's revolution around the Sun. Thus civil time and date must rectify an atomic-based time with an astronomically based calendar (Boomkamp, 2013). This is not an issue as long as civil time is correlated with Earth rotation.

2.3 Requirements of a Standard Time Scale

The concept of a time scale intuitively seems easy to grasp, for example it could be explained as a system used to order events. However, the term ‘time scale’ can be defined in different ways, such as:

- “A time scale can be defined as an arrangement of events used to measure duration…defined as the assignment of numerals to objects or events according to rules” (McCarthy, 2013).
- “…a useful time scale is generated by any process which enables dates to be assigned to events.” (Muller and Jappel, 1977)
- “…a standard of measurement that is reasonably invariant to human experience and the creation of a measurement language capable of independent empirical reproduction so that one laboratory can share experience with another using only a written language to do so.” (Stratton, 1976)
- “…the concept (and the means to achieve that concept) of a set of numerical values that relate changes in a designated four-dimensional reference system” (McCarthy, 2011).
- “…a system which makes it possible to assign without ambiguity a temporal coordinate to any event” (Guinot, 1994).

At its most basic level to be a time scale the system of ordering events must have a known starting epoch and an interval that can be measured and used to mark the passage of time since the starting epoch (Nelson et al, 2001). Also, a time scale should be unambiguous and monotonic (Stenn, 2013). Last, in a world with more than one time scale it must be possible to convert from one time scale to another (Redman, 2013).

For computer systems a time scale can be viewed as a system of time codes. Redman (2013) expands the basic definition of time scale into five properties relevant for use as time codes so that they can be used to order and synchronize time unambiguously:

- "the underlying [reference] coordinate time
- a particular implementation of the underlying coordinate time by a named clock
- a date-time conversion algorithm (ideally bi-directional)
- a range of time in which the date-time conversion algorithm is well-defined, with a mandatory starting epoch, and (optionally) an ending epoch after which the time-scale may be undefined or ambiguous
- a starting value for the time-scale at the starting epoch" (Redman, 2013)

Three time scales are relevant to the discussion of leap seconds: UT1, UTC and International Atomic Time (TAI). As mentioned above the solar second is obtained by dividing the day into 86400 seconds, but this interval was derived from the length of the day in approximately 1820 and the duration of a current day does not match exactly with the duration at that epoch. UT1 does not use the solar second as its interval; rather it is, "strictly proportional to the Earth Rotation Angle (ERA) around the moving rotation axis". (Gambis, 2013) ERA is, "the angle between the terrestrial and celestial origins…[and]…is proportional to UT1" (USNO, 2012a).

The other two time scales both use the atomic second as their interval. TAI has a starting epoch of 00:00:00 on January 1, 1958 and was oriented such that UT1-TAI ≈

0 at that time. It is a strictly continuous time standard, where every minute consists of 60 seconds. UTC differs from TAI by the accumulated number of leap seconds that have been applied to UTC as needed to allow |UT1 – UTC| ≤ 0.9 s. When the practice of leap seconds was initiated the difference between UTC and TAI was +10s and as of the date of this report UTC differs from TAI by +35 s (IERS, 2012). Table 2.1 shows the leap second adjustments to UTC.

Date	**Offset (s)**	**Date**	**Offset (s)**	**Date**	**Offset (s)**
-------	10	12/31/1979	19	6/30/1993	28
6/30/1972	11	6/30/1981	20	6/30/1994	29
12/31/1972	12	6/30/1982	21	12/31/1995	30
12/31/1973	13	6/30/1983	22	6/30/1997	31
12/31/1974	14	6/30/1985	23	12/31/1998	32
12/31/1975	15	12/31/1987	24	12/31/2005	33
12/31/1976	16	12/31/1989	25	12/31/2008	34
12/31/1977	17	12/31/1990	26	6/30/2012	35
12/31/1978	18	6/30/1992	27		

Table 2.1: Leap Second Adjustments (IERS, 2012)

Any discussion of changing the definition of UTC inherently includes ideas about what will make the time scale useful, and perceived future needs have been suggested as a justification for structuring time scales in one way or another. However, determining the time scale needs of the future is an extremely difficult notion. UTC as currently defined may or may not be useful in the future. While time and technical experts of today may believe that they are able to project future uses of time scales, in truth there is no way to know whether a time scale selected for use today will be adequate in the future (Seidelmann and Seago, 2013).

2.4 Time Transfer and Dissemination

In order to coordinate events or synchronize systems and system components it is necessary to share information based in the same time standard or reference frame. In order to discuss the synchronization of time standards it is useful to present a few definitions.

- Time Signal – "a process that creates and passes time stamps through some medium with a transit delay that can be characterized. Examples include the radio signals used to broadcast UTC, and the protocols used to distribute time over the internet" (Redman, 2013)
- "Traceable Time Signal" – a time signal with, "a specifiable uncertainty relative to a reference time scale. Traceability…[includes]…taking account of the uncertainties introduced during transmission" (Redman, 2013).
- "Distributable Time Scale" - "…a specific real-time implementation for creating time signals that are traceable to a source of reference coordinate time" (Redman, 2013).

The legal civil time scale, UTC is maintained by the Bureau International des Poids et Mesures (BIPM). BIPM uses data from a system of observatories and national institutes or timekeeping services around the globe. The observatories make direct measurements of time based on astronomical observations. Each national timekeeping service maintains a bank of atomic clocks and the times from all the clocks within the bank are averaged and represented as UTC(k), where k represents the abbreviation for the institute and UTC is an ensemble time (Redman, 2013). For example in the United States has two institutes: The National Institute of Standards and Technology (NIST), and the USNO. Their respective UTC measurements are UTC(NIST) and UTC(USNO). Each institute maintains close synchronization with

UTC(BIPM). For example, “UTC(NICT) has been synchronized with UTC(BIPM) almost within ±20 ns” (Imamura, 2010).

Each contributor to BIPM provides its measurements of time via methods with known uncertainty, and the information provided is averaged to determine the UTC standard, denoted as UTC(BIPM). TAI(BIPM) is determined similarly. While the times determined and supplied to BIPM are measured in real-time, UTC(BIPM) is not a real-time measurement; it is a weighted average of all of the UTC(k) values. In the context of the definitions above the transmission between BIPM and the national institutes are traceable time signals (Redman, 2013). Both UTC(BIPM) and TAI(BIPM) hindcasts are disseminated monthly by BIPM in Circular T (IERS, 2013).

The national timekeeping services also are responsible for the dissemination of civil time within their respective nations. Since UTC(BIPM) is obtained from averaging the UTC(k) values post real-time it is not a distributable time scale, but UTC(k) is and that information is made available for use via radio signals, telephony, and internet protocols (Koyama, et al., 2013). While UTC is officially disseminated for public use, TAI(k) is not even though it meets the same stability and measurement standards (Redman, 2013). Although TAI is related to UTC via leap seconds, converting between the two time scales requires correct application of leap seconds.

Time information regarding leap seconds and the value UT1-UTC is disseminated by the International Earth Rotation Service (IERS) in Bulletins C and D, respectively. These bulletins are available in ASCII format, which is not suitable to all purposes. Automatic systems are not able to access the information and other virtual methods are being investigated (Gambis, 2013).

Chapter Three: Background and Basics

3.1 History of the Leap Second

The conflict between technology and civil time that is at the heart of the current leap second debate is not new; similar issues drove the selection of UTC with leap seconds in 1970. Prior to 1960, disparity existed between time signals generated by different sources that were received at the same location. To resolve this, standard time signals were based on an atomic second, but the frequency at which the signals were transmitted differed from the nominal atomic frequency by a factor that was determined from Earth rotation. Small millisecond level step adjustments also were used to adjust the frequency when Earth rotation varied unpredictably. An international coordination effort employed this approach to standardize time and frequency from multiple sources and the resulting time came to be called UTC in 1962 (McCarthy, 2009).

That version of UTC had a unique, variable interval that did not match either the solar or atomic seconds. In 1965 in an attempt to provide time that matched UT and had the atomic second as its interval a new system of broadcast time was devised, called Stepped Atomic Time (SAT). It used the atomic second without carrier deviation but employed frequent millisecond level step adjustments to match UT2 to within 0.1s. For several years both UTC and SAT were distributed. Concerns arose about the variable interval used in UTC and about the jumps in UTC and SAT because of their changing frequency and offset adjustments. Television and radio stations needed to be able to maintain their designated frequencies precisely and contemporary methods of electronic navigation required precision tuning of oscillators. The advent of air traffic control systems with collision avoidance made the use of frequency offsets unacceptable (McCarthy, 2009).

The idea of the leap second was introduced in 1968 as a way to create a uniform time scale without frequency adjustment. The proposed leap second step would replace the millisecond level steps with an integer second and would avoid rate offsets and frequency changes. This new scheme of UTC including leap seconds was approved in January 1970 and would generate UTC such that, "(a) carrier frequencies and time intervals should be maintained constant and should correspond to the definition of the SI second; (b) step adjustments, when necessary, should be exactly 1s to maintain approximate agreement with Universal Time (UT); and (c) standard signals should contain information on the difference between UTC and UT" (McCarthy, 2009). This version of UTC went into effect in January 1972.

3.2 A Discontinuous Time Scale

UTC is not a uniform time scale. As mentioned above, leap seconds are, "an intentional change in the number of seconds per minute" (Redman, 2013). Thus, though the vast majority of minutes consist of 60 seconds, when a leap second is inserted the minute of insertion contains 61 seconds and it also is possible for a minute to contain 59 seconds. This change, in principle, also changes the length of the day when the adjustment is made.

If one examines UTC from the aspect of mathematical discontinuity then it becomes obvious that UTC has a step function relationship to time scales in which a minute always contains the same number of seconds, such as TAI. A mathematical function is continuous if and only if the limit of that function is the same as it approaches from both the left and the right. At moments of leap second insertion the function

$$F(t) = UTC - TAI \qquad \text{(McCarthy, 2013)}$$

is not the same approaching from the left as from the right. For the leap second inserted in June 2012 $F(t)_l = 34$ and $F(t)_r = 35$. Clearly $F(t)_l \neq F(t)_r$. This relationship between UTC and TAI can be seen when looking at the difference between both time scales and UT1, as seen in Figure 3.1. Fundamentally, UTC and TAI are the same except for leap seconds.

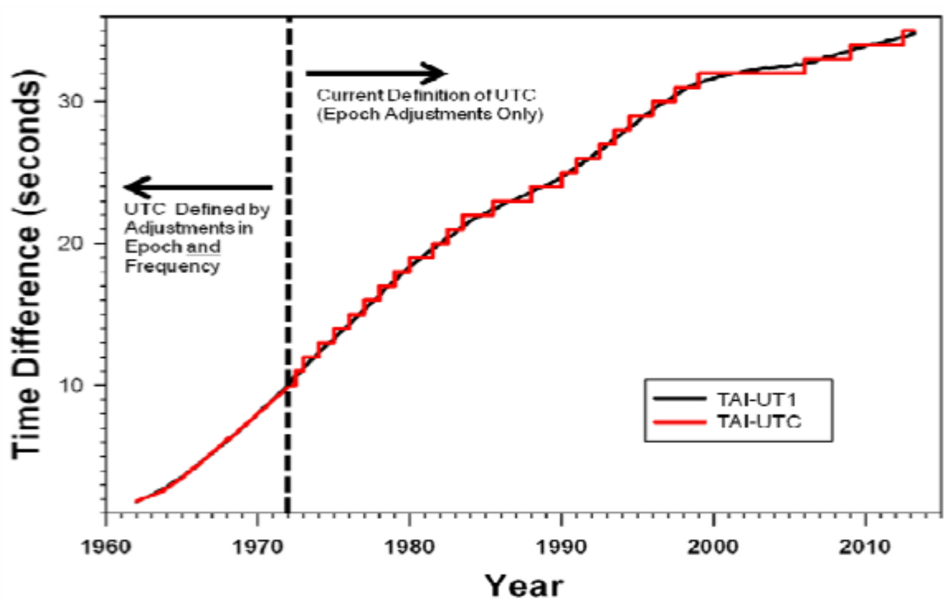

Figure 3.1: Step Function Relationship Between UTC, TAI and UT1 (McCarthy, 2013)

Although in UTC, time *does* move forward monotonically, and by some definitions could be called ‘continuous’ because it represents an unbroken, “…progression of seconds of equal length” (Seidelmann and Seago, 2013) representations of time in UTC appear to jump when leap seconds are inserted. These *apparent* discontinuities make the mathematical definition of discontinuity fitting when describing UTC and using it for certain purposes.

3.3 Leap Second Implementation

Timing systems and computer software implement leap seconds in different ways. The decision regarding whether a leap second needs to be inserted is made by the IERS/Paris Observatory by estimating the difference between UT1 and UTC and predicting when an adjustment will be required. Information about upcoming leap seconds is disseminated primarily by the IERS's Bulletin C, which is published semi-annually (IERS, 2013). If a leap second adjustment is to be made it will be done at 23:59:60 on the last day of the month specified in the announcement. By ITU-R Recommendation 460 the months of June and December are preferred (ITU-R, 2002).

Notice of upcoming leap seconds is disseminated further via additional methods. National timekeeping services provide the information to users via radio frequency, internet time services, and automated computer time services. These signals indicate whether a leap second is to be inserted at the end of the current month (NIST, 2012). GPS also transmits information warning of leap second adjustments including the planned time of insertion as a service to users who are affected by the leap second, even though the system uses a GPS-specific time scale that is unaffected by leap seconds instead of UTC.

Software systems that are capable of addressing leap seconds internally do so by issuing a warning flag once they have received notice of a pending leap second. The extent of advance warning given by the notice depends on settings within the system (Burnicki, 2013).

Leap seconds are inserted at 23:59:60 and the following second is 00:00:00 of the next day. However, most clock representations, including many computer time stamping systems, cannot either display or count the 61st second of a minute, that second labeled as '60' (ITU-R, 2002). In systems with this incapability an adjustment to the system time must be made to keep the first second of the following day, 00:00:00, from being shifted by the value of the leap second.

As Burnicki (2013) explains, the count of seconds at the start and end of leap second insertion must be the same in Portable Operating System Interface (POSIX) compliant systems running on UTC. There are different ways to handle the necessary time system adjustment:

- Freezing or stopping the clock at the 60th second for the 61st second
- Stepping time back at the beginning of the leap second
- Stepping time back at the end of the leap second
- Slowing down time across the leap second and slewing time over two seconds
- Smearing time over a specified interval around the time of leap second insertion

For systems that are capable of counting a 61st second an indicator must be flagged to alert the system of the presence and timing of the leap second. Note that in the event of a leap second deletion the affected day would end at 23:59:58 and leap second handling adjustments would have to be done in the opposite direction (Redman, 2013).

If time is frozen then, practically, it is not progressing monotonically and real events that occur during the frozen period cannot be assigned a timestamp. When time is stepped back a duplication of time stamps occurs and time does not progress monotonically. If events are synchronized to occur in a sequence according to system time stamps and then a time stamp is either missed or is duplicated events may not happen in the correct order or may not happen at all. For these options there is ambiguity in the time stamps surrounding leap seconds. This issue can lead to synchronization errors or system locks. Another negative effect of the duplicate time stamps is that data being collected with second or sub-second frequency ends up with data that has duplicate time stamps which presents problems in processing the data in the proper order (Burnicki, 2013).

Slewing time is a way for systems that are ill equipped to handle leap seconds to slow the system clock down at the start of the leap second and allow time stamps to increment by a fraction of the normal time interval. For example, "the Windows version of the NTP reference implementation slows the system clock down to half the nominal speed for 2 seconds [and]…after 2 seconds the system time is again aligned to UTC" (Burnicki, 2013). This alternative ensures monotonic time stamping through the leap second event.

Smearing time around leap seconds is a method that varies the time interval for a selected period of time, usually longer than slewing, which can start and end at the users choice and continue for an arbitrary period of true time (Burnicki, 2013). This method can be used to help Unix systems process the leap second event, but causes time to differ from 'real' time. It also can result in a loss of timing accuracy or synchronization if some components of a system use it while others do not. Slewing and smearing time is the equivalent of varying time, "…to fit traditional representations of time in software and hardware" (Seago, 2013).

3.4 PTP vs. NTP

Network Time Protocol (NTP) and Precision Time Protocol (PTP) are networking procedures that are used to synchronize clocks and timing of computers, servers, and networked systems to a reference time (NTF, 2012). A benefit of using PTP or NTP servers to coordinate time is that when leap seconds occur, the change only needs to be addressed on the time protocol server. The other servers and systems that obtain their times from these servers automatically will stay synchronized (Burnicki, 2013). In practice these protocols function somewhat differently.

NTP gets the time that is used from a definitive time source such as an atomic clock attached to a time server. Systems interface with NTP by polling at specified time intervals that vary between 64 and 1024 seconds depending on conditions between the polling system and the NTP server. "No more than one NTP transaction per minute is needed to synchronize two machines" (Cisco, 2008). NTP uses a hierarchical system of tiers, called stratum, to rate available NTP servers and choose the best one to update the polling system. A rating of Stratum 0 is assigned to reference time sources. A rating of Stratum 1 is assigned to NTP servers interacting directly with the reference, Stratum 0, clocks (Cisco, 2008). For example, national time institutes, like USNO, provide time to and via, NTP. The USNO, "…operates an ensemble of stratum 1 NTP servers which are synchronized to the UNSO Master clocks or to GPS as their stratum 0 reference clocks" (USNO, 2013b). The servers and systems that receive their information from the Stratum 1 servers are classified as Stratum 2, and so on, as shown in Figure 3.2. This classification structure allows a computer system to identify the closest, best choice for use when updating its system time via NTP.

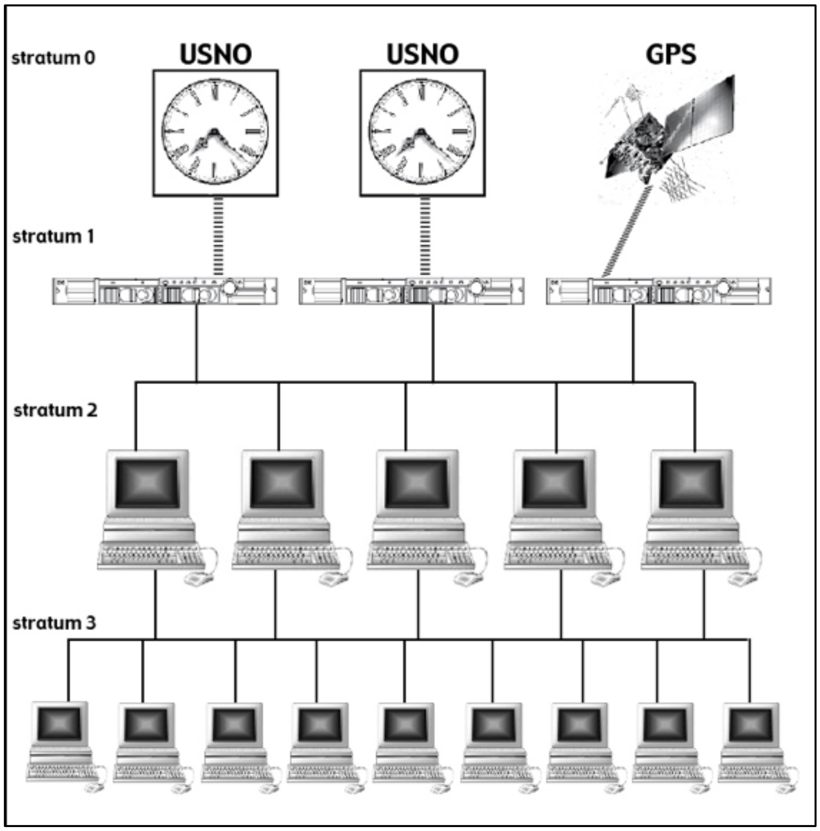

Figure 3.2: Illustration of NTP Time Dissemination Network (USNO, 2013c)

The procedures of NTP allow estimation of network delay, clock error between the two servers or systems, and clock offset. This procedure routinely achieves clock synchronization to the 10ms level for wide-area networks and to the 1ms level for local-area networks (Cisco, 2008).

For updates generated via PTP the time on the master PTP server is obtained by connection directly to an atomic clock or GPS receiver and synchronized to that time. Then the master PTP server sends messages containing precise time values to systems configured to receive time from the PTP servers. These units are called slaves. The process of PTP can be completed by one of two methods, but ultimately for both the information sent from the master includes the time of transmission so that the slave is able to determine its clock offset and then apply this correction to synchronize time. This procedure usually achieves an accuracy on the 1μs level (IEEE1588, 2010).

Typically NTP will produce, or pass through, time updates in whatever input time scale it receives and unlike POSIX compliant systems that require stepping back at the beginning or end of a leap second, NTP clocks usually are frozen (Stenn, 2013). PTP can use different time profiles, the default of which is TAI, but it also can be set to serve local zone time (Stenn, 2013). In truth most timing protocols distribute time as a binary representation or binary time scale which can be converted into time scales such as UTC or TAI within the system, but not all protocols implement binary representations of the basic reference coordinate time correctly. PTP does, but NTP does not when it is configured to UTC. Neither do Windows or POSIX-compliant operating systems (Redman, 2013).

“We note in passing that the Precision Time Protocol (PTP), unlike the more widely used Network Time Protocol (NTP), explicitly uses a representation of TAI during transmission to avoid the ambiguities introduced by the current, flawed implementations of leap seconds in NTP” (Redman, 2013).

Google made a very unique use of its internal NTP servers during the 2008 leap second. Due to problems encountered during the previous leap second in 2005 the company chose to implement what has been dubbed the “Google Leap Smear”. Essentially this approach was a smear as described above that was implemented on Google’s private servers. “Those NTP servers send a “modulated” time to their clients by gradually adding a couple of milliseconds to every update, varying over a time window before the moment when the leap second actually happens. For the clients, this looks like a phase adjustment similar to the time corrections required due to temperature drift, but at the end of an inserted leap second they have already gained the extra second." The benefit of this procedure was that only the NTP servers had to be adjusted, but the disadvantage was that time varied from true UTC over the entire smearing period (Burnicki, 2013). In this way Google was able to avoid the manifestations of real issues that resulted when the previous leap second was inserted.

3.5 Longer Leap Second Projections

Predictions of upcoming leap seconds are made by The Earth Orientation Center at the IERS. The Earth Orientation Center conducted two polls, in 2002 and 2011, to find out whether users of Bulletin C prefer the current definition of UTC or would favor a definition without leap seconds. In response, the majority of users, 89% in 2002 and 75% in 2011, stated that they were, "…satisfied with the current definition of UTC which includes leap seconds" (Gambis et al., 2011). Of the other 25% of respondents to the 2011 poll 19%, "…favored switching to the new definition of UTC" without leap seconds, 5% preferred a different solution, and 1% didn't have an opinion (Gambis et al., 2011). A breakdown of the respondents by industry and response is shown in Figure 3.3.

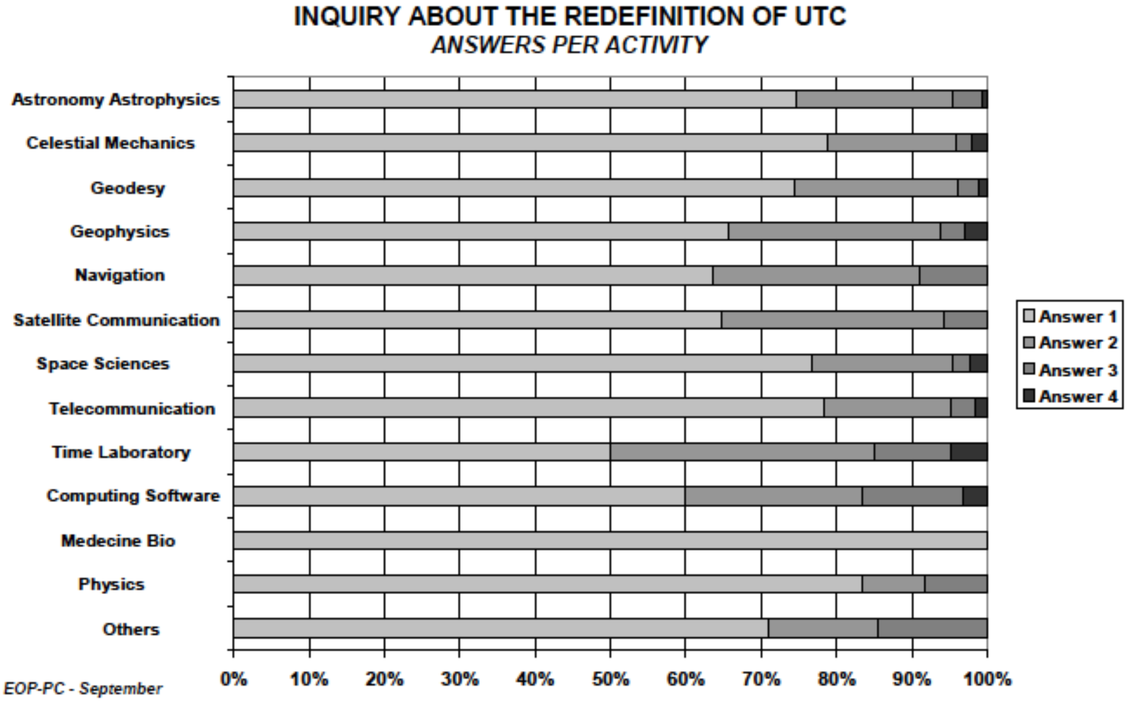

Figure 3.3: Percentage of Survey Responses by Industry (Gambis et al., 2011) where Answer 1 was satisfaction with UTC as is with leap seconds, Answer 2 was preference for re-defining UTC to be an uniform atomic timescale, Answer 3 was another preference, and Answer 4 was no preference.

A number of the respondents, approximately 5%, commented that there is a need for a longer interval of prediction than the current 6-month standard (Gambis et al., 2011). As other sources have noted, it is necessary for sufficient notification (McCarthy, 2013) to be given in advance of planned leap seconds to ensure smooth implementation. In response the Earth Orientation Center modeled four aspects of UT1 prediction, simulated past DUT1, and compared the values to observed UT1 to examine how far in advance accurate predictions could be made. The components modeled were:

- “a secular drift due to the tidal torque
- a decadal fluctuation due to the core mantle interaction including
    - the seasonal term using Least Squares fitting
    - the sum of the secular drift and the decadal variation considered as a trend over a few years
    - irregular variations based on an autoregressive filtering.
- seasonal variation that is relatively stable
- irregular variations” (Gambis, 2013)

Four prediction intervals were simulated: 2.5yrs, 3yrs, 4yrs, 8yrs, and 12yrs. The resulting confidence levels are shown in Table 3.1. Simulation success was based on whether the simulated past DUT1 values matched the historical DUT1 data.

Prediction Interval (Years)	**Simulation Success (%)**
2.5	95
3	85
4	75
8	25
12	10

Table 3.1: Success Rate Vs. Prediction Interval (Gambis, 2013)

It appears that the required 0.9s prediction accuracy currently is achievable over a 2.5 year interval with 95% confidence (Gambis, 2013).

3.6 A Note on Naming Convention

UTC is a time scale standard. According to the International Standards Organization (ISO) standardization only is achieved if all parties understand the subject matter being discussed (Finkleman and Warburton, 2013). Thus terminology plays an important role in setting standards.

According to Redman (2013) the ISO objects "…to the proposal to change the meaning of the physical significance of the term UTC without changing its name" (Redman, 2013) because this would make the term UTC polysemic. Polysemy is "having many meanings" (Gove, 1976). Some polysemy already can be afforded to the term UTC because UTC existed prior to the acceptance of the current definition with leap seconds (Seago, 2013).

If the definition of UTC is altered to remove the use of leap seconds for the purpose of closely aligning civil time with Earth rotation by adhering to UT then the argument can be made that the new time scale should have a new name. A change in name could have other implications, particularly legal ones. Whether the definition of UTC is changed or not, it is necessary that the terminology used to denote the standard time scale be unambiguous.

Chapter Four: Non-Technical Considerations

4.1 Public Perceptions of Time

Public perceptions of civil timekeeping are an important part of the discussion about changing the definition of UTC. Though anecdotal this author has mentioned the subject of this report to several lay people and discovered that outside of specific communities where timing expertise and precision are required, people are unaware of the existence of leap seconds. Additionally, people are used to mean solar time, time zones, and daylight savings time. This leads many experts, particularly those in favor of abolishing leap seconds, to contend that the general public would be unaware of, and unaffected by, a change in the definition of UTC (Hudson, 1967).

Simply because lay people are not familiar with time terminology does not mean that they have no relevance to the discussion (Birth, 2013a). Human beings learn to associate time and the passage of a day with the position of the Sun in the sky from the earliest years. Though local apparent time is no longer the means of standard time systems, people still have the perception that the Sun should be approximately overhead at 12 o'clock midday and that night occurs from sunset to sunrise, more or less centered around 12'o'clock midnight (Birth, 2013a), even if the connection is symbolic (Gabor, 2011). Additionally, the Gregorian calendar which is used as a standard throughout most of the world, and to which UTC is tied, is based on the revolution of the Earth around the Sun (Boomkamp, 2013).

Discontinuing the insertion of leap seconds would mean discontinuing the practice of closely maintaining civil time to solar time. The present system of mean solar time with time zones and daylight savings shows that people seek to match local time to solar time (Seidelmann and Seago, 2013). In 2011 BIPM noted that there, "is also the feeling that a break in the present system of synchronization of UTC to the Earth rotation will decorrelate 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" (BIPM, 2011).

Decoupling of UTC from Earth rotation will not go unnoticed (Seidelmann and Seago, 2013). As the value DUT1 increases slowly, civil time would drift away from mean solar time (BIPM, 2011). Even though it could take nearly 70 years for this increase to reach 1 minute UTC without leap seconds would not match public perceptions of time.

4.2 Religion

Questions about potential effects on religious timekeeping have been raised during the course of the discussion. Religions have requirements for rites that are tied to certain astronomical phenomenon (Birth, 2013b). Whether it is the determination of the correct time for daily prayer, astronomical influences upon important life events, or the correct timing of a holy day the recognition of the correct 'time' for the event, and the dissemination of that information is paramount.

The determination of the correct day to celebrate a religious holiday may be tied to the Gregorian calendar or based on an older religious calendar. For example, in Christianity Christmas is always celebrated on December 25th according to the Gregorian calendar, whereas the date of Easter is based upon a luni-solar calendar relating the full Moon to the spring equinox (WCC, 2013). This type of date determination is not sensitive to leap seconds.

Some religions have much greater relationship to precision timing, such as Judaism and Islam. Both refer to a lunar calendar to indicate the date of significant events and both employ apparent solar time to dictate specific prayer times throughout the day. They also both make use of means other than clock time to indicate the appropriate time to pray and, "rely on UTC to represent times derived from [these] traditional ways of reckoning time" (Birth, 2013a). These other means include measurement of the lengths of shadows throughout the day, the position of the Sun in the sky, the length of time required to travel a specified distance, and visible perception of light on the horizon during twilight, sunrise, and sunset. These methods of traditional time determination based on direct observation have existed for thousands of years and are independent of any clock time (Birth, 2013b).

Knowing when to pray and when not to pray is religiously important. In Islam believers must know the apparent local solar time to determine four of the five daily prayer times – those that occur during daylight hours. These prayer 'times' actually are ranges of time that surround sunrise, noon, and sunset, but specifically avoid prayer during those solar events, i.e. praying just before or after sunrise, but not *during* sunrise. Additionally, "fasting during the month of Ramadan [begins] when a white and black thread can be distinguished in the early morning light" (Birth, 2013b). Similarly, in Judaism the Shema prayer is to be recited exactly at sunrise, "beginning when a blue thread can be distinguished from a white or green thread" (Birth, 2013b).

Timing also is of importance in Hinduism for relating life events to astrology. For example experts within the religion use the exact time and location of a birth to learn about the relationship of the newborn child's soul to its new life on Earth and to determine certain aspects of the child's name. This is achieved by examining the alignment of astrological bodies at the precise time of birth, which requires converting time into a Hindu time scale (Birth, 2013b).

In all three of these religions believers must rely upon religious experts' knowledge of time. In Israel and many Muslim countries there are systems of audible cues indicating that it is the correct time for religious rites. In other countries Muslims and Jews must rely on different means to know the correct times if direct observation of traditional cues is unavailable. For each religion there are published tables, smart phone applications, and websites that calculate and disseminate timing information in the correct UTC based time zone for the user. These means of dissemination use algorithms that convert religious time to UTC, but are verified via direct observations and the non-clock-related cues mentioned above (Birth, 2013a).

Currently, experts and algorithms that calculate religious time and represent it in UTC can view UT1 as UTC. If the practice of leap seconds is abolished then these calculations will have to be adjusted to ensure that they account for the difference between UT1 and UTC (Birth, 2013b).

These religions have been determining the correct time for their rites since long before the current definition of UTC was accepted and they employ means other than clock time to verify that their time determinations are correct. Though it is impossible here to examine all of the world's religions for timing sensitivities these examples illustrate that the experts within a specific religion, or those who operate a religious timing dissemination service, need to be aware of the current definition of civil time so that they correctly apply it to their calculations and algorithms when converting between religious time and civil time. However, while religious time experts must be aware of the definition of UTC it does not appear that the cessation of leap seconds would impact those determinations negatively (Birth, 2013b).

4.3 Legal Implications

ITU membership includes 193 countries (ITU, 2013) and, "ITU-R terminology is used for legal purposes by many administrations" (Redman, 2013). Nations for whom UTC is the civil and legal time scale may or may not define UTC specifically in their own regulations. It may be defined by incorporating it into their laws by reference to the ITU-R recommendations, or a definition of astronomical time. "[A]…requirement for mean solar time is reflected in all timekeeping law today; legal time is explicitly referenced to Earth rotation in some countries, in other is it based on atomic time adjusted for Earth rotation, but in no country is legal time known to disregard Earth rotation" (Seago et al., 2011).

It is unclear how countries that use UTC as their civil and legal time would be affected, and to what degree, if the ITU-R altered the definition of UTC to cease leap seconds. This could be done either by keeping the term UTC intact or by creating a new name for the new time scale. As noted above changing the definition of UTC without changing the term creates confusion, however, if UTC is re-named then countries who define their legal time by referencing the name UTC instead of by incorporating the appropriate ITU-R resolutions or recommendations would be in the position of defining their time by a standard which no longer exists. To avoid this scenario, "ITU-R study groups recommended continuing with the term UTC" (Seidelmann and Seago, 2013) for the continuous time scale. However, any change in the definition of UTC would take effect immediately in countries that incorporate ITU-R Recommendation 460 by reference (Redman, 2013).

Re-defining UTC to eliminate leap seconds would create a fundamental difference between time in nations that use an astronomically based time scale, like UT, and those that would be using the de-coupled version of UTC. Currently UT and UTC can effectively be considered the same time, but if UTC no longer uses leap seconds to track with astronomical time then those time scales would cease to be related and time in countries under these difference schemes would begin to drift apart. The impacts of this are unclear (Seago et al., 2011) as it is unknown how nations using these different time scales would exchange time and coordinate events. Although rare it is possible for nations to ignore the recommendations of the ITU and some nations could choose to do this if they disagree with any changes made to the definition of UTC (Redman, 2013).

The European Union (EU) has a unique problem related to the concept of changing the name UTC (Seago et al, 2011). There are 23 official languages in the EU, all accorded equal standing, and agreements and treaties in any of the 23 languages are equally binding. Already linguistic challenges exist is translating time concepts from one official language into another. In some cases literal translation does not convey the correct meaning. In others cases, terms that convey one meaning to experts in the field of timing convey another meaning to lay people. These terms and their meanings are used interchangeably by the non-time experts doing the translation. For example, it appears that, "the translations of the terms Universal Time, Greenwich Mean Time, Universal Coordinated Time, UTC, UT1, and GMT" (Gabor, 2013) are used to convey the same meaning of time even though UTC and GMT are, "not the semantic equivalent of the other between any two languages" (Gabor, 2013). This is in addition to the fact that UTC, GMT, UT, and UT1 all denote specifically different concepts of time.

The mandate of the European Commission allows that, "The Commission shall promote the general interest of the Union and take appropriate initiatives to that end...It shall exercise coordinating, executive and management functions, as laid down in the Treaties..." (Gabor, 2013). Under this article the EU Commission is authorized to pass a directive addressing legal time throughout the EU to aid consistency in legal efforts. Gabor (2013) states that, "If the Directive in its equally binding linguistic versions implies that “UT” and “GMT” designate the same thing, then in the context of the Directive they truly designate the same thing” (Gabor, 2013). The European Commission could pass such a directive, but whether it would pass one regarding civil/legal time is unknown. In the absence of a coordinating directive it is difficult to resolve the linguistic ambiguity mentioned here or any that would be added by a change in the definition of UTC (Gabor, 2013).

Further, if the definition of UTC is changes, “…consideration of national laws seems necessary to ensure that internationally broadcast time standards remain acceptably legal across all jurisdictions” (Seago, et al., 2011). Careful consideration of the legal implications should be given before accepting a new definition of UTC. The issues of defining legal time, disparity between countries that use UTC and time scales other than UTC, and timing coordination between countries do not lend themselves to redefinition of UTC without leap seconds.

4.4 Politics

Ultimately the decision regarding leap seconds and civil time will be made by a majority of the ITU-R member states, each with its own views. The majority of people interested in the cessation of leap seconds represent a small minority of those member states and even within powerful states there may not be a consensus regarding the proposed changes (Seidelmann and Seago, 2013).

Unless the case to change the current definition of civil time is clearly one-sided, which it is not, the case will be difficult to make. As Birth (2013b) put it, “Since the nations pushing for change in UTC are not even close to a majority of the membership of the ITU-R, and since for much of the world, these nations represent the colonizers of the not so distant past, these nations will be consistently outvoted, not because they should be, not because their arguments are weak, not because the science is no good, but because of the complex variety of resistances…to anything proposed by former colonizers" (Birth, 2013b). Whether or not he is correct in his assessment is unknown, but it provides a good example of the role politics can play.

Much could be said about the political motivations of proponents of changing the definition of UTC, those who prefer not to, and those who see no reason to. However, such commentary is outside the scope of this report. Let it be sufficient to say that politics will play a role in decisions made regarding UTC.

Chapter Five: Technical Aspects

There are many technical and scientific fields where expertise in timing and knowledge of leap seconds are relevant including astronomy, computer science, systems engineering, geodesy, and metrology. Within these fields issues have been experienced that are believed to be the fault of leap second insertion.

5.1 Orbit Determination, Astronomy and Geodesy

Space geodesy uses several timing sensitive techniques to make measurements of the Earth. Laser ranging (LR) enables precisely determined satellite orbits, geophysical parameters, and histories of position and velocity of ground stations. Very Long Baseline Interferometry (VLBI) is used to measure the motions of and within the Earth in an inertial reference frame by measuring time delays in the arrival of quasar-generated radio waves. Space geodesy and Global Navigation Satellite Systems (GNSS) work together to accurately pinpoint GNSS receiver location. Dual frequency Doppler measurement systems also are used for precise point positioning (NASA, 2012).

Astronomy uses various techniques to quantify the orbits and motions of celestial bodies in order to better understand our solar system. Astronomical observations and the tables derived therefrom are used in the field of celestial navigation. In some practical senses celestial navigation has been superseded by electronic navigation techniques such as GNSS because they provide position information more rapidly and without regard to the conditions of the sky and horizon. However, celestial navigation remains relevant and its continued availability is a requirement in maritime fields.

These techniques are illustrated here because each of them requires precise timing knowledge that is related to the rotation of the Earth. Information from several time standards is required, including UT1, UTC, and TAI, and the ability to convert from one time scale to another is imperative, i.e. their conversion algorithms must be known and understood (Boomkamp, 2013).

Geodetic techniques and astronomical measurements are the means of quantifying the difference between UT1 and UTC and they also require information relating UTC and TAI. Timekeeping services have a "broad relationship with UTC in many aspects" (Koyama et al., 2013) that includes precise orbit determination relying on the relationship between UT1, UTC, and TAI (Koyama et al., 2013). In fact UTC with its link to Earth rotation is one way to relating TAI to UT1. The other method is to use DUT1, but this approach is more cumbersome (Boomkamp, 2013).

Even though GNSS systems such as the US Global Positioning System (GPS) use unique time scales based on continuous counts of seconds, specific information regarding Earth Orientation Parameters (EOP) continues to be necessary for GNSS operations (Johnson et al., 2013). This need results from the rotation of the Earth and its perturbations. The difference between UTC and UT1 is one EOP. Current GPS operational standards require that |UT1-UTC| be less that 1 second (Malys, 2011) because GPS orbit processing it related to UTC(USNO). UT1, and its relationship to ERA, provided by this information is used in the coordinate transformations between the Earth Centered Inertial (ECI) and Earth Centered Earth Fixed (ECEF) reference frames for highly accurate orbit determinations (McCarthy, 2013).

The IERS has defined a model specifically for the transformation from to the terrestrial ECEF from the celestial ECI reference frames. This model also depends upon DUT1 and polar offset information (Boomkamp, 2013). Software performing this computation uses TAI and UT1; however, other aspects of the system, i.e., inputs or outputs, may require a UTC or GNSS time format and therefore the system must be capable of converting between time scales (Boomkamp, 2013). In order to model satellite orbits with a high level of precision computational software must be able to rectify TAI-like continuous second counts with ERA. TAI like time structures are chosen for use in computer programs because they can be viewed as pure integer counts.

“Proposals regarding UTC redefinition have not clearly addressed [the] passive UT1 accessibility…” (Seidelmann and Seago, 2013) and availability to ERA information necessary for astronomy, geodesy, celestial navigation, and orbit determination. Re-definition of UTC to end the practice of leap seconds could impact these applications negatively.

5.2 High Precision Time Users

“There is no exact specification for how leap seconds are to be handled by clocks providing time with resolution below 1 second“ (Burnicki, 2013) and the 1-second precision level is not accurate enough for many applications. Current high precision applications, particularly research applications, may demand nanosecond or even picosecond level precision. Timing information disseminated by NTP and PTP only reaches an accuracy of 1ms and 1μs, respectively, which leaves users requiring higher precision than these levels with one of two options.

- Users may choose to use UT1, or apply DUT1, directly instead of correlating time stamps to UTC or TAI. This requires, “…full evaluation of the IERS models, involving frequent updates of the empirical DUT1 parameters from the Bulletin B publications…" (Boomkamp, 2013) but the IERS can provide the required precision levels.

- Users may set up their own internal time system based on precise time determinations from GNSS and maintain these networks for their own uses.

The need for disseminated civil time to address the requirements of high precision timing is not a future consideration. This need already exists. Although this aspect of timing is somewhat external to the debate over leap seconds, it is mentioned here in an attempt to be comprehensive as consideration should be given to this issue when decisions are made regarding the future of UTC and standards are created for the next generation of civil time.

5.3 Datasets and Data Collection

With regard to future data collection activities, many proponents of leap second cessation suggest that such cessation will eliminate the need to consider leap seconds in future software formats. This is true in some cases, but not in others.
To stop inserting leap seconds now would not get rid of the need to address them in the future because they already exist in data sets recorded from 1972 to the present. Knowledge of them would be required to accurately manipulate any historical data sets from this time period (Boomkamp, 2013). For example in many fields, such as geodesy, it is common to reprocess historical data with newer techniques. Since it is impossible to un-do past timing adjustments computer systems and software will have to be able to address them.

Additionally, some current data formats or collection systems have been designed with the assumption that |UT1-UTC| will not exceed 1 second (McCarthy, 2013).

Thus if the practice of leap seconds is discontinued the assumptions within these systems will need to be revisited.

5.4 Computer Systems Correctly Implementing Leap Seconds

Although much of the ‘press’ given to leap seconds focuses on the failure chain in systems that experienced negative side effects around leap second insertion, most of the systems updating UTC do so correctly and without issue (Seidelmann and Seago, 2013). These systems conform to ITU-R Recommendation 460 (ITU-R, 2002). No readily available quantification could be found that estimates the number systems that experience leap second issues against those that do not.

Similar to the notion of historical data sets, certain software applications either assume the |UT1-UTC| will not exceed 1 second or correctly implement leap second updates without issue. If the practice of leap seconds ceases then the handling of timing within these systems will need to be revisited (Seidelmann and Seago, 2013).

5.5 Computer System Leap Second Issues

Numerous computer systems have had trouble around leap second insertion. Similar to systems that correctly implement leap seconds no comprehensive survey of systems that have experienced these problems exists. For this reason specific outages will not be discussed, but outages that have been included in source papers have been dissected and lend themselves to being divided into categories based on the type of problems encountered.

- The Windows Operating system ignores leap seconds altogether (Redman, 2013), as is required of POSIX compliant systems (Allen, 2013). When a system contains components that do not address leap seconds and components that do, time stamps within the system become unsynchronized during leap second insertion. The system's taskmaster is unable to sort the unsynchronized time stamps and the systems experience process failures and/or system lock-ups (Allen, 2013).

- UNIX systems handle leap seconds by one of several methods. They incorporate the leap seconds by stepping back time either at the beginning or end of the leap second, or by freezing time for the second of insertion. (Burnicki, 2013). A 61st second, labeled 23:59:60, is not assigned to the last minute of the specified day, rather it has two 60th seconds, both labeled 23:59:59 in the same minute. If one is logging data or assigning time stamps to other information, two seconds end up being labeled the same so it becomes impossible to distinguish the events and place them into the proper order. Even though the events occurred monotonically in real time the timestamps will be non-monotonic and ambiguous. This ambiguity in the system's time stamps allows confusion of synchronized events and can lead to errors and software locks (Allen, 2013). These system failures occur commonly in systems that have components that address leap seconds in different ways.

- Computer software assigns time stamps using date-time conversion algorithms. Leap seconds affect the, "labeling of time by a date-time conversion algorithm that breaks the time of day into hours, minutes and seconds" (Redman, 2013). Systems that use a time scale based on a continuous count of seconds, like TAI, or that use UT1 can use a uniform algorithm. This type of algorithm is written including the correct assumption that the number of time intervals within a day remains constant. On the other hand, UTC requires a UTC-specific, non-uniform algorithm for conversion because even though most days include 86400 time intervals, when leap seconds occur there are either 86399 or 86401 intervals in a day. However, "a large body of software has been written that incorrectly uses the uniform date-time conversion algorithm to convert UTC to and from a binary "count of seconds" that nominally starts at some epoch" (Redman, 2013). This is a seemingly easy mistake to make, but can lead to synchronization issues similar to mixed-component systems.

- When systems that have become unsynchronized fail or lock-up the usual method of re-synchronizing is to reboot the system. Sometimes systems do not come back online after the reboot (Allen, 2013). When these boot failures occur in conjunction with leap second insertion, leap seconds may receive the blame even if the boot problem is unrelated and would have occurred despite the reason for the reboot.

- False leap second notifications have been generated and circulated in the past, both within closed private systems and GPS (Johnson et al., 2013). While this is not exactly a glitch around leap second insertion it is a problem of the leap second process. The causes of these glitches are not obvious and may be unique to each occurrence. For GPS, system procedures were altered to make this type of glitch much less likely to propagate notifications regarding false leap seconds (Johnson et al., 2013).

The leap second debate is meaningful in computer and software applications where the insertion of a leap second triggers these issues. Much of the current irritation with UTC containing leap seconds is justified by these existing incompatibilities that manifest themselves in the difficulty of, or complete inability to, correctly represent leap second adjustments. Some of these issues originate from faulty assumptions or limited definitions of the basic time designation scheme (Main, 2013). Some are generated by system components that handle time in different, incompatible ways and may be attempts to comply with conflicting standards (Allen, 2013). The software bugs and system lock-ups that have been experienced are the real manifestation of these problems, but the leap second is not the true cause, instead it is the indicator. If more universal assumptions are used to define time scales in the future – if a new standard is set - then whether leap seconds continue or not will not impact sensitive computer systems (Main, 2013).

5.6 Standardization vs. Independent Time Scales

Much fear has been expressed that if the debate over leap seconds and the definition of UTC is not resolved that numerous independent time scales will be developed (McCarthy, 2013). People expressing this fear have reason to be concerned; already these independent time scales have begun to immerge. "Sophisticated time scale users will, inevitably, make their own choice of time scale for each application" (Main, 2013). Such a situation is the opposite of standardization.

Different entities maintain internal time scales for specific purposes. NASA maintains a Mars Solar Time for use with Mars missions, but this only impacts people directly involved with those missions who are aware of the time scale difference (Stenn, 2013). When countries or global companies make the decision to create and use an independent time scale it has the potential for a global effect because this type of independent time system interfaces with millions of people daily, particularly lay people with little knowledge of time who are unaware that they are using something based on a time scale different from civil time. Some of these internal time scales have appeared as a result of issues encountered around leap second insertion and arise from a desire to avoid future problems by smoothing operations with a continuous time scale or second count (McCarthy, 2013).

The developers of Java, which is used by approximately 9 million web developers, have carefully created their own Java time scale. In response to a need for a more user-friendly time scale Java determined that the four main complications in assigning date and time, in decreasing order of significance are:

- "months of different lengths
- leap years
- daylight savings time
- leap seconds" (Colebourne, 2013)

As a result, the decision was made that leap seconds are not considered important by users of Java and, "are not an important problem for most developers" (Colebourne, 2013). As a result of this assessment a new Java time scale was created. This new time scale breaks the day into 86400 intervals, but each interval can differ from the atomic second. The scale uses this unique interval in conjunction with a time line that has different sections corresponding closely to civil time within each segment. Whenever civil time is adjusted (for example with a leap second) it will be necessary to add a new segment to the time line (Colebourne, 2013). While this may be an effective solution to problems experienced by Java users, it has a potential to create confusion. Note that although a new version of Java is soon to be released this new time scale is not included; it is set to be employed by a future version of the software (Colebourne, 2013).

Other examples of independent time scales are the unique time scales created for various GNSS networks. The United State Department of Defense created it's own unique time scale for GPS. The epoch for this time scale is UTC at 00:00:00 January

6, 1980. This time scale uses weeks and atomic seconds of week as its interval, and is permanently offset from TAI by +19s. This was done to avoid the problem of changing month, year, and minute length pointed out by Java above, and because the format was compatible with data transfer options available at the time of GPS development (Misra and Enge, 2012).

While the reasons for implementing independent time scales in GNSS may differ, much of the basic reason behind the development of other independent time scales, particularly computer time scales, directly results from a lack of standardization or conflicting existing standards.

Computer software has been developed under two conflicting standards regarding time: ITU-R Recommendation 460 which calls for the application of leap seconds and POSIX which ignores leap seconds. POSIX requirements are maintained by the Institute of Electrical and Electronic Engineers (IEEE). The standards requiring leap second adjustments went into effect in 1972 and in 1978 the predecessor to the ITU-R accepted the recommendation that UTC with leap seconds would be adopted as the basis for civil expression of time and date (Allen, 2013). Concurrently, throughout the 1970's computing systems and Unix platforms were developing and eventually operators realized the need to "standardize their interfaces" (Allen, 2013). "At that time the text of…[ITRU-R Recommendation 460]…was not freely available, and standards for computing systems evolved among committees who did not have access to…[its]…details…" (Allen, 2013). As a result the POSIX standards were developed without consideration of a time scale that includes a variation in the number of seconds per day. These dual standards force software developers to choose how to comply with conflicting standards or to choose to completely ignore one standard or the other (Allen, 2013).

Other timing shortcomings exist within POSIX. There is not a requirement for applications to be notified upon a change in system time. Also when POSIX compliant systems supply time in seconds and decimal seconds with an epoch they do not display the reference time scale or any projection of the error surrounding the time stamp (Stenn, 2013).

5.7 Ways to Better Represent Time in Software

A need to re-examine the handling of time in coding and software has immerged. Several means have been proposed to reduce ambiguity and address the conflict between POSIX-compliant systems and those that comply with ITU-R Recommendation 460.

The ability to convert between time scales accurately is imperative and there is a need to be able to generate unique, monotonic time stamps during leap second events. Essentially this means altering the assumptions that go into the way time is represented in software and changing date/time representation and conversion constructs in a way that allows proper handling of leap seconds.

Main (2013) suggests using an approach that labels the day with a modified Julian date (MJD) and allows for up to 86401 seconds in a day. This would allow the inserted leap second to be labeled as second 86401 on MJD (Y) and the next second of time to be 00001 on MJD (Y+1). This convention allows the expression of time to increase monotonically and without duplication of time stamps or freezing clock time (Main, 2013).

Another suggestion asserts that in current software, time stamps do not include sufficient information and suggests providing more information in time stamps and instituting a time scale library to interpret these new time stamps and convert between different time scales. For example, including, "…the following elements: the current reported system time, the expected difference between the system time and "true" time, the expected error in the time and the time scale used" (Stenn, 2013). Here the positive or negative leap second would be included in the expected difference when they occur. Time stamps also should indicate, "error bounds for the system timestamp" (Stenn, 2013).

As mentioned previously, most computer software actually represents time in a binary format. "A long-standing position of the [committee that]…oversees BIPM, is that TAI—realized by time laboratory k as TAI(k)—may be made available and should be recommended for use in applications that need a uniform time-scale…Recall also that, outside the hours-minutes-seconds format, any binary or decimal count of seconds in UTC that validly represents [the reference coordinate time] is identical to the count of seconds in TAI… [but]…relatively few applications use TAI in this way" (Redman, 2013). Whether an approach to use TAI in this manner could gain acceptance is unknown.

If a standard for addressing binary representations of reference coordinate time could be established it might be part of a comprehensive solution to the issues surrounding leap seconds because it would allow transformation of timing information freely from one time scale to another (Redman, 2013). Ultimately addressing time and time/date in computing software is imperative (Main, 2013) and will aid in establishing time scale standardization.

Chapter Six: Proposed Solutions

The question of whether the definition of UTC should be altered to cease the practice of leap seconds to maintain a close relationship between civil time and Earth rotation is not answered easily. The perfect solution might be a time scale with no apparent discontinuities which uses the atomic second as its interval while matching with the Earth's rotation (Diaz and Tuason, 2013). However, to date, no such time scale has been achieved.

ITU-R Resolution 653, passed at WRC-12 calls for, "consider[ion of] the feasibility of achieving a continuous reference time-scale, whether by the modification of UTC or some other method, and tak[ing] appropriate action…" (ITU-R, 2012a). Several possible solutions exist. Note that whatever solution is devised there will be a cost to implementation of the solution (McCarthy, 2013). Which entities will be burdened with costs and how expensive they will be depends upon the solution (Redman, 2013).

6.1 Maintain the Status Quo

If the current definition of UTC is retained and no other changes are made to ITU-R Recommendation 460 then the needs of high precision users will continue not to be met, new independent time scales will continue to be introduced, and standardization in timekeeping will not be achieved.

6.2 Re-defining UTC to Eliminate Leap Seconds

This option was discussed at WRC-12 and consensus to accept the change was not achieved. While this option has received the most attention it may not be the best option. UTC without leap seconds would eliminate future issues with leap second insertion and may eliminate the desire to develop independent time scales that employ continuous second counts. However, independent time scales may be developed by users requiring access to UT1. (Seidelmann and Seago, 2013).

Re-defining UTC to cease the practice of leap seconds could be done by creating a new name for the new time scale or by preserving the name UTC. If UTC is re-defined, but not renamed the term UTC would become polysemic (Finkleman and Warburton, 2013).

6.3 Re-define the Second:

The second could again be re-defined. The suggestion has been made that it could be once again 1/86400th of a mean solar day, perhaps beginning at a new epoch (Diaz and Tuason, 2013). Although this approach preserves the link between civil time and Earth rotation it would result in the loss of stability provided by atomic clocks and eventually the issue that the length of a day not exactly match 86400 seconds would re-manifest itself as time moved away from the new reference epoch.

6.4 Dual Standard Time Scales:

A possibility for the "other method" (ITU-R, 2012a) sought as a solution to the leap second debate could be the acceptance of two parallel standard time scales as outlined below.

- Maintain UTC as is for use as civil time. This preserves the legal definition used by many nations and preserves the link between civil time and Earth rotation that is inherent in public concepts of time (Seidelmann and Seago, 2013).

- Establish a continuous time scale, or accept TAI for this purpose if there is not a clear reason why a separate time scale should be introduced for those purposes that require a continuous scale (Seidelmann and Seago, 2013).

- A fundamental requirement of dual time standards is that information relevant to the continuous time scale MUST be disseminated in real time, as is the case currently with UTC (Redman, 2013).

6.5 Longer Leap Intervals

The concept of replacing the practice of leap seconds with a longer leap interval has been suggested. Essentially this would allow the drift between civil time and Earth rotation to grow for many years and then once the drift has grown to 60s or 3600s correct the difference with a leap minute or a leap hour, respectively. There have been 35 leap seconds over the 40 year period from 1972 to 2012 for an average of 1 leap second each 1.14years, although this interval is highly variable. At this rate a leap minute would not be required for 68.4 years and a leap hour would not be required for several millennia. This projection shows leap hours to be an unreasonable approach as there is no way to guess how people will conceptualize time in the distant future (Seago, 2013), however, let us look at the pros and cons of leap minutes.

Pros:

- "Leap minutes cope well with quadratic UT1 separation in the very long-term…[however]…that technical aspect may not be relevant for perhaps a millennium." (Seago, 2013)

- Leap minutes, "avoid the possibility of negative correction…" (Seago, 2013)

Cons:

- "…at this stage it is unclear how a proposed leap minute should work any differently than the leap second works now" (Seago, 2013)

- "…using larger leap intervals than an integer second is really not different from the notion of abandoning Universal Time altogether" (Boomkamp, 2013)

- The, "…inaugural leap minute is expected to happen beyond the professional lifetimes of current advocates, and there is no evidence that its official adoption now would ensure its operational acceptance later" (Seago, 2013).

- Kamp (2011) argues that intercalary adjustments "once every couple of years is not nearly often enough" to ensure that systems handle them correctly (Kamp, 2011).

- "The duration of a leap minute is significant enough that many relatively inaccurate timekeepers would not be able to ignore it; thus, awkward representational issues with leap minutes would be more widespread than with leap seconds" (Seago, 2013).

- "…it is quite unclear how a leap minute—scheduled decades in advance—would be successfully "transmitted" to a future generation…" (Seago, 2013)

Clearly a longer leap interval puts the problem off until later and allows inconsistent standards to continue to develop without offering any clear advantages over the current leap second - other than not having to be concerned with it presently. When it comes time for the leap minute, there is no way to know how successfully it would be implemented or whether it would be implemented at all (Seago, 2013).

6.6 GNSS Time Standards

While GNSS has the benefit of coming with existing dissemination capabilities, the proposal of using a GNSS time standard has problems of it's own. First, are the issues of national pride and political divisions that likely would prevent a majority of ITU-R members voting to accept the GNSS time scale developed and managed by one nation or a subset of nations.

Second, even if a consensus to use a time scale based on GNSS could be reached, using GNSS as civil time is infeasible. While GNSS systems use highly stable atomic clocks these clocks are set to compensate for orbital influences and are "adjusted in frequency and epoch…to meet…operational needs" (McCarthy, 2013). Also, it is impossible to maintain the clocks once they have been launched into space.

Last, GNSS clocks run a continuous count of seconds and can be viewed as a, "shifted TAI-like scale[s]" (Boomkamp, 2013). The only benefit GNSS systems provide over TAI is the existing dissemination capability built into GNSS.

6.7 Creating a New Unique Time Scale

Several unique new time scales have been suggested. A few discussed at the 2013 *Colloquium Addressing a Continuous Time Standard* are:

- Adapted Universal Time – a concept of time using "Letter Time Format" with 25 letter hours that allows for "stretching each day with milliseconds" to generate a globally uniform time scale (Diaz and Tuason, 2013).

- Mean Solar Time – a concept based on the mean synodic day which would enable the word "day" to mean the same thing on any celestial body within our solar system (Seaman, 2013).

While interesting and thought provoking, unless there is a clear reason to switch to an entirely new concept of time, the unfamiliarity of these concepts do not justify the switch. Additionally it is impossible to know whether these time scales would be any more useful in the future than current time scales.

Chapter Seven: Summary

- Re-defining UTC to cease leap second adjustments would establish a uniform, continuous time scale for use as civil time. It also would decouple civil time from Earth rotation which could be problematic for processes involved in orbit determination, geodesy, and astronomy, and would be at odds with public perceptions of timekeeping.

- Clearly, changing the definition of UTC to eliminate leap seconds would eliminate the computer system failures that are sparked during leap second insertion. However, the majority of computer systems do not experience failures around leap second insertion and systems that either correctly use UTC with leap seconds or implement the insertion of leap seconds without issue would need to be reconfigured.

- The extent to which changing the definition of UTC will impact legal time in countries around the world is unknown. Similarly, it is unclear how timing relationships will be affected between countries that use UTC for legal and civil time and those that use other standards related to Earth rotation.

- The true problem behind the noted negative impacts of leap second insertion is a lack of standardization. In order to achieve standardization decisions regarding the future of civil time must consider the needs of users who require a continuous representation of time as well as the needs of high precision users. Otherwise, independent time scales will become increasingly prevalent. Additionally, software standards regarding time scales and time/date representations must be revisited to ensure that computer systems handle time in compatible ways.

- A change in the definition of UTC would benefit some groups and be to the detriment of others. Implementing change is expensive. Whether the definition of UTC is altered or not some groups involved in the leap second debate will have to change practices in order to achieve time scale standardization and expend the resources required to do so. The groups and entities required to bear the costs of change will be determined by decisions made about leap seconds.

- If the practice of leap seconds is discontinued then UTC would become another atomic time scale with a constant offset from TAI, similar to GPS time. Such a time scale would be no different practically than TAI itself. This has no benefit over choosing TAI as civil time and has the cost of losing the link between civil time and Earth rotation.

- Choosing to maintain *and* disseminate dual time standards, such as both UTC and TAI, appears to be the best solution to the question about leap seconds. Both time scales already exist. Both are based on the stable atomic second. Time experts already are familiar with them. Known conversion algorithms exist for transforming time from one scale to the other. Additionally this solution avoids change to the legal time systems around the world and matches people's perception of time with reality. If TAI is disseminated to a higher level of accuracy, such as the nano- or pico- second, it could satisfy the needs of both high precision users and those needing a continuous, uniform time scale.

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