(Preprint) AAS 11-662

LEGISLATIVE SPECIFICATIONS FOR COORDINATING WITH UNIVERSAL TIME*

John H. Seago,† P. Kenneth Seidelmann,‡ and Steve Allen§

The abolition of intercalary (leap) seconds within Coordinated Universal Time (UTC) would create a new civil timekeeping standard fundamentally different from solar timekeeping or Earth rotation. Such a standard has no known civil precedent and would present national governments with certain legal, technical and philosophical questions brought by the abandonment of the long-standing mean-solar-time standard. This paper elevates awareness of some of these questions; specifically, the laws of some nations and international unions require time based on the mean solar time at the meridian of Greenwich, or, if one prefers, Universal Time (UT). Since statutory specifications have not demanded ultra-precise uniformity of rate for civil timekeeping based on mean solar time, the continued synchronization of atomic UTC with Universal Time has allowed UTC to proliferate as a legally acceptable world standard. It is presumable that some nations promoted the legal status of "UTC" in the belief that a time scale named "Coordinated Universal Time" might remain coordinated with Universal Time in perpetuity. For this reason, a civil broadcast standard no longer coordinated with UT might not be easily reconciled with existing national statutes, thus requiring changes to statues or exceptional broadcast realizations. Civil broadcast standards failing to approximate Universal Time would best avoid the label "Coordinated Universal Time" and its acronym "UTC", since these descriptions have always implied a realization of Universal Time, in title and purpose, both inside and outside statutory and regulatory prescriptions.

INTRODUCTION

Coordinated Universal Time (UTC) establishes a base for the coordinated distribution of standard frequencies and timing signals per ITU-R Recommendation 460.[1] UTC has the same rate as International Atomic Time (TAI) maintained by the International Bureau of Weights and Measures (BIPM), but UTC epochs are infrequently adjusted relative to TAI by inserting (positive) or neglecting (negative) intercalary ("leap") seconds to assure its rough concordance with Universal Time. These adjustments are announced by the International Earth Rotation and Reference Systems Service (IERS), a scientific analysis organization established by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG).

---

* This paper updates the unpublished manuscript "National Legal Requirements for Coordinating with Universal Time" written in 2003 by John H. Seago and P. Kenneth Seidelmann.

† Astrodynamics Engineer, Analytical Graphics, Inc., 220 Valley Creek Blvd, Exton, PA, 19341-2380.
‡ Research Professor, Astronomy Department, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904.
§ Programmer/Analyst, UCO/Lick Observatory, ISB 1156 High Street Santa Cruz, CA 95064

There are at least two concepts that define the modern duration of time known as the second. *Universal Time* (UT or UT1) is a precise astronomical measure of the rotation of the Earth on its axis, synonymous with *mean solar time at the meridian of Greenwich*, sometimes known simply as *Greenwich mean tim*e (GMT).[2, 3] The mean astronomical second is $^{1}/_{86400}$ of the mean solar day.[4] The more recent *Système International d'Unités* (*SI*) second is based on 9192631770 periods of the radiation emitted from cesium 133 at a temperature of 0 K.[5] This atomic second was calibrated against the theoretically uniform "Ephemeris time"—the pre-relativistic independent variable of solar-system ephemerides based on astronomical observations from the 18th and 19th centuries.[6] Astronomical time serves as the basis for civil time, but Ephemeris time was never intended or designed to represent mean solar time exactly.[7,8] Rather, at its inception, Ephemeris time was considered to be a specialty time scale "for the convenience of astronomers and other scientists only," whereby it "seemed logical to continue the use of mean solar time […] for civil purposes."[9] Clock adjustments are therefore needed if civil time (based on Earth rotation) is also expressed in terms of *SI* seconds (calibrated by Ephemeris time).[10]

UTC is a continuous[*] time scale having duality of purpose: it completely preserves the ultra-precise uniformity of atomic frequency standards while maintaining a system of labeling epochs that remains in close proximity to Universal Time. Specifically, UTC has always respected national statutory requirements for mean solar time at Greenwich to better than one second. The *Conférence Générale des Poids et Mesures* (CGPM) endorsed the usefulness of UTC as a basis of civil time only after "considering that […] UTC is […] an approximation to Universal Time, (or, if one prefers, mean solar time)."[11] Prior to CGPM endorsement, few (if any) countries had recognized UTC by statute. Almost all countries now acknowledging UTC as a legal or regulatory standard adhered to a UT standard previously, with UTC also being a realization of Universal Time in title and purpose at the time of adoption. Consequently, a requirement for mean solar time is reflected in all time-keeping law today; legal time is explicitly referenced to Earth rotation in some countries, in others it is based on atomic time adjusted for Earth rotation, but in no country is legal time known to disregard Earth rotation.

Because the global transmission of UTC began wirelessly, international responsibility for its definition historically landed with the Radiocommuncation Bureau of the International Telecommunication Union (ITU-R). The ITU-R is an administrative body chartered under the United Nations, providing regulatory recommendations that affect information and telecommunication technology.[12] After

> *considering… that UTC is the legal basis for time-keeping for most countries in the world, and de-facto is the time scale used in most others…*

via Study Question ITU-R 236/7 "The Future of the UTC Timescale" (2001), the ITU-R Assembly agreed that the following should be studied: [13]

> *What are the requirements for globally-accepted time scales for use both in navigation and telecommunications systems, and for civil time-keeping?*
>
> *What are the present and future requirements for the tolerance limit between UTC and UT1?*

[*] The practice of coercing mean-solar-time clocks to display UTC results in the unfortunate mischaracterization of the atomic UTC as a time scale lacking sequence or coherence (*e.g.*, is "discontinuous"). UTC is completely sequential and coherent within the prescriptions of the UTC standard.

Implied by the ITU-R Study Question is that the timekeeping requirements for "navigation and telecommunications systems" may be distinct from those of "civil time-keeping", although requirements may overlap. Within the context of the ITU-R's purview, c*ivil time-keeping* is, arguably, time kept for purposes beyond navigation and telecommunications systems. As implied by the Study Question, civil timekeeping requires "legal" context for precise definition and assessment of "present and future requirements."

ITU-R Working Party 7A appointed a Special Rapporteur Group (SRG) on the future of UTC in October 2000 to address its Study Question.[14] One of the earliest public reports of the SRG's activities noted that consideration of legal aspects were highly relevant to its decision making:

> …the second meeting of the ITU-R Special Rapporteur Group met in Paris 21-22 March 2002. The Special Rapporteur Group has converged to the opinion of freezing the present difference between UTC and International Atomic Time (TAI) at the current value of 32 seconds. It was decided at the Paris meeting that it would be necessary to retain the name "Coordinated Universal Time" and the abbreviation (UTC) to avoid potential problems regarding the definition of national time scales. UTC is the legal basis for time in many countries. Consequently, many laws might have to be rewritten to account for this change. [15]

The practical effect of halting leap seconds is to change the basis of civil time-keeping from mean solar time and/or Earth rotation. Thus, national laws might have to be rewritten regardless; jurisdictions that recognize Universal Time or mean solar time at Greenwich as an explicit legal standard instead of UTC (United Kingdom, Ireland,[16] provincial Canada, *etc*.) cannot be spared from addressing the legality of a fundamentally new civil standard like UTC without leap seconds. Only very recently have some industrialized nations come to recognize UTC explicitly by statute (*e.g*. provincial Australia by 2005, the United States of America in 2007). For nations that have legally recognized "UTC" for many decades (France, Germany, the Netherlands, Switzerland, *etc*.), there may be a legal question of whether the meaning of the time scale entitled "Coordinated Universal Time," once legally adopted should be changed without further legislative endorsements. Legal and technical considerations may therefore necessitate a uniquely different name for such a fundamentally different standard, contrary to the reported opinion of the study group.

WHAT TIME IS "IT"?

Civil Time

The ultimate nature of time is a deep and uncertain philosophical question.[17] In the 15th century, Leonardo da Vinci noted that time-keeping involved concepts of position and extension or duration, the former responding to the question of "When?" while the latter responding to the question of "How long?"[18] When atomic time scales became available, philosophical arguments flourished about the fundamental distinction between the astronomical practice of *dating events*, versus the atomic measurement of *time interval*, because "the difference between these concepts of date and time interval is important and has often been confused in the single word *time*." [19] One argument for having civil atomic time closely coordinated with Universal Time was that atomic oscillators, generating ultra-precise frequency, only provided for a measure of "time interval" from an arbitrary epoch but not a measure of "time" in the traditionally understood sense of date epoch.[20] This appears to be one of the motivating reasons for the UTC time scale as it exists today with leap seconds and why this practice has served as a legally acceptable standard internationally.

Another motive for the current definition is continuity with solar time-keeping going back to antiquity. Historically, civil time has been recorded by recurring astronomical phenomena, these being moderately verifiable by the general public. According to Newcomb (1906), the distinction between "day" (as a calendar date) and "time of day" had resulted in two divisions for time expression:[21]

> The main purpose of a measure of time is to define with precision the moment of a phenomenon. The methods of expressing a moment of time fall under two divisions: one relating to what in ordinary language is called the "time of day," and depending on the earth's rotation on its axis; the other on the count of days, which leads us to the use of years or centuries. In any case, the foundation of the system is the earth's rotation. The time of this rotation we are obliged, in all ordinary cases, to treat as invariable, for the reason that its change, if any, is so minute that no means are available for determining it with precision and certainty. [*sic*] There are theoretical reasons for believing that the speed of rotation is slowly diminishing from age to age, and observations of the moon make it probable there are minute changes from one century to another. If such is the case the retardation is so minute that the change in the length of any one day cannot amount to a thousandth of a second. Yet, by the accumulation of a change even smaller than this through an entire century, the total deviation may rise to a few seconds and, in the course of many centuries, to minutes.

Of Newcomb's two divisions for time expression, recurring "time of day" appears less fundamental, being a subdivision of the fundamental unit of astronomical civil and religious calendars— the "day". Newcomb's basic understanding of time is also interesting because the non-uniformity of the mean solar day was already presumed, even before it was widely adopted as a statutory basis for legal and civil times.

Mean Solar Time

By precisely measuring the duration of the year in terms of sidereal days (*i.e.*, 366.242 transits of the vernal equinox), and by recognizing that there is one less solar day per annum than sidereal days, *mean solar time* is realizable with a clock whose diurnal rate of operation exceeds the rate of sidereal time by approximately 3^m56^s (1/366.242) per sidereal day.[22] The rates of mean solar time and mean sidereal time are thereby proportional to Earth rotation which is measured by observing cataloged celestial objects beyond the solar system.[23] Historically this was done from fixed observatories such as the Airy transit circle at Greenwich.[24] Today, this is done with Very Long Baseline Interferometry observing extra-galactic quasi-stellar radio sources. As a uniform time scale, mean solar time remained basic to both civil and scientific time keeping into the 20th century, but mean solar time is especially useful for civil timekeeping purposes, being the form of sidereal time that keeps pace with the synodic day on average.

While mean solar time had been used for centuries, the introduction of Newcomb's *Fictitious Mean Sun* enhanced the practicality and accuracy of this standard. Explicit almanac references to the Mean Sun were used until the official implementation of Ephemeris time in 1960.[25] Today, Universal Time is not explicitly based on an analytical Mean Sun, but it is defined to be linearly proportional to Earth rotation angle using a constant of proportionality traceable to Newcomb's determination of the mean motion of the apparent Sun.[26] This makes UT1 a very close approximation to the mean diurnal motion of the Sun, such that the rates of "Universal Time" and "mean solar time" are practically equivalent in the very long-term.[27]

Mean Solar Time at Greenwich

Earth-rotation angle provides a sequentially increasing continuum that is everlasting and widely apparent, and its rate of uniformity is far superior to most mass-produced clocks and computers in use today.[28] To define a global time scale based on Earth rotation, the specification of a standard reference meridian on the Earth is necessary. The International Meridian Conference of 1884 resolved to adopt "the meridian passing through the center of the transit instrument at the Observatory of Greenwich as the initial meridian for longitude."[29] Their decision was facilitated by the fact that many nautical charts and almanacs were referenced to the Greenwich meridian and mean solar time at Greenwich was already commonly used for navigation.

Often described as *Greenwich Mean Time* (GMT), mean solar time at Greenwich is the legally recognized basis for civil timekeeping of most nations now or historically. The acronym GMT survives as a common navigational synonym for UT1 despite admonitions from as far back as 1928 that "astronomers are advised not to use the letters GMT in any sense for the present."[30, 31] The decrease in GMT's technical usage over time has caused its description to suffer in more general literature, with some dictionaries and encyclopedias now vaguely defining Greenwich mean time or GMT as simply as "the local time at Greenwich, located on the 0° meridian."[32] Such imprecise descriptions are sometimes coupled with factually incorrect statements: one example that has now multiplied into the definitions of some dictionaries and technical glossaries is the unusual claim that "GMT was replaced by UTC in 1986."[*]

While the rates of Universal Time and "mean solar time" have been made practically indistinquishable by virtue of definition, the specification of what is meant by "at Greenwich" may be a different question. In 1925 astronomical and navigational almanacs in the USA and Great Britain changed from "astronomical days" which began and ended at noon to adopt "civil days" beginning and ending at midnight. Thus, the epoch previously referred to as 31.5 December 1924 in pre-1925 editions became known as 1.0 January 1925 starting with the 1925 edition. However, the British *Nautical Almanac* continued to label this new convention as GMT, resulting in the recommended use of the term "Universal Time" by the IAU.[33] Nevertheless, this 12 h ambiguity posed no apparent issues in the context of legal statutes, as *Greenwich mean time* was already codified before 1925, and in legal contexts it unambiguously meant civil time of day beginning and ending at midnight.

A more subtle matter might be the precise location of the prime meridian from which to reference Earth orientation. The reference meridian of the modern global terrestrial reference frames (*e.g.*, ITRF, WGS-84) no longer passes directly through the Transit Circle Room at Greenwich, but is presently located about 100 m to the east, or, advanced by roughly one-third of a second of Earth rotation (Figure 1). Without elaborating on the very many details, this situation is mainly due to the fact that terrestrial reference frames are now maintained using different techniques, and are also affected by gradual geophysical effects such as polar motion and plate tectonics.[34] The celestial reference frames from which Earth orientation is determined have also changed substantially in terms of accuracy and observing techniques since the Airy transit circle was commissioned in the mid-19th century.[35]

Because *Greenwich mean time* is no longer maintained according to the same methods as when it was adopted into law, these technicalities can lead to questions over its legal relevance. For example, in response to concerns of legality, the Report of the International Union of Radio Science (URSI) Commission J Working Group on the Leap Second (2000) parenthetically suggested that Greenwich mean time "has not existed for thirty years."[36] The question of whether

[*] Time-keeping nomenclature is often inaccurate in general literature, but the origin of this incorrect claim is particularly unclear. The significance of "1986" might refer to CCIR Recommendation 460-4 (1986), which was the defining document for UTC in force when the IERS was officially established.

"Greenwich mean time is ambiguous" has also been debated within the UK Parliament's House of Lords. [37] However, these concerns may be assuaged as one considers the different levels of legality that may address such.

Figure 1. Greenwich Transit Circle Room v. the IERS Reference Meridian.

"Official Time"

Within the context of this discussion, *legal time* is that prescribed by the law or decree of a sovereign national authority within its own jurisdictional boundaries. The word *legal* means "of or relating to law," where *law* implies imposition by a sovereign authority and obligation of obedience by all subject to that authority.[38] The matters of "imposition" and "obligation" become complicated when internationally recommended practice conflicts with national legality. Furthermore, there are various classes of national law: *statute law* is that prescribed by legislatures, *case law* is established by judicial decisions (sometimes owing to an interpretation of ambiguous legal nomenclature or obsolete terminology), and *regulation* deals with details or procedure by one so legally authorized.[39] Related to case law is presumptive *common law*, the body of law "that derives its force and authority from the universal consent and immemorial practice of the people," sometimes unwritten in statute or code, and constituting the basis of English legal systems.[40] When statutes and regulations conflict, they are often resolved by changes in regulation or through the consideration of case law and/or common law, rather than by revision of statute.

The large majority of statutory citations of legal time seem concerned with the management and application of time as a commodity, rather than the basis of its definition.[41] For example, the specification of official holidays, so-called "blue laws" restricting commercial activity or labor to certain days or times, *etc*. all make use of timekeeping at a level where the use of UTC versus UT1 has no practical consequences. This is not unexpected however, for…

> With very limited exceptions, however, common law legal systems have long reckoned periods of legal significance by the calendar, not by the clock. *See Mason v. Bd. of Educ.,*

> 375 Md. 504, 826 A.2d 433, 435 (2003) ("[A] day is usually considered by the law to encompass a single, indivisible moment in time."); *State v. Stanley,* 67 S.W.3d 1, 3 (Tenn.Crim.App.2001) ("[T]he general rule for computation of time is that the law knows no fractions of a day." (internal quotation marks and citation omitted)); 2 WILLIAM BLACKSTONE, COMMENTARIES ON THE LAWS OF ENGLAND 141 (1769) ("In the space of a day all the twenty four hours are usually reckoned; the law generally rejecting all fractions of a day, in order to avoid disputes.").[42]

Indeed, common law pressed into wide use the time span called "a year and a day" that should include the date of an event (such as an offense) without regard to the time of day of its occurrence, to avoid calculating precise time intervals.[43]

Statutes often defer the details of official realizations to an authorized regulatory agency or another responsible entity; however, there is some question of how well time of day realized by national regulatory authorities remains true to the intentions of its legal prescription. There is little choice but for regulators to suppose that national statutory specifications are important, if only because of their existence, yet because of potential differences, it may be prudent to give this kind of time a different label, such as *official time* or *regulatory time*. For common-law legal systems, one might offer:

> *Official time* or *regulatory time* is a realization of the legal time legislated by a sovereign authority which intends to satisfy public expectations for civil time based on historical, philosophical, religious, and technological prejudices, precedents, and requirements.

Within the context of Question ITU-R 236/7, "civil time-keeping" presumably refers to legal time enforced and maintained—that is, *official* or *regulatory time* at a national level. UTC is primarily a regulatory time (defined by what is foremost a regulatory body, the ITU-R), the legal status of which has been codified in many, but not all, jurisdictions.

THE NEED TO CONSIDER NATIONAL TIME-KEEPING LAWS

International treaties serve to establish and harmonize standards insofar as the civilian user communities recognize, and their local governments enforce, those definitions and recommendations through national legislation (where "enforcement" might include the disbursement of public monies for the national maintenance and distribution of so-called official or regulatory time). Because national governments maintain their own realizations of UTC for official use in real time, the Study Question "What are the requirements… for civil time-keeping?" seemingly urges careful consideration of national statutes establishing time standards for individual governments. However, this viewpoint may not be shared by all who study this issue. For example, Nelson *et al.* (2001) suggest "should the definition of UTC be revised, the effect on legal codes may need to be investigated." [44] This implies that the laws of individual nations are an afterthought when revising the definition of UTC; the rationale may be that few national laws numerically stipulate a required proximity between official time and astronomically based legal concepts like mean solar time or Universal Time.[45]

Consideration of what might be satisfactory to national authorities contributed to a "consensual opinion" reached within the SRG and presented to interested and representative parties at the ITU-R *Special Colloquium on the Future of UTC* in 2003.[46]

> Serious consideration was given to a contribution proposing that the maximum tolerance of DUT1, the difference between UT1 and UTC, be increased to one hour. This alternative was based on a similar concept of daylight saving time. This modification of standard time used by nations that is determined by national civil authority appeared to satisfy all civil requirements and concerns.[47]

However, that the leap-hour proposal "was based on a similar concept to daylight saving time" should not suggest that it satisfies "all civil requirements and concerns" in the sense of "globally-accepted requirements" for civil timekeeping. This becomes evident through consideration of national legislation.

Presently, the majority of the world does not practice summer-time, or, daylight-saving-time clock adjustments, whether measured by population, number of countries, or regional land mass (Figure 2). In tropical regions where the duration of daylight is less variable, summer-time adjustments are generally unwarranted and undesired.[48] Nations that still practice summer-time adjustments do so at different times of the year, with the northern and southern hemispheres exercising seasonal clock adjustments out of phase with each other. In the history of civil timekeeping, daylight-saving adjustments are relatively new and its long-term practice is unclear.[*]

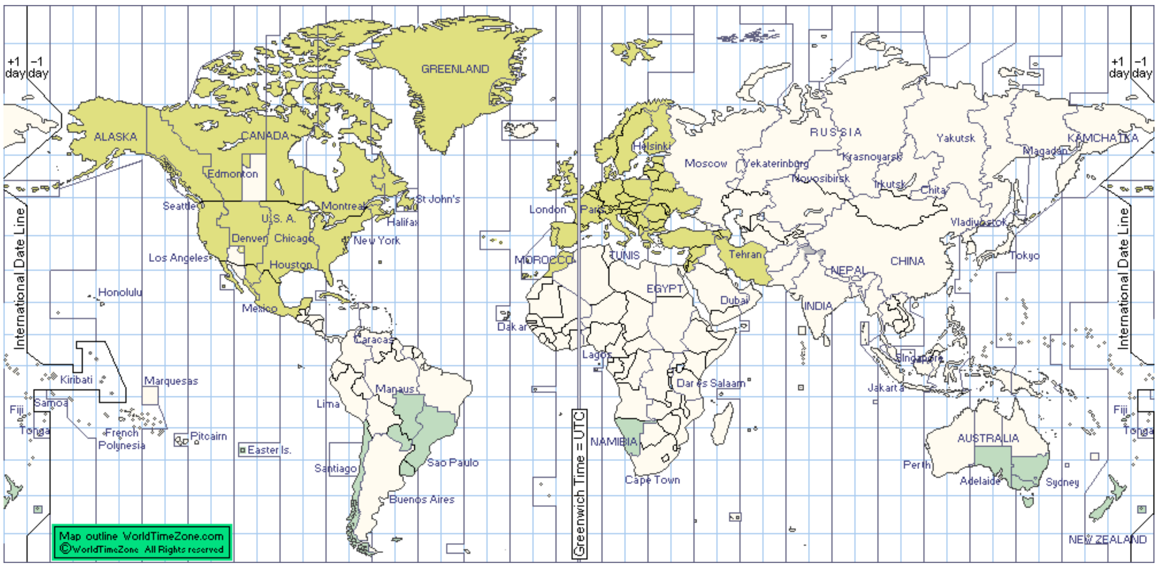

Figure 2. Daylight-Saving Time Practice (shading indicating current legislated practice). Source: WorldTimeZone.com, used with permission.

Also, national statutory prescriptions for standard (zone) time and daylight-saving time describe two distinct concepts. One concept is the local or regional time indicated by official clocks; the other concept is the coordinated background or *basis time* from which all official clocks are offset, such as mean solar time or UTC. Some (but not all) nations allow for summer-time adjustments of local civil clocks, but no nation is yet known to express legal tolerance for significant adjustments to the coordinated background or *basis time* which underlies and regulates civil time-keeping.

Finally, while the proposed leap-hour adjustment attempts to manage statutory expectations that UTC must remain coordinated with Universal Time, there is no evidence that coordination to the nearest hour (15 degrees) has any technically useful purpose. Therefore, there is no technical

[*] The eight members of the SRG, and its three special representatives, were from nations where daylight-saving time was practiced at the time of the proposal.

basis by which regulatory authorities should interpret the statutory specifications for Universal Time or Greenwich Time so inaccurately.

The leap-hour proposal was questioned by attendees of the ITU-R Special Colloquium; because the label "Universal Time" has always been a term reserved for time linked to Earth rotation, continued use of the terms "Coordinated Universal Time" and "UTC" seemed inappropriate for atomic timekeeping uncoordinated with Earth rotation.[49] Any small problems now associated with leap seconds would be greatly amplified by larger adjustments in the future. The need for a leap-hour adjustment would likely not occur for another six to eight centuries, such that it appeared presumptuous to codify such adjustments now.[50] Rather, the cessation of leap seconds simply relinquishes the long-standing mean solar day, supplanting it with a "metric" day of exactly 794,243,384,928,000 cycles of cesium-133 radiation, or 86400 *SI* seconds.[51]

LEGAL REQUIREMENTS FOR MAINTAINING UNIVERSAL TIME

Statutory standards for timekeeping have been historically expressed and understood in navigational or astronomical terms (*e.g.*, "longitude", "meridian", "Greenwich", *etc*.).[*] Many timekeeping statutes still reflect some expectation that Earth rotation regulates the civilian notion of Time (including the meanings of commonly understood concepts and words such as "day", *etc*.). Even time legislation explicitly based on "UTC" often includes navigational or astronomical elements or terminology (time zones, "antemeridian", *etc*.)

Today, the navigational use of "Greenwich mean time" still implies UT1 as the instantaneous orientation of Earth determined by the IERS. Yet the uniformity of UT2—UT1 corrected for seasonal variations of Earth rotation (measured in milliseconds)—also made UT2 the basis for standard-time broadcasts for many years.[52] However, the original (legal) concept for mean solar time predates the various other realizations of Universal Time (*e.g*., UT0, UT1, UT2, UTC). Universal Time is also something to be observed and extrapolated, or reduced after the fact, and different people may acceptably observe and reduce Universal Time differently (the methods of which are also unspecified under law). This further implies that the law does not place extremely rigid statutory prescriptions on the realization of Universal Time for legal purposes; rather the meaning of any technical term must be assessed within the context of the state of the art.

For these reasons, one cannot definitively assign a specific realization of Universal Time within most legal contexts. This may also be why UTC has endured as a legally acceptable proxy for Universal Time; atomic UTC is a technically useful realization of Universal Time. Certainly, the unchallenged juxtaposition of UTC for "mean solar time at Greenwich" in many applications suggests that a fraction of a second may already be a legally allowable level for civil-time ambiguity, but a redefinition of UTC that exceeds this tolerance should necessitate consideration of national statutes. Technically "day" and "year" are non-*SI* units and the status of a calendar maintained with metric days versus Earth rotations also becomes a potential legal question of the future. Hence, consideration of national laws seems necessary to ensure that internationally broadcast time standards remain acceptably legal across all jurisdictions.

Standard Time of the United States of America

Statutory authority over standard time in the United States of America resides with its Congress. When the US Congress first enacted the Standard Time Act of 1918, it legislated

[*] For example, Argentina's final summer-time declaration in 2009 references the "meridiano de Greenwich." http://www.hidro.gov.ar/Noticias/RENoticias.asp?idnot=197

> "That, for the purpose of establishing the standard time of the United States, [...t]he standard time [...] shall be based on the mean astronomical time of [...] longitude west from Greenwich."[53]

At this time there were only two concepts that could be interpreted as "mean astronomical time": mean sidereal time and mean solar time. Both are defined by Earth rotation, the rate of one proportional to the other, and it was already thought that the length of the mean solar day was increasing at a rate of many seconds per century.[21] Newcomb had suggested that "astronomical mean time" technically described the day starting at noon, but the difference of twelve hours between civil and astronomical time was as apparent as night and day and there was little concern over the need for more specialized legal nomenclature. So within the technical and historical context of long-standing civil conventions, the phrase "mean astronomical time" was all that Congress needed to convey a precise legal notion of the mean solar day beginning at midnight relative to Greenwich.

By 1958 however, the IAU had defined the more uniform astronomical time scale known as Ephemeris Time, the rate of which was adopted by the CGPM in 1960 to define an *SI* second.[54, 55] The specification of another uniform, yet fundamentally different, astronomical time scale approximately one-half minute from mean solar time perhaps rendered the previous legal descriptor "mean astronomical time" ambiguous. When Congress passed the Uniform Time Act of 1966, language was clarified by replacing the phrase "mean astronomical time" with "mean solar time" which ensured that standard time would be regulated by the astronomical concept of Universal Time rather than the astronomical concept of Ephemeris Time.[56]

Such Congressional action afforded unambiguous legal protection for mean solar time when a more uniform (but secularly deviating) time scale was available and might have been interchanged owing to the obsolete wording of law. In hindsight, this action might also suggest a low legal tolerance for a basic time standard differing more than several seconds from what was legally intended or required at the time of adoption. But perhaps just as important, the distinctions in the realization of broadcast Universal Time (*i.e.*, UT2), and even the more astronomically precise term "Universal Time" itself, went unrecognized under the Uniform Time Act. This further suggested that legislation was not only tolerant of subtle ambiguities in the realization and legal meaning of "mean solar time" (all being well below one second), but statutes chose to emphasize the conceptual aspect of "solar" time in an astronomical standard.

While Congress left standard time defined in astronomical and navigational terms, addenda to federal code acknowledged UTC as an acceptable regulatory proxy for mean solar time where limited to most practical purposes associated with radio regulations and telecommunication.[57] Specifically

> *Coordinated Universal Time (UTC).* Time scale, based on the second (SI), as defined in Recommendation ITU-R TF.460–6…
>
> Note: For most practical purposes associated with the ITU *Radio Regulations*, UTC is equivalent to mean solar time at the prime meridian (0° longitude), formerly expressed in GMT.

Thus "UTC" in this context still refers to an atomic time scale that remains within ±0.9 seconds of Earth rotation, per the Federal Radionavigation Plan (an official US policy published jointly by the US Departments of Transportation* and Defense).[58] But as a legal basis for regulating civil time, US code is not known to have otherwise acknowledged or supported the use of Ephemeris Time, or any parallel variants of its successors such as TAI. Instead, US code legally authorized the use of the *SI* second as a measure of time interval as part of the metric system.[59] Mean solar time measured in *SI* seconds thereby appears to be legal in the US. This, of course, describes UTC with leap seconds.

In 2002, the *National Institute of Standards and Technology* (NIST) *Authorization Act of 2002* was introduced into the US Senate.[60] Primarily an appropriations bill for NIST, Section 207 of the bill proposed to amend the Uniform Time Act of 1966 by changing the basis of standard (zone) time from the "mean solar time" of standard meridians west of Greenwich to "Coordinated Universal Time" retarded by specific numbers of hours. It also added the following statutory definition for UTC:

> Coordinated Universal Time Defined—In this section, the term 'Coordinated Universal Time' means the time scale maintained through the General Conference of Weights and Measures and interpreted or modified for the United States by the Secretary of Commerce.

The 2002 Senate bill did not pass, but the language reappeared within the so-called America COMPETES Act of 2007, which became public law on August 9, 2007.[61] In the final version the statutory definition for UTC was amended with "…in coordination with the Secretary of the Navy."† That UTC needed a statutory definition (whereas the astronomical concepts of "mean solar time" and "mean astronomical time" did not) implies there might be greater legal uncertainty or ambiguity as to its meaning without such a definition.

The statutory change from "mean solar time" to UTC was offered as a technical amendment to revise "Outdated Specifications" associated with use of the metric system. Within this context, the General Conference of Weights and Measures (CGPM) is the international delegation under the Treaty of the Meter that manages arrangements for sustaining and improving the metric system, including major decisions concerning the organization and development of the International Bureau of Weights and Measures (BIPM). However, there is no BIPM service by which one can obtain official UTC time signals or otherwise set a timekeeping device.[62] Officially, UTC is evaluated in arrears by the BIPM through published corrections to the emissions of primary frequency standards via *Circular T* a month or more after the fact.[63] However, the multitudes of ordinary users require an instantaneous realization for legal purposes. Moreover, the CGPM does not define UTC; UTC is a real-time broadcast specification defined by ITU-R Recommendation 460 which is not under the direct purview of the CGPM.

While the accuracy of civilian timepieces has greatly improved to a point where a leap second might be detectable, very few timepieces support (display) leap seconds. Arguably, clocks of such manufacture are still generic mean-solar-time clocks. Such anecdotal evidence might further imply that generic Universal Time is the standard being upheld, employed, or expected. Therefore, it might be argued that, after more than a century of statutory recognition and civil usage, time based on Earth rotation is anticipated by custom and precedent. Congress is presumed to legislate against the background of the common law, but Congress can override any common-law pre-

* The responsibility for standard time and time zones in the USA resides with the Secretary of Transportation, per US Code Title 15, Chapter 6, Subchapter IX, Sec. 262.
† The Secretaries of Transportation and the Navy are named because NIST and the US Naval Observatory respectively operate under their authorities.

sumption with express language.[64] Yet, because UTC was a realization of mean solar time at Greenwich at the time of its adoption, it could be suggested that Congress intended to substitute one expression for mean solar time at Greenwich for another having more regulatory precision.

Standard Time of the United Kingdom

When *Greenwich mean time* became a legal standard across Great Britain in 1880, there was no other civil meaning associated with it beyond mean solar time at Greenwich.[65] Today, one confusing aspect is that some civilian applications casually describe UTC broadcasts as "GMT". Furthermore, Parliamentary law did not specify a legal title for British Summer time (which is GMT plus one hour); this too results in occasional descriptions of British summer time as GMT.*

However, that Greenwich mean time has come to be recognized as being casually synonymous with UTC in ordinary language does not further imply that these two concepts are to be permissibly interchanged. Rather, the presence of leap seconds makes UTC synonymous with *Greenwich mean time* and justifies the practical use of UTC as a proxy for GMT wherever GMT is prescribed today. In 1978, Donald Sadler commented that "the two forms of [atomic and solar] time-scale are fundamentally different; both are essential […] and it would seem important to ensure that no unnecessary confusion between them is introduced."[66] Yet in those countries where UTC has not been made explicitly legal, one may conclude that Earth rotation, and not atomic frequency, was intended as the ultimate basis for civil time. This intention seems most explicit within the UK, where bills attempting to replace GMT with UTC have been debated yet failed to overcome Government neutrality.[67, 68] This is because English speaking countries tend to make statutory distinctions between UTC and GMT; for example, New Zealand amended its Time Act of 1974 effective 30 March 1987 to henceforth reference UTC in place of GMT.[69]

Standard Time of Canada

Canada is an example of a nation where both UTC and Greenwich mean time (or, simply "Greenwich time") are simultaneously legislated by different provinces. Québec's recognized standard has been UTC since 2006,[70] while other provinces such as Alberta,[71] Manitoba,[72] Ontario,[73] Saskatchewan,[74] *etc*., recognize Greenwich mean time. Therefore, legal consistency between the Canadian provinces suggests a need for continued coordination of Coordinated Universal Time and Greenwich mean time.

Standard Time and the European Union

The directives of European Parliament reconciling the application of summer-time adjustments across the European Union is an example of an instruction applicable to EU member nations having different bases for national time.[75] Of the twenty-two (22) versions of the directive available in their original languages, twelve (12) cite *Greenwich mean time*, *Greenwich time*, or *GMT*, six (6) cite *Universal Time*, three (3) cite *world time*,† and two (2) cite *UTC* or *Coordinated Universal Time* explicitly (Table 1). Thus, 59% make explicit reference to GMT or "Greenwich" by name in their original language versions, while only 9% of the versions unambiguously declare UTC. An interesting question might be whether the dominance of *Greenwich time* within translations because the original text was expressed that way. Regardless, it appears that legal

* A similar situation exists in the USA, where the term *Daylight-Saving Time* is not explicitly codified and the exact wording of statute implies that *Standard Time* changes according time of year. Nevertheless, in practice the time in effect designated either *Standard Time* or *Daylight-Saving Time*.

† Traditionally, "world time" is synonymous with and translated as either *Universal Time* or GMT, although the Danish version annotates that UTC was specifically meant.

consistency between member countries of the European Union may require close coordination of Coordinated Universal Time and Greenwich mean time.

Table 1. Specifications of National Time Bases in EU Directive 2000/84/EC on Summer-Time Arrangements

	Language	Original Language Quotation	Translation
BG	Bulgarian	*по Гринуич*	Greenwich time
EL	Greek	*ώρα Γκρίνουιτς*	Greenwich time
EN	English	Greenwich Mean Time	Greenwich mean time
ET	Estonian	*Greenwichi aja järgi*	Greenwich mean time
LT	Lithuanian	*nakties* GMT *laiku*	Greenwich mean time
LV	Latvian	*pēc Grīnvičas laika*	Greenwich mean time
HU	Hungarian	*greenwich-i idő*	Greenwich mean time
MT	Maltese	Greenwich Mean Time	Greenwich mean time
SK	Slovakian	*greenwichského času*	Greenwich mean time
SV	Swedish	*Greenwichtid* (Greenwich Mean Time, GMT)	Greenwich time (Greenwich Mean Time, GMT)
FI	Finnish	(GMT)	(GMT)
CS	Czech	*světového času* (GMT)	universal time (GMT)
PL	Polish	*czasu uniwersalnego* (GMT)	universal time (GMT)
ES	Spanish	*hora universa*	universal time
FR	French	*temps universel*	universal time
IT	Italian	*ora universale*	universal time
PT	Portuguese	*tempo universal*	universal time
RO	Romanian	*timp universal*	universal time
DE	German	*Weltzeit*	"world time"
NL	Dutch	*wereldtijd*	"world time"
DA	Danish	*verdenstid* (UTC)	"world time" (UTC)
SL	Slovenian	*univerzalnem koordinirane času* (UTC)	coordinated universal time (UTC)

Historic Universal Time (GMT) in France

Prior to its complete legal adoption of UTC on August 9, 1978,[76] France decreed its legal standard for Greenwich mean time as "Paris mean time, retarded by 9 minutes and 21 seconds."[77] This previous decree specified a level of precision of one (1) second for GMT or Universal Time. By design, UTC has never deviated from France's originally designated legal resolution for Universal Time; France thereby adopted a UTC time scale historically compatible with, if not identical to, Universal Time as previously acknowledged under French law.

There are two types of solar time, mean and apparent, which are unbiased with each other and differ ±15 minutes annually. It has been suggested that civil authorities are likely to be tolerant of large differences between UT and UTC, insofar as they remain at levels near the difference of mean and apparent solar times.[78] However, it is noteworthy that the static difference between Paris and Greenwich local time is smaller than the periodic difference between mean and apparent solar time, and much smaller than the eventual static offset implied by "leap hours." Paris and Greenwich time differed to such a degree that France found it necessary to legally account for the difference, suggesting another precedent for legal intolerance of standard-time differences beyond one second of what may have been intended or required.

Legal Time of All Nations

As mechanical time pieces flourished, civil conventions for uniform time became almost exclusively expressed with relation to mean solar time. Even after uniform atomic time became available as a broadcast standard, its civil and legal acceptability was secured through leap-second adjustments for the sole purpose of emulating the mean-solar-time standard. The International Radio Consultative Committee (CCIR)[*] affirmed that the establishment of UTC was to provide a realization of Universal Time and mean solar time at Greenwich, *e.g.*,

> The CCIR, *considering*… the continuing need of many users for Universal Time (UT)… *unanimously recommends*… that the transmitted time scale should be adjusted when necessary in steps of exactly one second to maintain approximate agreement with Universal Time (UT)… [79]

and "GMT may be regarded as the general equivalent to Universal Time."[80] It is reasonable to presume that some—perhaps most—countries elevated the legal status of UTC understanding that a time scale named "Coordinated Universal Time" would remain coordinated with Universal Time in perpetuity.

POLITICAL CONCERNS FOR UTC WITHOUT LEAP SECONDS

Even among experts in horology, precision time-scale definitions have not come easy.[81, 82] UTC without leap seconds would be a time scale equal to International Atomic Time (TAI) plus a static offset. It is therefore interesting to speculate about whether the formal definition of TAI may be insufficiently terse for legal purposes, owing to the complexity of the subject. In 1971, the CGPM requested the *Comité International des Poids et Mesures* (CIPM) give a definition to International Atomic Time already in use,[83] the tenuous submission of the *Comité Consultatif pour la Définition de la Seconde* (CCDS)[†] having been

> International Atomic Time (TAI) is the time reference coordinate established by the Bureau International de l'Heure[‡] on the basis of readings of atomic clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of Units.[84]

Later, it became necessary to burden the definition of TAI with General Relativity Theory. By 1980 its definition was reportedly "completed" in this sentence:[85]

> TAI is the coordinate time scale defined in a geocentric reference frame with the *SI* second as realized on the rotating geoid as the scale unit.[86]

---

[*] The CCIR was the predecessor of the ITU-R
[†] The CCDS was predecessor of the CCTF, *Comité Consultatif du Temps et des Fréquences*
[‡] This responsibility is now with the BIPM.

But to astronomers understanding that atomic resonators can only define time as an interval relative to some (arbitrary) epoch, this definition was still insufficient. A further clarification was advanced by the IAU in 1991:*

> TAI is a realized time scale whose ideal form, neglecting a constant offset of 32.184s, is Terrestrial Time (TT), itself related to the time coordinate of the geocentric reference frame, Geocentric Coordinate Time (TCG) by a constant rate.[87]

The IAU resolution implies that the origin of TAI is ideally defined in terms of TCG, although practically speaking, TAI is the realization based on the *SI* second (accurate to the level of the frequency standards) and TCG is practically realized by an ideal mathematical prescription relative to it. To complicate matters a bit more, the IAU further refined the definition of TT in 2000.[88]

The realization of TAI (or, UTC without leap seconds) is more involved than these definitions indicate.[89] TAI is a "paper clock" determined from the weighted average of contributions from frequency standards in many countries. Some less accurate national standards are included with minimal weight, mainly for political reasons. There are different realizations of TAI determined on a monthly basis as well as after the end of the calendar year.

The global establishment of mean solar time at Greenwich overcame many political obstacles and took several decades. Placing atomic UTC without leap seconds in the legal foreground may place additional political or regulatory demands on atomic civil time that background TAI has beneficially avoided. So far TAI continues to be practically defined through BIPM edict, unfettered by national legislation. National law may do well to avoid the subject, but it may not be able should the basis of official time seem arbitrary. US Code has already assigned UTC a legal definition that can differ from what the BIPM prescribes. Without international unanimity on the subject of UTC redefinition, there remains a possibility that different nations could slip onto differing time bases, depending on how closely they preferred these bases to be aligned to Earth rotation.

CONCLUDING SUMMARY

Two legal bases for timekeeping are codified globally. Mean solar time at Greenwich (also known as Greenwich mean time, GMT, or Universal Time, UT1) is an astronomical measure of Earth rotation referenced to the international reference meridian. Coordinated Universal Time (UTC) is a precise timescale based on atomic frequency and used for broadcasting and telecommunications. Because atomic resonators maintain a rate different than mean solar time, an atomic realization of mean solar time must be adjusted; for UTC this adjustment is made to the length of the "UTC day" (the day being a non-*SI* base unit) using occasional *leap seconds*. UTC is therefore an atomic realization of Universal Time in title and practice, which is, in turn, the modern-day complement of Greenwich mean (solar) time.

By international agreement, UTC broadcasts have never differed from UT1 by more than ±0.9 seconds. This is a tolerance which appears to satisfy most legal requirements for civil time scales defined in relation to the mean solar day at Greenwich as stipulated under law by most nations (now or historically), and allows UTC to be used in jurisdictions where astronomical time is (or was) legally prescribed. Allowable deviations larger than this have no known legal precedent in modern times and do not appear to have been tested or reviewed by national judicial or legislative systems.

---

* As far as the authors have been able to discover, this clarification has yet to be recognized by the CGPM.

A proposal will come before the ITU-R Radiocommunication Assembly in January 2012 on whether to create a new time scale uncoordinated with Universal Time. This scale will still be called *Coordinated Universal Time* but it will lack UTC's original duality of purpose to provide both time of day and fundamental frequency. The abandonment of the long-standing mean-solar-time standard will present governments with certain legal, technical and philosophical questions of which this paper attempts to elevate awareness. While the discussion is not intended to be complete or authoritative, it suffices to illustrate that UTC without leap seconds may not be easily reconciled with some existing national statutes. Legislation endorsing a time scale called "Coordinated Universal Time" that is no longer coordinated with Universal Time will remain legally and technically confusing. The potential for legal complications in national courts is conceivable given the complexity of national legal systems, even in countries that acknowledge "UTC" by name as a legal standard. Therefore, fundamental changes to the UTC standard would require explicit changes to national laws.

UTC without leap seconds also creates a new question: is a precisely maintained, indefinite sequence of synthetically generated time intervals a sufficiently viable concept to permanently displace humanity's long-standing precepts of what ultimately regulates Time? This question is not related to satisfying the technical conveniences of today's telecommunication and navigation systems, but is more of a moral, philosophical, or historical question to be thoughtfully upheld by civil law. Similar questions were already considered somewhat by the CCIR and the IAU four decades ago, and the answer was UTC with its existing system of leap seconds.

As currently defined, the existing UTC system appears capable of uniquely tagging any event that may possibly occur during the next 1000 years with full atomic accuracy, and at this time, there does not appear to be any legal requirement for ultra-precise uniformity in civil time beyond what is already being supplied with existing UTC. For decades, applications with very stringent timing requirements (including the US Global Positioning System) have continued to operate successfully despite the existence of leap seconds. Almost all applications non-compliant with UTC came into existence within the last four decades—well after today's UTC standard was established. With the proposal now under consideration, national governments may do well to investigate why certain modern-day applications are still either unwilling or unable to comply with international time-keeping standards while others are functionally compliant. National legislative investigations would help discover what, if any, changes to UTC are warranted. This could avoid unnecessary changes to, or tests of, existing (inter)national legislation, and avoid unnecessary burden to systems, applications, and industries already compliant with current standards.

REFERENCES

[1] Recommendation ITU-R 460-6 (2002), Standard-frequency and time-signal emissions (Question ITU-R 102/7), in ITU-R Recommendations: Time Signals and Frequency Standards Emission, Geneva, International Telecommunications Union, Radiocommunication Bureau.

[2] Seidelmann, P.K. (ed., 1992), *Explanatory Supplement to the Astronomical Almana*c. University Science Books, Mill Valley, CA, p. 6.

[3] Stratton, F.J.M. (ed., 1929), Transactions of the IAU Vol. III, Proceedings of the IIIrd General Assembly, Leiden, The Netherlands, July 5 - 13, 1928, Cambridge University Press, p. 224.

[4] Chadsey, H., D. McCarthy (2000), "Relating Time to the Earth's Variable Rotation." Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, Reston, Virginia, November 28-30, 2000. pp. 237.

[5] 13th CGPM (1967-8), Resolution 1, (CR, 103). Also, *Metrologia*, 1968, Vol. 4, p. 43.

[6] Markowitz, W., R.G. Hall, L. Essen, J.V.L. Perry (1958), "Frequency of Cesium in Terms of Ephemeris Time." *Physical Review Letters*, Vol. 1, pp. 105-7.

[7] McCarthy, D.D. (1991), "Astronomical Time." *Proc. IEEE*, Vol. 79, No. 7, pp. 915-920.

[8] *Explanatory Supplement to The Astronomical Ephemeris and The American Ephemeris and Nautical Almanac* (1961). Her Majesty's Stationery Office, London, p. 66-7.

[9] Clemence, G.M (1948), "On the System of Astronomical Constants," *Astronomical Journal,* Vol. 53, No. 6, Issue 1170, pp. 171–72.

[10] McCarthy, D.D. (2000), "Future Definition of UTC", in *Proceedings of IAU Colloquium 180, Towards Models and Constants for Sub-microarcsecond Astrometry*, K.J. Johnston, D.D. McCarthy, B.J. Luzum, G.H. Kaplan, eds., U.S. Naval Observatory, Washington DC, USA, pp. 363-371.

[11] 15th CGPM (1975), Resolution 5 (CR, 104). Also, *Metrologia*, 1975, Vol. 11, p. 180.

[12] Finkleman, D., S. Allen, J.H. Seago, R. Seaman and P.K. Seidelmann (2011), "The Future of Time: UTC and the Leap Second." *American Scientist*, Vol. 99, No. 4, p. 316.

[13] Jones, R.W. (2001), Question ITU-R 236/7, "The Future of the UTC Time Scale." Annex I of ITU-R Administrative Circular CACE/212, March 7, 2001.

[14] Document CCTF/01-33, "Report of ITU-R Working Party 7A in the Period 1999 to 2001 to the 15th Meeting of the CCTF (Sevres, 20 – 21 June 2001)."

[15] Capitaine, N., Chapront, J., Hadjidemetriou, J. D., Jin, W., Petit, G., and Seidelmann, K. (2003). "Division I: Fundamental Astronomy (Astronomie Fondamentale)," in *Reports on Astronomy 1999-2002, Transactions of the International Astronomical Union*, Vol. 25A, edited by H. Rickman (San Francisco: Astronomical Society of the Pacific), p. 8.

[16] Houses of the Oireachtas, Ireland, Standard Time (Amendment) Act, 20th July 1971: "An Act To Provide For A Period Which Shall Be Known As Winter Time And During Which The Time For General Purposes In The State Shall Be Greenwich Mean Time, And To Provide For Other Matters Connected With The Matter Aforesaid."

[17] Green, R.M. (1985), *Spherical Astronomy*. Cambridge University Press, London. p. 236.

[18] Klein, H.A. (1988), *The Science of Measurement: A Historical Survey*. Dover Publications, Inc. New York, p. 169.

[19] Blair, E.B., (ed.), NBS Monograph 140, Time and Frequency Fundamentals, p. 4.

[20] Sadler, D.H. (1978), "Mean Solar Time on the Meridian of Greenwich." *Quarterly Journal of the Royal Astronomical Society*, Vol. 19, p. 307.

[21] Newcomb, S. (1906), *A compendium of spherical astronomy*. Macmillan Company, p. 114-7.

[22] Seidelmann, P.K., J.H. Seago (2011), "Time Scales, Their Users, and Leap Seconds." *Metrologia*, Vol. 48, pp. S186–S194.

[23] *Explanatory Supplement to The Astronomical Ephemeris and The American Ephemeris and Nautical Almanac* (1961). Her Majesty's Stationery Office, London, p. 67.

[24] Lewis, T., (1885), "The Greenwich system of sympathetic clocks and the distribution of time-signals**."** *The Observatory*, Vol. 8, p. 364.

[25] Seidelmann, P.K. (ed., 1992), *Explanatory Supplement to the Astronomical Almanac*. pp. 78-9.

[26] Capitaine, N., Guinot, B., and McCarthy, D.D., "Definition of the Celestial Ephemeris Origin and of UT1 in the International Celestial Reference Frame," *Astronomy &. Astrophysics*, Vol. 355, 2000, pp. 398-405.

[27] Seidelmann, P.K. (ed., 1992), *Explanatory Supplement to the Astronomical Almanac*. p. 51.

[28] Finkleman, D., J.H. Seago, P.K. Seidelmann (2010), "The Debate over UTC and Leap Seconds". Paper AIAA 2010-8391, from the Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, Toronto, Canada, August 2-5, 2010.

[29] US Government, International Conference held at Washington for the purpose of fixing a prime meridian and a universal day, October 1884: Protocol of the Proceedings. pp. 199-201.

[30] McCarthy, D.D. (2011), "Evolution of timescales from astronomy to physical metrology." *Metrologia*, Vol. 48 p. S134.

[31] IIIrd General Assembly - Transactions of the IAU Vol. III B Proceedings of the 3rd General Assembly Leiden**,** The Netherlands, July 5- 13, 1928 Ed. F.J.M. Stratton Cambridge University Press, p. 224.

[32] *The Macmillan Encyclopedia 2001* (2000), Market House Books Ltd.

[33] Sadler, D.H. (1978), "Mean Solar Time on the Meridian of Greenwich." p. 300.

[34] Guinot, B. (2001) "Solar time, legal time, time in use." *Metrologia*, Vol. 48, S181-S185.

[35] McCarthy, D.D. (2011), "Using UTC to Determine the Earth's Rotation Angle." Paper AAS 11-666, , from Seago, J.H., *et al*., *Decoupling Civil Timekeeping from Earth Rotation—A Colloquium Exploring Implications of Redefining UTC*. American Astronautical Society Science and Technology Series, Vol. 113, Univelt, Inc., San Diego, 2012

[36] Matsakis, D., et al. (2000), Report of the URSI Commission J Working Group on the Leap Second, July 2, 2000. (URL http://www.ietf.org/mail-archive/web/ietf/current/msg13828.htmll)

[37] *Lords Hansard*, Parliament of the United Kingdom, 27 Nov 1996: Columns 257-60.

[38] Merriam-Webster's Collegiate Dictionary 10th Ed. (1998), Merriam-Webster, Inc.

[39] *Ibid.*

[40] Bouvier, J. (1856), *A Law Dictionary, Adapted to the Constitution and Laws of the United States.*

[41] Rakoff, T.D., (2002), *A Time for Every Purpose: Law and the Balance of Life*. Harvard.

[42] *Lagandaon v. Ashcroft,* 383 F.3d 983, 985 (9th Cir. 2004),

[43] *Ibid.*

[44] Nelson, R.A., D.D. McCarthy, S. Malys, J. Levine, B. Guinot, H.F. Fliegel, R.L. Beard, T.R. Bartholomew, (2001), "The leap second: its history and possible future." *Metrologia*, Vol. 38, p. 524.

[45] Levine, J., (2001) "GPS and the legal traceability of time." *GPS World,* Vol. 12, No. 1, pp. 52-58.

[46] Press Release "UTC Timescale Conference", *The Institute of Navigation (ION) Newsletter*, Vol. 12, No. 4 (Winter 2002-2003)

[47] Beard, R. (2011) "Role of the ITU-R in time scale definition and dissemination." *Metrologia*, Vol. 48, p. S130.

[48] Steel, D. (2000), *Marking Time – The Epic Quest to Invent the Perfect Calendar*. John Wiley & Sons, New York, pp. 276-77.

[49] CCTF (2004), Consultative Committee for Time and Frequency (CCTF) Report of the 16th meeting to the International Committee for Weights and Measures (April 1–2, 2004), Bureau International des Poids et Mesures. p. 17.

[50] Stephenson, F.R., L.V. Morrison (1995), "Long-term fluctuations in the Earth's rotation: 700 BC to AD 1990." *Philosophical Transactions of the Royal Society of London, Series A*, 351 pp. 165-202.

[51] Taylor, B.N. (ed., 2001), *The International System of Units (SI)*, NIST Special Publication 330, p. 16.

[52] Sadler, D.H., (ed., 1960), Transactions of the IAU Vol. X, Proceedings of the Xth General Assembly, Moscow, Russia, August 12 - 20, 1958, Cambridge University Press, p. 489.

[53] S. 1854 [Public, No. 106.] 40 Stat. 450, March 19, 1918.

[54] Sadler, D.H., (ed., 1960), Transactions of the IAU Vol. X, Proceedings of the Xth General Assembly, Moscow, Russia, August 12 - 20, 1958, Cambridge University Press, p. 500.

[55] 11th CGPM, 1960, Resolution 9, (CR 86) "definition of the unit of time (second)."

[56] S. 1404 (Public, No. 89-387), 80 Stat. 109, April 13, 1966.

[57] US Code Title 47, Chapter 1, Part 2, Subpart A, Section 2.1, Terms and Definitions.

[58] US Departments of Transportation and Defense, 2001 Federal Radionavigation Plan, DOT-VNTSC-RSPA-01-3 / DOD-4650.5, January 2000-December 2001, Appendix A (Definitions), p. A-2.

[59] US Code Title 15, Chapter 6, Subchapter I, Sec. 204

[60] S.3177—National Institute of Standards and Technology Authorization Act of 2002.

[61] 110th Congress Public Law 69—America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act.

[62] Arias E F, G. Panfilo, G. Petit (2011), "Timescales at the BIPM." *Metrologia*, Vol. 48, pp. S145– S153

[63] Arias, E.F. (2005), "The Metrology of Time." *Phil. Trans. R. Soc. A* Vol. 363, p. 2291.

[64] *Astoria Fed. Sav. & Loan Ass'n v. Solimino,* 501 U.S. 104, 108, 111 S.Ct. 2166, 115 L.Ed.2d 96 (1991).

[65] "An Act to remove doubts as to the meaning of Expressions relative to Time occurring in Acts of Parliament, deeds, and other legal instruments." 2nd August 1880. Statutes (Definition of Time) Act, 1880 (43 & 44 Vict. c. 9)

[66] Sadler, D.H., "Mean Solar Time on the Meridian of Greenwich." p. 291.

[67] Lords Hansard, Parliament of the United Kingdom, 27 Nov 1996: Columns 257-60.

[68] Lords Hansard, Parliament of the United Kingdom, 11 Jun 1997: Columns 964-76.

[69] General Assembly of New Zealand in Parliament, Time Act of 1974, (1974 No. 39, "An Act to consolidate and amend the law relating to fixing the time for general purposes in New Zealand"), substituted by No. 57 of 1987.

[70] *Legal Time Act* (States of Québec, 2006, c. 39)

[71] Daylight Saving Time Act, *The Revised Statutes of Alberta*, 2000, Chapter D-5.

[72] *The Official Time Act*, C.C.S.M. c. O30

[73] Time Act, 1990, Revised Statutes of Ontario, Chapter T.9, last amendment: 2009.

[74] *Time Act*, Chapter T-14 of *The Revised Statutes of Saskatchewan*, effective February 26, 1978.

[75] Directive 2000/84/EC of the European Parliament and of the Council of 19 January 2001 on summer-time arrangements, *Official Journal of the European Communities* (English ed.), 02/02/2001, L 31 , p. 21.

[76] Décret no. 78-885 du 9 août 1978, loc. cit. 3080.

[77] Howse, D. (1997), *Greenwich Time and the Longitude*. Philip Wilson Publishers Ltd., London.

[78] Nelson *et al*. (2001), "The leap second: its history and possible future." p. 525, 526.

[79] CCIR, "Standard frequency and time-signal emissions." (Recommendation 460), in *XIIth Plenary Assembly CCIR*, (New Delhi 1970), Vol. III, p. 227 (ITU, Geneva, Switzerland, 1970).

[80] CCIR, "Standard frequency and time-signal emissions." (Recommendation 460-2), in *XIVth Plenary Assembly CCIR*, (Kyoto 1978), Vol. VII, p. 9 (ITU, Geneva, Switzerland, 1978)

[81] Guinot, B., P.K. Seidelmann, "Time scales: their history, definition and interpretation." *Astronomy and Astrophysics*, Vol. 194, pp. 304-308.

[82] Seidelmann, P.K., T. Fukushima, "Why new time scales?" *Astronomy and Astrophysics*, Vol. 265, pp. 833-8.

[83] 14th CGPM, 1971, Resolution 1 (CR, 77). Also, Metrologia, 1972, 8, p. 35.

[84] CIPM Recommendation S2, PV, 38, 110 (1970). Also, Metrologia, 1971, 7, p. 43.

[85] Taylor, B.N. (ed., 2001), The International System of Units (SI), NIST Special Publication 330, p. 54.

[86] Declaration of the *Comité Consultatif pour la Définition de la Seconde*, 1980, 9, S15. Also, *Metrologia*, 1981, 17, p. 70.

[87] Bergeron , J. (ed., 1992) Transactions of the IAU Vol. XXIB, Proceedings of the XXIst General Assembly, Buenos Aires, Argentina, July 23 - August 1, 1991, Kluwer Academic Publishers, Dordrecht.

[88] Seidelmann, P.K., (2000), "Summary and Conclusions", in *Proceedings of IAU Colloquium 180, Towards Models and Constants for Sub-microarcsecond Astrometry*, K.J. Johnston, D.D. McCarthy, B.J. Luzum, G.H. Kaplan, eds.,

U.S. Naval Observatory, Washington DC, USA, pp. 411-12. (adopted by the XXIVth General Assembly of the IAU, Manchester, August 2000).

89 Guinot, B. (1986), "Is the International Atomic Time TAI a Coordinate Time or a Proper Time?" *Celestial Mechanics*, Vol. 38, pp. 155-61.