UTC Redefinition and Space and Satellite-Tracking Systems[*]

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The abolition of intercalary (leap) seconds within Coordinated Universal Time (UTC) would create a new civil-time standard fundamentally different than Universal time, and a civil-broadcast standard no longer coordinated with Universal Time may not be easily reconciled with the existing operational practices of some space systems. This paper attempts to raise awareness of some of the technical, operational, and financial issues due to a proposed change to UTC with an emphasis on space and satellite-tracking systems. Preliminary research already suggests that many astrodynamic, space-science and satellite-surveillance systems would be particularly burdened by the rapid adoption of proposed changes to the UTC time scale. To avoid confusion, proposed standards failing to approximate Universal time may best forego use of the label "Coordinated Universal Time" and its acronym "UTC", since these descriptors have always implied a realization of Universal time across many different disciplines of science, technology, and engineering.

INTRODUCTION

Coordinated Universal Time (UTC) is a time scale maintained by the *Bureau International des Poids et Mesures* (BIPM), with assistance from the International Earth Rotation Service (IERS).[†] It 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 BIPM, but UTC is adjusted relative to TAI by inserting (positive) or neglecting (negative) intercalary ("leap") seconds to assure its rough concordance with Universal time. UTC therefore differs from TAI by an integral number of seconds.

The International Telecommunication Union Radiocommuncation bureau (ITU-R) has recently assumed international responsibility for the definition of UTC by forming a Special Rapporteur Group (SRG) to report to the ITU-R with recommendations regarding possible future changes to the current procedure relating UTC to International Atomic Time (TAI). At its second meeting in Paris, 21-22 March 2002, the SRG reportedly

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[*] These comments are solely attributable to their authors and do not present an official view of the United States.

[†] The IERS recently elected to rename itself the International Earth Rotation and Reference Systems Service (*Service International de la Rotation de la Terre et des Systèmes de Référence*), pending approval of its sanctioning bodies.

converged to the opinion of freezing the present difference between UTC and TAI at the current value of 32 seconds.[2] It further decided 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 in countries where UTC is the legal basis. Should no new leap seconds be inserted, the best long-term estimates suggest that Universal time would diverge from the redefined “UTC” at the rate of roughly one second of time (15″ of Earth orientation) per year.[3] The practical effect of the proposal is to relinquish Earth rotation and the mean solar day as the bases of civil time-keeping.

Question ITU-R 236/7 “The Future of the UTC Timescale” asked that the following be studied:[4]

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

Because the basis of civil time is related to Earth orientation, this relationship is implicit to many scientific, technological, and engineering applications.[5] In response to the SRG’s call for contributed papers to address the technical issues, operational impacts, and financial aspects associated with modifying the UTC standard at its Colloquium on the UTC Time Scale, this paper attempts to raise awareness of some potential consequences of modifying the guidelines for the production of transmitted UTC, with an emphasis on satellite-tracking systems.

UTC AS A REALIZATION OF UNIVERSAL TIME

Astronomical time, based on the rotation of the Earth and its revolution about the Sun, serves as the basis for civil time.[6] Universal time (UT) 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 as Greenwich mean time.[7,8] UTC is an elegant, continuous[*] time scale having duality of purpose: it completely preserves the ultra-precise uniformity of the atomic *Système International d’Unités* (SI) second while maintaining close proximity to Universal time. UTC has always respected national statutory requirements for Greenwich mean (solar) time 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).”[9] Almost all countries now acknowledging

[*] The practice of coercing generic "UT clocks" to display UTC results in unfortunate mischaracterizations of the atomic UTC time scale. One is that UTC lacks sequence or coherence (*e.g.*, is "discontinuous"), when in fact, UTC is completely sequential and coherent within the prescriptions of the UTC standard.

UTC as a standard adhered to a UT standard prior, and at the time of its adoption generally recognized UTC to be a realization of Universal time in title and purpose. Consequently, the requirement for mean solar time is reflected in all time-keeping practices today. Legal time is referenced to Earth rotation in some countries; in others it is based on atomic time adjusted for Earth rotation; but in no country has the basis of time been known to disregard Earth rotation. Because the astronomical basis for time is legally protected in many places, citizens are entitled to acquire a reasonably unbiased measure of astronomical time directly from the basis of civil clocks. This has perpetuated the elementary equality of clock time and Earth rotation across many disciplines.

Universal time is generally required to relate the position and/or orientation of objects beyond the Earth to its surface. Disciplines reliant on Universal time include astronomy, with a critical sub-application being celestial navigation, as well as astrodynamics, geodesy, meteorology (terrestrial and space), oceanography, satellite communications, *etc*. Applications needing Universal time also include those requiring the "local time" of a location on the Earth (sidereal time relative to the "stars" or some fixed celestial basis), and perhaps many other scientific endeavors where temporal, geographically distributed data are approximately regulated at diurnal frequencies. Almost all astrodynamic applications (such as orbit determination, space mission planning, satellite tracking, satellite visibility, sensor visibility, *etc*.) require some knowledge of the sidereal orientation of the Earth implied by Universal time. In very many cases, this knowledge is only needed at the level approximated by the current UTC standard.

Satellite Tracking Systems

The development and documentation of many operational space programs and space surveillance systems was accomplished during the 1950's and 1960's before the existing UTC standard with its intercalary (leap) seconds. These programs and systems carried an inherent assumption that civil "wall-clock" time was based on reasonably unbiased realizations of Universal time. While Universal time is not uniform at the nanosecond level like atomic time, it is still highly uniform at about the millisecond level. Millisecond level ambiguity of time results in a position uncertainty of 10 meters or less for orbiting satellites, which move faster than any other vehicles in the vicinity of Earth.

Some operational satellite-tracking systems are relatively old, or have legacy components that are relatively old. These systems have not been decommissioned because they continue to serve satisfactorily within their operational mission requirements or are otherwise too expensive to replace. Many can reliably operate for decades owing to stockpiles of spare parts and back-up software, where the investment of spare-part stockpiles constitutes a measurable part of the initial fabrication and maintenance cost of some space systems. The US Naval Space Surveillance System (NAVSPASUR) is an example of an operational space-surveillance system pre-dating the introduction of the existing UTC standard. The system detects satellites autonomously without any prior knowledge of the orbiting satellite population, and collects about 175,000 direction cosine observations daily.[10] Designed by the US Naval Research Laboratory and having been in almost continuous operation since 1961 by the US Navy,* some elements of this system still assume that a "day" is the mean solar day at the Greenwich meridian and "time of day" refers to Universal time.

Besides the NAVSPASUR system, there are over one hundred other contributing, collateral, or dedicated sensors that perform some kind of satellite tracking or communications for the US. Many are part of a globally distributed network of interferometer, radar and optical tracking systems known as the US Space Surveillance Network (SSN).[11] This network is largely managed and/or operated by the US Air Force Space Command (AFSPC). The purpose of the SSN is to collect observations for US Department of Defense (DoD) databases of known orbiting objects maintained since the launch of the first Sputnik in 1957. These databases are known as the US Space-Object Catalogs, or simply the "space catalog."[12] At this time, the number of cataloged space objects is over 10,000.

Satellite Tracking Software

Astrodynamic theories are used to maintain the space-object catalogs. So called "general-perturbations" orbit-determination theories represent a general analytical solution of the satellite equations of motion.[13] The orbital elements as a function of time, and their associated partial derivatives, are expressed as series expansions in terms of the initial conditions of the differential equations. The general-perturbations theories operated efficiently on the earliest electronic computing machines, and have been adopted as a primary means for space-catalog orbit determination. Simplifying assumptions, as well as model enhancements, have been made to some of these analytical theories over the years.[14,15,16] These general-perturbations elements are "mean" elements that have specific periodic features removed to enhance long-term prediction performance, and require special software to reconstruct the compressed trajectory.[17] The most commonly used software is the SGP4 analytic theory maintained by AFSPC, although the US Navy also maintains its own PPT3 theory.[18,19] Both theories assume that the independent variable is generic "Universal time," including the time stamps of satellite observations. The Space Control Center (SCC) at Cheyenne Mountain Air Force Station widely distributes UTC-tagged orbital elements compatible with the SGP4 theory. NASA also maintains civilian

* The operation of the NAVSPASUR system is currently transitioning to the US Air Force.

databases of general-perturbations orbital elements, sometimes known as the NASA or NORAD* "two-line elements" also based on SGP4.[20]

General-perturbation theories are extremely practical as well as computationally efficient. Their accuracy is sufficient to allow a radar to quickly locate satellites of interest, then continue tracking them closed-loop. More importantly, their speed of execution allows space-surveillance sensors to quickly distinguish between catalogued and possibly unknown targets within a sensor's field of regard. This is particularly important for a missile-warning system, or for NAVSPASUR which must be able to autonomously detect and identify orbiting objects at the average observation rate of two (2) observations per second. Analytical theories have been in operational use for decades, and AFSPC has documentation acknowledging several-hundred users of the SGP4 theory going back ten years. The efficiency and ease-of-use of general-perturbations theory has allowed it to proliferate into many non-expert civilian personal-computer systems as well. Regrettably, there are no firm records on the large number of anonymous civilian users currently relying on general-perturbations orbital elements distributed through NASA. For these reasons, it is highly unlikely that the analytic general-perturbations theories can be retired in the foreseeable future.

The satellite-tracking data have a dual purpose; specifically, these data are also used to maintain special-use catalogs of higher accuracy, known as the "special perturbations" (SP) catalogs. Special-perturbations methods follow from the direct numerical integration of the satellite equations of motion.[13] Although special-perturbations orbit determination is more computationally intensive than general-perturbations theory, centralized special-perturbations catalogs are now becoming feasible because computer capacity has grown much faster than the size of the Space Catalog.[21] They currently support certain civilian missions requiring increased accuracy, such as collision avoidance for the manned Space Shuttle and the International Space Station.[22] Special-perturbations orbit-determination theory therefore benefits from the uniformity of UTC and accurately accounts for any difference between UTC and UT1. The general- and special-perturbation theories are examples of how space systems now make good use of the dual-purpose UTC standard.

SOME TECHNICAL CONSIDERATIONS OF UTC REDEFINITION

Orbit determination requires a celestial reference frame (which defines the Newtonian-inertial space in which the differential equations of satellite motion are valid), and a terrestrial reference frame (from which the satellite observations are taken). The terrestrial frame is related to the celestial frame through the series of rotations known as

* North American Aerospace Defense Command

the Earth-orientation model. The complete model is sometimes divided into partial sequences of rotations, where intermediate frames may be defined between these partial sequences. This transformation takes the following vector-matrix form:

$$\mathbf{r}(t_i)_{TRF} = [\mathbf{W}(t_i)]\,[\mathbf{R}(t_i)]\,[\mathbf{NP}(t_i)]\,\mathbf{r}_{CRF}$$

where $\mathbf{r}(t_i)_{TRF}$ is a three-dimensional position vector with respect to a terrestrial frame at date t_i, $\mathbf{r}_{CRF}$ is the position vector with respect to a (time-invariant) celestial frame, $[\mathbf{NP}(t_i)]$ is the precession-nutation matrix at date t_i, $[\mathbf{R}(t_i)] = \mathbf{ROT3}(\theta)$ is the sidereal rotation matrix using the stellar angle at date t_i, and $[\mathbf{W}(t_i)] = \mathbf{ROT2}(-x_p)\,\mathbf{ROT1}(-y_p)\,\mathbf{ROT3}(s')$ is the polar motion matrix at date t_i. The stellar angle θ is a function of UT1 (= UTC + ΔUT1), the Earth-orientation parameters x_p, y_p, and ΔUT1 are tabulated by the IERS, and s' is an integral quantity defined by the polar motion angles x_p, y_p and their derivatives.[23,24] The ΔUT1 corrections can never exceed 0.9 seconds (or 14″) by convention, although they rarely exceed 0.7 seconds (11″) in practice.

Many applications (including general-perturbations theory) do not require the level of accuracy provided by supplemental Earth-orientation parameters. In these cases, the transformation is sufficiently approximated by:

$$\mathbf{r}(t_i)_{TRF} \approx [\mathfrak{R}(t_i)]\,[\mathbf{NP}(t_i)]\,\mathbf{r}_{CRF}$$

where $[\mathfrak{R}(t_i)]$ is a realization of $[\mathbf{R}(t_i)]$ with UT approximated by UTC. (A small-angle rotation matrix, accurate to the milliarcsecond level, can be applied after the fact should an application require or desire correction via Earth-orientation parameters.) Neglecting the polar-motion angles causes orientation errors of about 1″ or less. Neglecting ΔUT1 causes orientation errors generally limited to 12″ or less. This is already more than an order of magnitude larger than polar motion.

Any increase in the tolerance between UT1 and UTC also increases the approximation error; the point at which this becomes intolerable is, of course, application dependent. The current 900-millisecond tolerance between UTC and UT is often barely acceptable for applications employing UTC as an approximation for UT1, and some applications might actually benefit from the insertion of leap seconds closer to |ΔUT1| ~ 500 milliseconds (~7.5″). Such refinements to the realization of UTC would keep the approximation error of UTC ~ UT1 within an order of magnitude of polar motion. To do this might imply staggering leap-second insertion at times other than the end of June or December.[25] However, insertion at the end of any UTC month is already allowable within the prescriptions of the current standard, so systems compliant with the UTC standard should remain unaffected by such improvements.

Even if leap seconds were eventually abolished from the atomic civil-time scale of the future, applications dealing with historically UTC-tagged data cannot be spared from responsibly accounting for leap seconds. The historical existence of two fundamentally different civil-time scales ought to encourage a new name for a significantly modified atomic civil time. The title "Coordinated Universal Time" applied to something uncoordinated with Universal time appears as an oxymoron, confusing to non-experts. Scientists and analysts would be able to convert historical data onto the new civil time scale if it were given the new name, after which the operational overhead of continually converting the former UTC nearly vanishes.

SOME OPERATIONAL EFFECTS OF UTC REDEFINITION

The proposed change to UTC affects space systems in at least two distinct ways, depending on the way UT is computed or approximated. Systems using UTC to approximate Universal time would be adversely affected because UTC becomes an increasingly poor approximation for Universal time. This degradation would compromise the accuracy of transformations between the terrestrial frame and the celestial frame. The solution would be to modify these systems so they apply the ever-growing ΔUT1 correction.

Systems already using a ΔUT1 correction could be adversely affected by the fact that ΔUT1 will now grow indefinitely. Some systems have files or databases for storing so-called "timing constants" including ΔUT1. Generally these files allow only a limited number of digits for storing ΔUT1, and the continual growth of ΔUT1 would eventually lead to an execution error when the ΔUT1 values can no longer be stored or properly read. In some cases, an error would occur as soon as ΔUT1 exceeded ±0.9 second. The solution would be to: modify the file format to accommodate an ever-growing range of ΔUT1, possibly change software containing the formatted read statements, and eliminate current software safeguards and tests on the magnitude of ΔUT1 values.

The latter point reflects the fact many systems have operational features designed around the long-standing UTC standard and the bounded nature of ΔUT1. For many operational systems lacking network connectivity, Earth-orientation parameters must be entered by a human operator, and the current ±0.9-second limitation serves as a necessary automated check against gross data-entry errors. Knowledge that the ΔUT1 can never be very large allows engineers to design systems to function even when the actual ΔUT1 value is unknown or invalid, perhaps at a slightly degraded performance level.

Some systems can automatically maintain Universal time approximately by consulting an accurately maintained civil clock, or otherwise assume data were tagged according to generic Universal time which may have been based on the civil clock. If UTC were redefined, systems would need to be evaluated on a large scale to understand the level of detrimental effect, and if the effect is significant, determine how to get ΔUT1 corrections into component applications where they never existed before. This would be a bigger effort for remote data-collection systems lacking automated network connectivity. This includes systems that are network-isolated for security reasons, or inexpensive satellite-tracking dishes or data-relay antennae.

SOME FINANCIAL ASPECTS OF UTC REDEFINITION

Changes to the UTC standard will financially impact many operational segments of space surveillance, tracking and communication systems. Even systems requiring no change would need to be very thoroughly assessed at moderate expense to determine this for a fact. Some specific examples are included below, along with approximate cost estimates in some cases. Where estimates are available, many are partially supported by recent costs actually incurred to study, modify, upgrade and reassess software prior to the "Y2K rollover." Highly reliable and/or official cost-estimates are often expensive to generate and approve, and the resources for this were not available during the thirty days spent preparing for this report. Therefore, these estimates are considered informational and are not official US government cost estimates.

Satellite Laser Ranging Systems

Government owned satellite-laser-ranging (SLR) systems provide an example of unclassified operational satellite-tracking systems, for which the upgrade costs and procedures can be discussed with reasonable detail. Today's NASA SLR systems are operated and maintained by Honeywell TSI (HTSI) and these systems contribute the majority of the data from the International Laser Ranging Service (ILRS) network and the Crustal Dynamics and Data Information Service.[26] These systems are some of the most accurate satellite-tracking systems ever put into routine operation. The existing NASA SLR systems rely on tables of Earth-orientation parameters including polar motion and ΔUT1. These tables are available to the remote tracking stations via the Internet from a central processing facility.

HTSI systems engineers familiar with these SLR systems noted that the ΔUT1 values are only required for occasional "star calibrations" conducted no more than once every six months. The purpose of these calibrations is to check the alignment of the telescopic optical path relative to the gimbals to assist in accurate "blind pointing" of the telescope. The operational tracking and data-processing segments of these systems do not operationally rely on ΔUT1 from day to day, but implicitly assume that UTC is an adequately unbiased realization of UT1.

HTSI dedicated over one man-hour of labor to review the current on-site software to confirm just how tables of ΔUT1 were currently being used. Only one occurrence in the system software could be found that used ΔUT1, and this was in the calibration code as expected. No dependence on ΔUT1 was found in the more critical system components, including the tracking system that actually steers the telescope to collect ranging measurements and the data-processing components that reduce the tracking data on-site. These components are still thought to assume that UTC time is generic Universal time.

Based on this preliminary effort, it was estimated to cost at least $10,000 in labor to create a conclusive impact assessment and subsequent cost estimate for the SLR systems. However, a good-faith estimate by HTSI employees suggested that, if UTC redefinition only required changes to the formats and read statements supporting Earth-orientation parameters for star calibration, the cost of upgrading nine (9) SLR systems would likely require a budget in excess of $100,000. More significant changes to the data-processing and tracking segments would likely result in a total cost closer to $500,000. This good-faith estimate includes labor to initially identify those places within the system software that needs modification or update, requirements development (planning meetings, regulatory paperwork and associated documentation, *etc*.), software development, testing and benchmark development, and implementation / installation at nine (9) SLR systems around the globe. The estimate did not include the value of data possibly lost from outages resulting from system upgrades or "approval costs" incurred by the government owner to manage and oversee changes to these operational systems. It also did not consider the cost to the other SLR systems within the ILRS. Currently there are over thirty (30) such systems, many of which are one-of-a-kind; a rough estimate of the cost to upgrade all contributors to the ILRS might be a seven- to eight-digit figure.

More investigation is certainly needed by all space-faring nations to determine the extent of the necessary software modifications resulting from UTC redefinition. However, the international SLR systems are an important example of high accuracy tracking systems relying on the dual-purpose UTC standard. Specifically, it appears that the majority of system elements intrinsically rely on UTC as a realization of UT, and a few specialized elements of the same system also further correct UTC using ΔUT1 to acquire a more accurate realization of UT1 as necessary.

Naval Network and Space Operations Systems

The US Navy's Global Command and Control System—Maritime (GCCS-M) is an example of an application that has the PPT3 general-perturbations orbit model embedded in it. This system has a satellite segment that supports mobile users who need to know the relative positions and visibility of satellites relative to their own (moving) location. It broadcasts PPT3 orbital elements throughout the system to an indeterminate user community estimated to number in the thousands. Since changes in the definition of UTC are expected to affect PPT3 accuracy, a review of customer accuracy requirements would need to be done. This is a reasonably hard effort within the GCCS itself, because there is no good large-scale method to notify users of possible changes to the accuracy of the components of this system. It would therefore take several years to find all the important users to understand their accuracy requirements. Because of the inherent uncertainties of gathering this type of information, no satisfactory cost estimate was immediately available.

Almost every application in the Naval Space Operation Center (NAVSPOC) at the US Naval Network and Space Operations Command (NNSOC) also relies on the PPT3 orbit model. As part of its role as the US Alternate Space Control Center (ASCC), NNSOC at one time proposed that its own internal systems migrate to a single special-perturbations-based system in the future.[27] To support the external users which rely on the PPT3 elements it supplies, NNSOC further proposed to fit or "tune" general-perturbations elements with higher accuracy special-perturbations ephemerides. This was originally proposed as a cost-savings measure so the ASCC could avoid maintaining GP and SP catalogs simultaneously. Because of the "tuning" aspects of the proposal, this type of process might also be able to accommodate (on some level) the adverse effects of a civil time scale divergent with Universal time for a while. However, the effect of redefining UTC on the GP-tuning process has not been investigated at all, and assessing the actual loss of accuracy would require an auxiliary research budget (where the large-scale transition of the ASCC to special-perturbations operations already lacks long-term financial support and operational adoption would require many years to fully implement). This situation is further complicated by the fact that many elements of NAVSPOC are now transitioning to the US Air Force and NNSOC is relinquishing its role as ASCC.

HQ Air Force Space Command

A preliminary review within the Air Force Space Command, Space Analysis Division (HQ AFSPC/XPY) was conducted in support of this paper. The review extended to the Force Enhancement, Force Application and Space Support Missions, as well as the Space Control Center (SCC) and Space Surveillance Network Systems.

Space Control Center and Space Surveillance Network Systems

Seemingly straightforward modifications can actually be very costly for some operational satellite-tracking systems. Simply because of their age, some of these systems no longer have adequate software support that would make seemingly simple changes easy to affect. For example, some hardware configurations no longer have operational compilers for the source codes and/or processors in use. As a result, some system components must be minimally maintained by manually editing the remaining binary object codes. The expertise to make software modifications at the level implied by a new UTC-standard may have to be developed at great expense. Many of the existing space surveillance systems also have no requirements to be upgraded for at least fifteen (15) to twenty (20) years, so the additional cost of UTC redefinition cannot be easily absorbed into the current overall plan of life-cycle costs. Also, many systems are tightly configuration-managed and have highly restricted access, and the additional regulatory requirements for extensive development, simulation and testing adds substantially to the cost of these systems in ways that may not affect less critical, or non-military, systems. For example, concerns of sabotage, accidental computer virus infection or bugs, *etc*., require the availability of specially trained, specially cleared personnel at increased expense.

In a detailed response to a query about UTC redefinition, an administrator familiar with operations at an optical-tracking facility provided a good-faith estimate for the upgrade costs at about $500,000 for each telescopic system at the facility. It would likely take a minimum of one to two years to implement a new standard for *each* of the telescopes, and likely require at least ten-year's advance notice in order for the total cost to be absorbed into an instrument's normal life cycle of maintenance and upgrades. To accommodate a redefinition of civil UTC, all users of SGP4 would also be required by AFSPC to modify their versions of SGP4-related software within a relative short time period (a few years), depending upon the application and the accuracy required. Given the very large number of users and the variety of SGP4 versions and applications involved, HQ AFSPC/XPY anticipated the cost to the SCC's user community to approach a few-hundred-million dollars.

Force Enhancement, Force Application and Space Support Missions (Mission Analysis)

The most significant impact of UTC redefinition identified by the Space Analysis Division's Mission Analysis branch appears to be within the US Missile Warning Mission and the US Force Application Mission (intercontinental ballistic missile defense forces). The Space Navigation Mission and the Space Support Missions ("space-lift", or launch support) are also expected to be affected, to a lesser extent. While there was no known impact discovered in this preliminary review for the Command's Communications Mission, there are likely to be some highly inaccessible systems and tools within the Command's Intelligence Surveillance and Reconnaissance (ISR) Mission that would need modification.

Software in the Missile Warning Center at Cheyenne Mountain AFS has a significant number of subroutines that either assume UTC is a generic realization of Universal time or otherwise computes UT1 from UTC by applying the ΔUT1 correction which is always assumed bounded. Error checking in the special-perturbations orbit-determination software at AFSPC currently checks that the ΔUT1 offset never exceeds a certain range, for example. There are many other missile warning and force application models that would be affected, but most are now obsolete or rarely used and therefore, do not impact costs significantly. A good-faith estimate of the cost to modify the active missile-analysis tools is a few-million dollars. In addition, the operational missile-warning system at Cheyenne Mountain AFS (called the Command Center Process and Display System - Replacement) was recently implemented in 1996. A good-faith estimate of the cost to modify this display system for changes in UTC definition is over one-hundred-million dollars.

HQ AFSPC/XPY also has a role in developing technical requirements, upgrading, and validating various space navigation tools. In particular, it is involved in upgrading and testing the GPS Interference and Navigation Tool, the GPS Navigational Accuracy tool, and the Satellite Navigation Accuracy Prediction Model. These three models, and other GPS accuracy and reliability models, assume UTC is a reasonably unbiased realization of UT1. The accuracy of Dilution of Precision values and error metrics, such as Circular Error Probable (CEP) and Spherical Error Probable (SEP), would gradually degrade with the proposed change to UTC. Some additional launch support software that uses UTC as a proxy for UT1 would have to be changed. A good-faith estimate to upgrade these models to handle UTC redefinition would likely cost on the order of a few-million dollars.

Systems Not Surveyed

Most of the information in this report was compiled within thirty days, and there are likely hundreds of other satellite tracking systems, commercial and military, that will need to be assessed for impact, should UTC be changed. In particular, all space systems employed by NASA would need to be investigated. For many of these systems, expenses associated with upgrading systems to handle “Y2K rollover” are thought by some to provide reasonably good preliminary estimates of the costs needed for upgrades and evaluation. This opinion has been expressed independently by different personnel from different organizations consulted during the preparation of this report. It is understood that the effect of Y2K-rollover problems were generally limited to a particular epoch; however, the effects of UTC redefinition are expected to be more subtle and will likely require more extensive testing and software simulations for extended time intervals.

SOME EDUCATIONAL ASPECTS POSSIBLY AFFECTING PERCEPTIONS OF UTC REDEFINITION

Limited feedback on the issue of UTC redefinition has been experience so far within the aerospace and astronautical disciplines in particular. The authors' limited correspondence with professionals and colleagues suggests that critical non-responders to the UTC-redefinition issue might be categorized into at least three groups. A few professionals seemingly consider the subject matter too tentative, or far-fetched, to be given significant consideration for the moment, while some may be ignoring the subject because they (incorrectly) believe that UTC redefinition will have no effect on their application. And, of course, there must be some who have yet to hear about UTC-redefinition proposals.

Not everyone is in a position (yet) to understand how their system(s) will be impacted, if at all. One subtle reason is that engineers often take the concept of "time" for granted and are not always taught the distinction between the concept of Universal time and the particular realization now known as UTC, especially at the undergraduate level. The study of orbital motion is a somewhat specialized branch of astronomy (known as dynamical astronomy) where such distinctions have not always been emphasized, even decades after their introduction.[28,29] Indeed, some of the most popular astrodynamics textbooks predate the current definition of UTC.[30,31] The problem is compounded by newer textbooks attempting to make a clear distinction between UTC and UT1, yet repeating extremely outdated information or presenting notable errors of fact.[32] A few well-regarded textbooks seem to ignore the subject altogether.[33]

Many of today's space applications are no longer influenced by the engineers who originally designed them. They are often administered and maintained by professionals having limited expertise with astronomical and atomic time scales who may not appreciate the impact on their own applications should the proximity of UTC relative to UT be relaxed or abolished. The effect is much more subtle than the so called "Y2K" problem and less obvious to those working with code developed perhaps decades ago. Lower accuracy orbit software models—historically unable to accommodate leap seconds or Earth-orientation parameters—are likely to be the ones required to find an external source of UT should UTC be redefined, since proposals to redefine UTC result in the degradation of accuracy of their current realization of UT over time. Anecdotal evidence already suggests that some (incorrectly) perceive the issue of UTC redefinition as only affecting systems relying on leap seconds and/or ΔUT1 corrections.

For many systems, it is possible to obtain a reasonably unbiased realization of UT through a computer system's UTC clock or a UTC receiver (such as GPS or WWV) without any conscious effort on the part of their operators. Because many inherited applications potentially affected by UTC redefinition do not currently rely on Earth-orientation parameters or leap-second insertion, their operators do not subscribe to (or even know about) the usual services, circulars, or announcements regarding leap seconds and/or Earth orientation. Therefore, the number of those impacted, yet unaware of the UTC-redefinition issue, may be quite large, since surveys and queries about this matter have been generally directed at groups familiar with precision timing, leap-second bulletins, precision Earth-orientation-parameter distribution lists, *etc*.

SUMMARY CONCLUSIONS

Coordinated Universal Time (UTC) has proven to be a successful and practical standard for civil time. It has always been a realization of Universal time in title and practice, and satisfies the needs of many scientific, engineering, and technical communities expecting a realization of Universal time from civil clocks. Proposals to eliminate leap seconds would also eliminate the multi-purpose role of UTC. Should the definition of UTC ever be significantly revised, it is advisable to abolish the title "Coordinated Universal Time" along with the leap second, since this title has always implied a realization of Universal time. To maintain this title could cause significant confusion across many disciplines now relying on the civil clock as a source of Universal time.

Applications deriving astronomical time solely from civil clocks drive the present and future requirements for the tolerance limit between UTC and Universal time. What are the *present requirements* for the tolerance limit between UTC and UT1? The answer is 0.9 seconds, this tolerance having been established by the long-standing UTC standard. This tolerance has been tightly integrated into many operational space-related systems during the previous three decades. Having such a tolerance mitigates specific technical risks now and in the future; specifically, the conventional proximity of UTC relative to UT1 acts as a safeguard (should Earth-orientation parameters ever become unavailable to a system, should a system operator make a gross error entering ΔUT1, *etc*.) What are the *future requirements* for the tolerance limit between UTC and UT1? Without ample economic and technical resources to evaluate and retrofit all systems now reliant on the existing UTC standard, this answer also appears to be 0.9 seconds. Many systems have specific operating assumptions and approximations designed around the fact that ΔUT1 is bounded at 0.9 seconds, and the proposed change to UTC will affect applications that cannot yet handle an ever-growing difference between UT1 and UTC. If the tolerance were to change, the extent of adverse operational impact is unclear and it is also unclear how to adequately establish a new threshold.

Any changes to Coordinated Universal Time will then have a financial impact on the systems of many space-faring nations, including many systems already compliant with the existing UTC standard. This paper presents some tentative results of a brief survey conducted by the authors, with consideration primarily limited to space and satellite-tracking systems operated by the US. The results are not a comprehensive or definitive presentation since the impact of UTC redefinition across the world will need more thorough and well-funded research. However, preliminary research already suggests that the cost impact could be measurable in hundreds of millions of dollars in the US alone. Given that the current process of discrete leap-second updates is well established, the cost associated with incorporating a redefined UTC appears particularly unnecessary within the network of satellite-catalog users. Although there may be occasionally glitches in the implementation of leap seconds, they tend to be easily detected and straightforward to correct, and the overhead associated with leap-second maintenance still appears trivial in comparison to the task of identifying and modifying systems tightly integrated with the UTC standard, including all systems that perform coordinate transformations between inertial and Earth-fixed coordinate frames.

Without documentary evidence supporting meaningful, consequential deficiencies in the existing UTC standard, it may be difficult for many other technical communities to accept significant changes to well-established international time-keeping conventions. The strongest argument for changing the definition of UTC apparently resides in the extremely long-term projections of Earth's rotational deceleration, since that would eventually require more frequent introduction of leap seconds. However, the practical consequence of that effect is so far away that its immediate relevance can be sensibly dismissed by detractors.[3] 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.

It is certainly possible that, given enough lead time, even the most expensive systems could be modified to eventually accept a redefined UTC with the cost prorated over many, many years. And also, given enough delay, well-funded research may help to find more cost-effective ways to implement proposed changes across existing systems. However, applications with very stringent requirements for timing accuracy (including the Global Positioning System) have successfully operated for decades within the current definition of UTC and continue to do so today. With questions having been raised, national governments may do well to investigate why certain modern-day applications are functionally compliant with existing international time-keeping standards while others appear unwilling or unable to comply. Coordinated, national investigations should help discover what, if any, changes to UTC are warranted. This could avoid unnecessary burden to systems, applications, and industries already compliant with current standards.

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