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TIME SCALES IN ASTRONOMICAL AND NAVIGATIONAL ALMANACS

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Commission 4 (Ephemerides) of the International Astronomical Union (IAU) includes astronomers from many countries responsible for the production of printed almanacs, software, and web services that provide basic data on the positions and motions of celestial objects, and the times of phenomena such as rise and set, eclipses, phases of the Moon, etc. This information is important for pointing telescopes, determining optimal times for observations, conducting night operations, and also for celestial navigation. Commission 4 also includes researchers involved in the more fundamental tasks of determining the orbits of solar system bodies based on a variety of observations taken from the ground and spacecraft. We assume that the data we produce are used by a variety of people that have a broad range of scientific sophistication.

In the almanacs, software, and web services that Commission 4 members produce, data that are independent of the rotation of the Earth, such as the geocentric celestial coordinates (right ascension and declination) of the Sun, Moon, planets, and stars, are generally provided as a function of Terrestrial Time (TT). In practice, TT is based on atomic time (TT=TAI+32.184s) and as such, it can be extended indefinitely into the future without ambiguity or error.

On the other hand, data that depend on the rotation of the Earth, such as Greenwich hour angles or the topocentric coordinates (zenith distance and azimuth) of celestial objects, have traditionally been provided as a function of Universal Time, specifically UT1. UT1 is inherently unpredictable because of natural irregularities in the length of day, but the current international time protocol guarantees that UTC, the basis for civil time worldwide, is never more than 0.9 seconds from UT1. For many users and software applications, the approximation UT1=UTC is adequate and is assumed. Many users, particularly navigators, are probably not even aware of the distinction between UTC and UT1.

A change in the definition of UTC that allows it to diverge from UT1 without bound therefore creates a challenge as to how to provide future data that are a function of the rotational angle of the Earth, and how to educate users on the change. Several ideas for how to proceed that have been circulating among Commission 4 members will be explored.

WHAT IS IAU COMMISSION 4?

The International Astronomical Union (IAU) was founded in 1919 and Commission 4, Ephemerides, was among the first group of commissions formed within the new organization. Its purpose was to facilitate international cooperation in the computation and distribution of information on the coordinates of celestial bodies, and related information such as rise and set times, predictions of eclipses, moon phases, etc., to facilitate astronomical observations, timekeeping, surveying, the comparison of dynamical theory with observations, and celestial navigation.

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It's worth remembering that at the time, computers were people doing arithmetic, the most accurate clock was the rotating Earth, the only distribution mechanism was print, and celestial navigation was the only means of determining position at sea. None of that is true today, of course, but the mission of Commission 4 is remarkably unchanged. Two years ago the organizing committee of the commission re-wrote our mission statement (or, in IAU terminology, our "terms of reference"), as the IAU periodically requires. Here is the latest version:

1. Maintain cooperation and collaboration between the national offices providing ephemerides, prediction of phenomena, astronomical reference data, and navigational almanacs.

2. Encourage agreement on the bases (reference systems, time scales, models, and constants) of astronomical ephemerides and reference data in the various countries. Promote improvements to the usability and accuracy of astronomical ephemerides, and provide information comparing computational methods, models, and results to ensure the accuracy of data provided.

3. Maintain databases, available on the Internet to the national ephemeris offices and qualified researchers, containing observations of all types on which the ephemerides are based. Promote the continued importance of observations needed to improve the ephemerides, and encourage prompt availability of these observations, especially those from space missions, to the science community.

4. Encourage the development of software and web sites that provide astronomical ephemerides, prediction of phenomena, and astronomical reference data to the scientific community and public.

5. Promote the development of explanatory material that fosters better understanding of the use and bases of ephemerides and related data.

There are two broad categories of work that the commission supports. The first type of work is the computation of fundamental solar system ephemerides, that is, using gravitational theory along with observations of many types to determine the orbits of bodies in the solar system. The second kind of work uses these fundamental ephemerides to compute practical astronomical data, such as the geocentric or topocentric coordinates of the Sun, Moon, planets and stars for any given time; the prediction of times of astronomical phenomena, such as the times of rise, set, and transit, and eclipse phenomena; the parameters that describe the apparent orientation and illumination of solar system objects at specific times; and various quantities that allow knowledgeable users to transform coordinates or vectors between standard reference systems.

In the U.S., the fundamental solar system ephemerides are computed by the Jet Propulsion Laboratory (JPL); their Development Ephemeris (DE) series, which has been the de facto international standard since 1984, dates back to the 1960s. Before that, the U.S. Naval Observatory (USNO) was the primary U.S. source for such information. High quality solar system ephemerides comparable to those produced by JPL are also now available from the Institut de Mécanique Céleste et de Calcul des Éphémérides (IMCCE) in Paris and the Institute for Applied Astronomy (IAA) in St. Petersburg. There has been a transition in the last half century from ephemerides based on analytical theories to those based on N-body numerical integrations, and that is an interesting story in itself, which parallels that of the development of electronic computers.

The organizations providing authoritative almanac data are more numerous, and these usually are national institutions of various countries. These include USNO and JPL in the U.S.; Her Majesty's Nautical Almanac Office (HMNAO) in the U.K. (one of the remnants of the Royal Greenwich Observatory); the aforementioned IMCCE in France and IAA in Russia; the National Astronomical Observatory of Japan (NAOJ); and the Spanish Naval Observatory. Obviously the distribution of almanac data has also undergone tremendous change in recent decades, first with the proliferation of personal computers, and later the Internet. Although printed publications are still produced, software and web services are now in the mix.

True to the purposes of Commission 4, there is quite a bit of cooperation and data exchange among the institutions involved. Certainly the solar system ephemeris work at IMCCE and IAA would not be of the high quality that it is without the active assistance of E. Myles Standish (now retired) and Bill Folkner of JPL's solar system dynamics group. There is now, within Commission 4, a number of people involved in analyzing the differences in the ephemerides produced by these three groups, in order to improve all of them. A formally established Commission 4 working group is currently investigating a common data format for these ephemerides, so that users can more easily switch among them. Among the almanac producers, USNO and HMNAO will, in two more weeks, celebrate 100 years of cooperation and joint publication arrangements, and information sharing among all the organizations active in Commission 4 is common.

THE TIME SCALES WE USE

I do not presume to be able to provide a definitive history of astronomical time scales; there are people at this symposium much more qualified than I am for that, and I refer interested readers to their papers. A little background is useful, however. From ancient times through the middle of the 20th century, time was defined by the rotation of the Earth; there was no better clock. Significant irregularities in the rotation of the Earth were first definitively established in the 1930s.[1] But it wasn't until after World War II that the astronomical community officially recognized the need for two time scales for ephemerides: one that is a function of the rotation of the Earth and one that is independent of it. The latter time scale, called Ephemeris Time, was introduced by the IAU in 1950s. At that point, astronomical information could be expressed in either Universal Time (UT) or Ephemeris Time (ET), as appropriate. These time scales were based, respectively, on the rotation of the Earth on its axis (the mean solar day) and the revolution of the Earth around the Sun (the tropical year).

At the same time, atomic clocks were being developed, leading to a revolution in practical time-keeping and eventually to the establishment of International Atomic Time (TAI). The length of the Système International (SI) second, the unit of atomic time, was set equal to that of the ephemeris second, the unit of Ephemeris Time. Formally, the SI second is 9,192,631,770 cycles of the radiation corresponding to the ground state transition of Cesium 133, which Markowitz and collaborators established in 1958 as the best estimate for the length of the ephemeris second, which is 1/31,556,925.9747 of the length of the tropical year at 1900.[2]

Things got more complicated in the 1960s, when a number of new high-precision measurement techniques were introduced into astronomy and geodesy, including radar ranging to the nearby planets, very long baseline radio interferometry (VLBI), lunar laser ranging (LLR), and various kinds of observations of and from spacecraft. These new types of data required that relativity be integrated into our dynamical theories and our data analysis algorithms. This has led to a proliferation of specialized time scales, based on general relativity, some of which are entirely theoretical — that

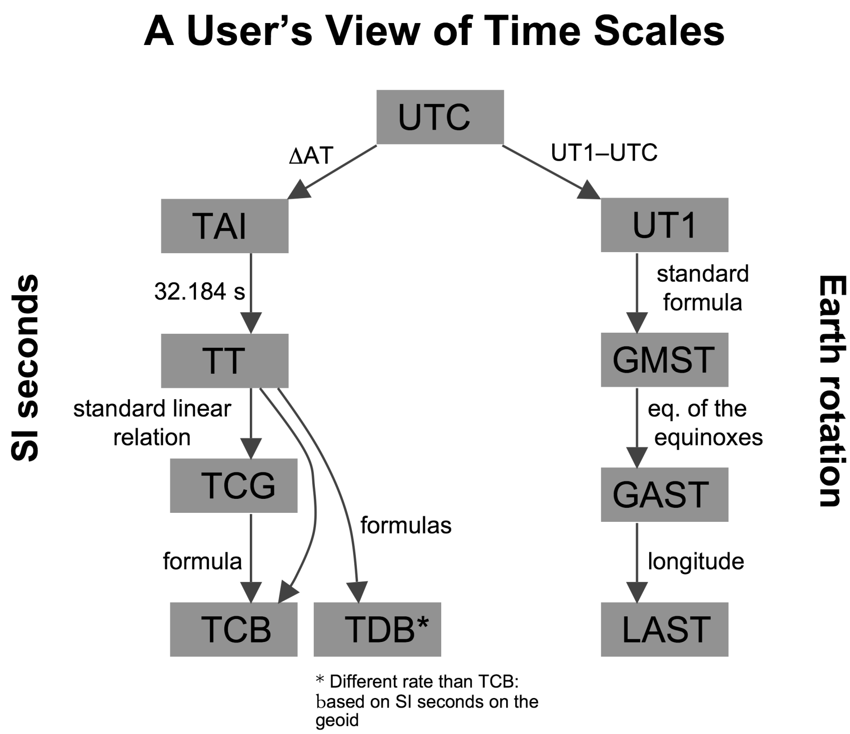

Figure 1. Relationships between time scales used in astronomy, from a user's perspective, starting from Coordinated Universal Time (UTC). The SI-based times scales (left side) are: International Atomic Time, Terrestrial Time, Geocentric Coordinate Time, Barycentric Coordinate Time, and Barycentric Dynamical Time. The time scales based on the rotation of the Earth (right side) are: Universal Time 1, Greenwich Mean Sidereal Time, Greenwich Apparent Sidereal Time, and Local Apparent Sidereal Time.

is, by their definition, they cannot be realized by an actual clock anywhere. (In the terminology of general relativity, they represent *coordinate time* rather than *proper time*.) This has been a rather messy business, with a confusing evolution of ideas about time and timekeeping over the last few decades, with time scales being defined then dropped altogether or redefined.

The current definition of Universal Time, specifically the relationship between the time scales UTC and UT1, was introduced at the beginning of 1972. That is when leap seconds as we currently know them began. UT1 is tied directly to observations of the rotation of the Earth, so it is continuous but irregular in rate; for example, the ≈25 ms annual term in UT1 corresponds to a fractional variation in rate of order 10^{-9}. Some would argue that UT1 is not a time scale at all, but a measurement of the Earth's rotational angle. UTC, the basis for the worldwide system of civil time, is a hybrid time scale, with the SI second as its unit but with occasional leap-second adjustments to keep it within 0.9 s of UT1. Some would argue that UTC is also not a real time scale because, although its rate is fixed and well defined, a day of UTC can comprise either 86,400 or 86,401 SI seconds (or, in theory, 86,399 SI seconds, although this has never happened) and there is no deterministic algorithm that provides the number of seconds between two UTC epochs. The difference between UT1 and UTC is measured and published daily by the International Earth Rotation and Reference Systems

Service (IERS Bulletin A*). The measurements are now based primarily on VLBI observations.

Figure 1 shows a schematic of the relationships between the currently used astronomical time scales, from a user's perspective, starting with UTC. Figure 2, borrowed from a paper by Seidelmann and Fukushima,[3] shows the differences between these time scales, in seconds, as a function of year. Readers interested in a more thorough explanation of modern astronomical time scales, along with the formulas for relating one to another, may refer to Chapter 2 of USNO Circular 179.[4]

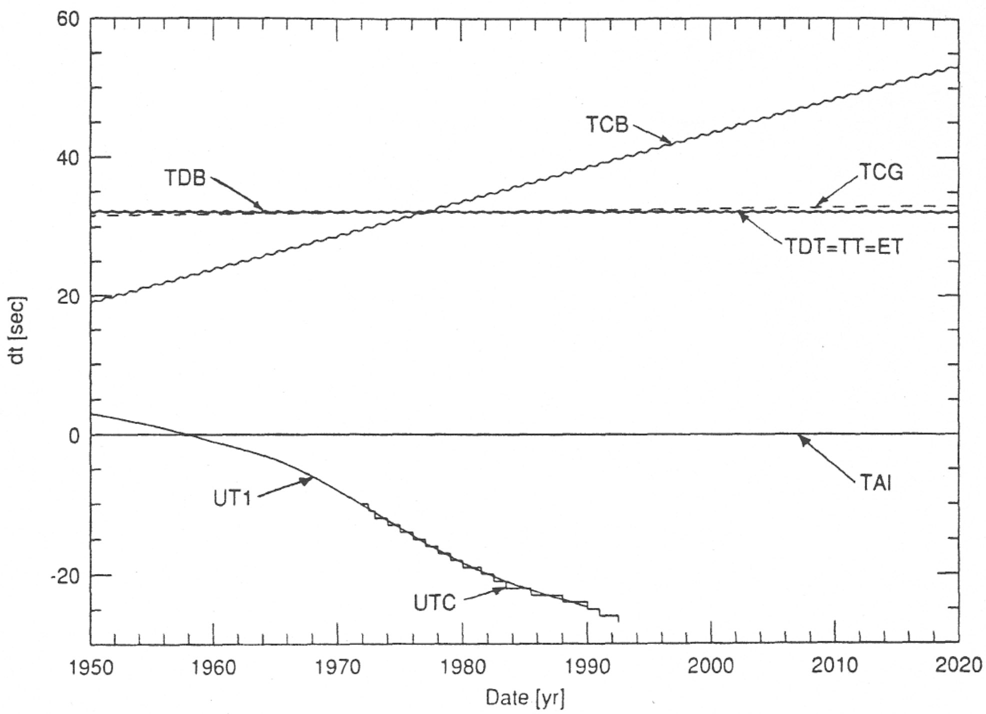

Figure 2. Difference, in seconds, between time scales used in astronomy as a function of year. Note especially the "stair-step" appearance of UTC, due to the leap seconds inserted in that time scale so that it approximates UT1. TT, TAI, and the "steps" of UTC are parallel because they are all based on the SI second on the geoid. The figure is taken from Reference 3.

In modern astronomical software, it is not unusual to have to keep track of three, four, or even five time scales. However, the almanac offices strive to keep this rather untidy situation hidden from our users. In modern almanacs, only two time scales commonly appear. For tabulations of astronomical coordinates and phenomena that do not depend on the rotation of the Earth, such as the celestial coordinates of the planets, Terrestrial Time (TT) is used. TT is the successor to ET and is considered continuous with it. For coordinates and phenomena that are a function of the rotation of the Earth, including the data for celestial navigation, UT1 is used, sometimes labeled simply UT.† For practical purposes, TT is equal to TAI + 32.184 s, and TAI can be obtained from UTC if one

*http://www.iers.org/nn_10968/IERS/EN/DataProducts/EarthOrientationData/eop.html?__nnn=true

†UT is also sometimes used for data that do not depend on the rotation of the Earth but are of public interest and are not given to high precision, such as the times of the phases of the Moon.

knows the leap-second count. Similarly, UT1 can be obtained from UTC if one knows the current value of UT1–UTC published by the IERS. So, both almanac time scales are related to UTC in a straightforward manner, but it is up to the user to do that transformation. The difference TT–UT1 (formerly ET–UT) is called ΔT and is tabulated separately; it is a smooth and (so far) monotonically increasing function that is free from leap-second discontinuities.

A third time scale, TDB, is the basis of heliocentric or barycentric ephemerides of solar system bodies but it differs from TT by less than 0.002 s. Most users can assume TDB=TT with negligible error for their applications.

Figures 3 and 4 show examples of modern almanac data.[5,*]

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UT		ARIES	VENUS −3.9		MARS −1.2		JUPITER −2.0		SATURN +0.7		STARS		
d	h	GHA	GHA	Dec	GHA	Dec	GHA	Dec	GHA	Dec	Name	SHA	Dec
		° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′		° ′	° ′
6	00	136 01.5	170 06.9	S15 08.5	5 24.6	N22 53.2	159 27.6	S10 46.4	311 13.5	N 0 35.7	Acamar	315 20.1	S40 16.0
	01	151 04.0	185 06.3	07.4	20 28.1	53.4	174 29.5	46.2	326 16.1	35.8	Achernar	335 28.6	S57 11.3
	02	166 06.4	200 05.7	06.4	35 31.5	53.6	189 31.4	46.0	341 18.6	35.8	Acrux	173 11.8	S63 09.2
	03	181 08.9	215 05.1 . .	05.4	50 35.0 . .	53.9	204 33.3 . .	45.8	356 21.2 . .	35.9	Adhara	255 14.1	S28 59.3
	04	196 11.4	230 04.5	04.4	65 38.4	54.1	219 35.2	45.6	11 23.8	35.9	Aldebaran	290 52.0	N16 31.8
	05	211 13.8	245 03.9	03.4	80 41.9	54.3	234 37.1	45.3	26 26.3	36.0			
	06	226 16.3	260 03.3	S15 02.4	95 45.4	N22 54.5	249 39.0	S10 45.1	41 28.9	N 0 36.0	Alioth	166 22.3	N55 53.9
	07	241 18.8	275 02.7	01.4	110 48.8	54.8	264 40.9	44.9	56 31.4	36.1	Alkaid	153 00.5	N49 15.4
S	08	256 21.2	290 02.0	15 00.4	125 52.3	55.0	279 42.9	44.7	71 34.0	36.1	Al Na'ir	27 47.1	S46 54.8
A	09	271 23.7	305 01.4	14 59.4	140 55.7 . .	55.2	294 44.8 . .	44.5	86 36.5 . .	36.2	Alnilam	275 48.6	S 1 11.8
T	10	286 26.2	320 00.8	58.4	155 59.2	55.4	309 46.7	44.3	101 39.1	36.2	Alphard	217 58.2	S 8 42.3
U	11	301 28.6	335 00.2	57.3	171 02.6	55.6	324 48.6	44.1	116 41.6	36.3			
R	12	316 31.1	349 59.6	S14 56.3	186 06.1	N22 55.9	339 50.5	S10 43.8	131 44.2	N 0 36.3	Alphecca	126 13.1	N26 40.5
D	13	331 33.6	4 59.0	55.3	201 09.5	56.1	354 52.4	43.6	146 46.7	36.4	Alpheratz	357 46.3	N29 08.9
A	14	346 36.0	19 58.4	54.3	216 13.0	56.3	9 54.3	43.4	161 49.3	36.4	Altair	62 10.9	N 8 53.6
Y	15	1 38.5	34 57.8 . .	53.3	231 16.4 . .	56.5	24 56.2 . .	43.2	176 51.9 . .	36.5	Ankaa	353 18.3	S42 15.2
	16	16 40.9	49 57.2	52.3	246 19.9	56.7	39 58.1	43.0	191 54.4	36.5	Antares	112 29.4	S26 27.3
	17	31 43.4	64 56.6	51.2	261 23.3	56.9	55 00.0	42.8	206 57.0	36.6			

Figure 3. Data from the Nautical Almanac. The time argument is UT1.

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#########################################################################################
                       EPHEMERIS OF SOLAR SYSTEM BODIES
#########################################################################################

 Planet  2 Venus
 Planetary theory INPOP10
 Apparent coordinates (true equator; equinoxe of the date)
 Frame center: geocenter
 Relativistic perturbations, coordinate system 0
 Equatorial coordinates (R.A, Dec.)

#########################################################################################

         Date TT               R.A              Dec.            Distance      V.Mag   Phase   Elong.  muRAcosDE     muDE      Dist_dot
             h  m  s         h  m  s          o  '  "            au.                  o       o       "/s         "/s        km/s

10  5  2011  0  0  0.00   13 32 49.11386 -08 48 53.7535    1.658916553   -3.90   18.61    13.50  0.477E-01 -0.202E-01   -4.5267
10  5  2011  6  0  0.00   13 33 58.67518 -08 56 10.2049    1.658261626   -3.90   18.70    13.56  0.477E-01 -0.202E-01   -4.5448
10  5  2011 12  0  0.00   13 35  8.28068 -09  3 25.9160    1.657604085   -3.90   18.79    13.63  0.477E-01 -0.202E-01   -4.5629
10  5  2011 18  0  0.00   13 36 17.93094 -09 10 40.8746    1.656943939   -3.90   18.88    13.69  0.478E-01 -0.201E-01   -4.5809
10  6  2011  0  0  0.00   13 37 27.62655 -09 17 55.0687    1.656281196   -3.90   18.97    13.75  0.478E-01 -0.201E-01   -4.5988
10  6  2011  6  0  0.00   13 38 37.36809 -09 25  8.4865    1.655615865   -3.90   19.05    13.82  0.478E-01 -0.200E-01   -4.6167
10  6  2011 12  0  0.00   13 39 47.15617 -09 32 21.1158    1.654947955   -3.90   19.14    13.88  0.478E-01 -0.200E-01   -4.6346
10  6  2011 18  0  0.00   13 40 56.99134 -09 39 32.9447    1.654277472   -3.90   19.23    13.95  0.478E-01 -0.200E-01   -4.6524
10  7  2011  0  0  0.00   13 42  6.87422 -09 46 43.9612    1.653604426   -3.90   19.32    14.01  0.478E-01 -0.199E-01   -4.6701
10  7  2011  6  0  0.00   13 43 16.80537 -09 53 54.1534    1.652928825   -3.90   19.41    14.07  0.479E-01 -0.199E-01   -4.6878
10  7  2011 12  0  0.00   13 44 26.78539 -10  1  3.5091    1.652250675   -3.90   19.50    14.14  0.479E-01 -0.199E-01   -4.7054
10  7  2011 18  0  0.00   13 45 36.81485 -10  8 12.0165    1.651569986   -3.90   19.58    14.20  0.479E-01 -0.198E-01   -4.7229
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Figure 4. Data from a web service provided by IMCCE. The time argument is TT.

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*http://www.imcce.fr/en/ephemerides/formulaire/form_ephepos.php

THE CHOICES WE FACE IF UTC IS REDEFINED

As we all know by now, the proposal before the International Telecommunication Union (ITU) for decision early next year is to cease inserting leap seconds into UTC by the end of the decade. If that happens, then the difference UT1–UTC will no longer be restricted to the range ± 0.9 s; UT1–UTC will grow (negatively), presumably without bound. On the other hand, the difference between UTC and TAI will become fixed at some integral number of seconds; therefore the difference between UTC and TT will also be frozen.

How will this affect almanac producers and users? Since almanac data are generally computed and displayed as a function of either UT1 or TT, the initial, naive, answer is that nothing changes; UTC is not used in the computation of the data and UTC is not the independent argument of any of the tabulations. It has been the user's responsibility to convert between UTC (or whatever his external time scale is) and the time scale(s) used for the almanac data, and we can simply assert that this responsibility remains unchanged. In fact, the basic conversion formulas from UTC to UT1 or TT won't change if leap seconds no longer occur.

On further reflection, though, we encounter both challenges and opportunities. I base the ideas in this section on a meeting of the almanac office personnel of USNO and HMNAO that took place earlier this year in which the consequences of a change in UTC were discussed. A few months ago, I inquired, as president of IAU Commission 4, whether the other almanac offices have had similar conversations, but with little response. One office replied that it had not done any specific thinking about the issue so far, and the others never responded at all.

In the previous section, I mentioned that in the almanacs, UT1 is sometimes labeled "UT" or "Universal Time", although the explanatory material always states that this means UT1. It is a safe bet that fewer than one astronomer in ten, and a similarly small fraction of navigators, know the difference between UTC and UT1, or even that there are two kinds of Universal Time. That's because, up to this point, the difference has been bounded at 0.9 s, and for the vast majority of purposes, we can set UT1=UTC to sufficient accuracy. The error in celestial navigation resulting from such an approximation is never greater than 0.225 nautical mile (0.4 km) and is more typically about half of that (the error is always only in longitude). These errors are less than the uncertainty of a typical position fix from hand-held sextant sights. Similarly, assuming UT1=UTC when pointing a telescope currently results in a pointing error of not more than 13.5 arcseconds and more typically less than 10 arcseconds (always in right ascension). That is less than the size of Saturn's disk; and on average, only stars fainter than about V magnitude 20 are separated by arcs this small, so confusion of targets is unlikely. A radio or radar dish operating at X band would have to be about 500 m in diameter to have resolution this good. So we can now get by with the UT1=UTC approximation very well for many ordinary astronomical applications.

Obviously, this will not be the case if leap seconds end and UT1–UTC becomes unbounded. At a minimum, we will have to re-label our time argument to be explicitly "UT1" and make sure that the explanatory text is very clear about the conversion from UTC, something that most users have not had to worry about. That is, people who have never heard of the IERS or the difference between UT1 and UTC will have to come up to speed on these time conversions. In the U.S. Navy, celestial navigation is generally performed by enlisted quartermasters, and we expect that some new training will be required. (It may come as a surprise that celestial navigation is still practiced by the Navy, but it is regarded as a basic seamanship skill, like piloting by visual navigation aids, that must be available in case of emergency.)

Aside: I suspect that there is a great deal of software out there in the broader astronomical community — beyond the influence of Commission 4 — that assumes that UT1=UTC, whether explicitly or not. If the change to UTC is made, these applications will simply slowly degrade in accuracy, unnoticed at first. This will be worse than the Y2K problem, because it is much more subtle; in many cases, the original coder may not even have been aware of the distinction between UT1 and UTC. This problem is outside the scope of this paper.

John Bangert of USNO has suggested that if leap seconds are dropped from UTC, we could switch our Earth-rotation-dependent tabulations from UT1 to UTC. This would require, in preparing the printed publications, that we predict UT1–UTC to sufficient accuracy a little more than two years into the future. The IERS publishes UT1–UTC predictions for a year in the future, and their estimated accuracy at the end of that time is currently 0.02 s. (This must be an underestimate; a recent authoritative paper[6] gives the prediction accuracy after one year as 0.04–0.15 s.) The IERS also provides a linear extrapolation formula for dates beyond those in the published table. Regardless of the expected accuracy of such predictions, the printed almanacs would probably have to provide correction tables so that users could, if necessary, adjust the data to be consistent with the better values of UT1–UTC that would be available closer to the time that the data are actually needed.

Online services would fare better with UTC as the time argument, because the value of UT1–UTC is known for past and current dates; but if users request data for dates more than a few months in the future, the same considerations apply as for the printed almanacs. In such cases, the web pages could, perhaps, supply a projected value of UT1–UTC that the user could change if she wants.

If we change to UTC as the time argument for Earth-rotation-dependent data, we might also do it for the other data. As I mentioned, TT would be simply a constant offset from UTC, so, aside from historical continuity arguments, there would be little point in *not* switching from TT to UTC. The heliocentric or barycentric tabulations now given as a function of TDB should probably remain that way, because these data are most appropriately expressed in the same time scale in which the fundamental ephemerides are computed. (Another time scale, TCB, shown on Figures 1 and 2, is likely to become more common for computing these data in the future.)

CONCLUSION

If leap seconds are removed from UTC, there is at least the possibility that most almanac data could in the future be tabulated as a function of UTC. That would undoubtedly be a great convenience for users. In the case of Earth-rotation-dependent data, however, the convenience would come at the price of some degradation in accuracy. It seems likely that the increased error (for tabulations computed about two years in advance) would not be worse than that from assuming UT1=UTC now, which is probably a common assumption. Furthermore, if necessary, the error could be removed by application of corrections based on the measured value of UT1–UTC for the date on which the data are needed.

On the other hand, if these tabulations continue to be provided as a function of UT1, a rather intensive user-education strategy will be required, because the approximation UT1=UTC will no longer apply. Users will have to understand the difference between UTC and UT1 and how to obtain and apply the UT1–UTC value from the IERS or other sources. This will be new to many current users of these data.

My personal view on the proposed change to UTC, which may not be shared by other members of Commission 4, is that it has not been widely enough discussed outside of the specialized communities that are most directly involved. I find it astonishing that an obscure technical organization like the ITU has the responsibility for defining the worldwide system of civil time — essentially, people who normally decide on radio spectrum allocation, satellite orbits, and communication protocols are being asked to decide the meaning of what our clocks say. I believe that the issue has so far been couched in terms (e.g., UTC, UT1, leap seconds) that are too technical even for many astronomers, and the low response to surveys and other inquiries reflects that. I think the title of this meeting has it about right: Should we decouple civil time from the Earth's rotation? I think a question like that needs more discussion, among a much wider audience.

Our concept of public time has evolved considerably over the centuries, and the U.S. experience has been well documented in the very readable book, *Keeping Watch: A History of American Time*.[7] Every change to our system of timekeeping has been a contentious issue for the general public, and I expect that if the proposed change to UTC is made, it will be equally contentious once the popular media really get hold of it. The recent article on UTC in the *American Scientist*[8] is one of several good contributions to a more public discussion, but I believe that much more education and debate needs to take place before a decision is made on changing something so fundamental as the system of civil time.

REFERENCES

[1] Spencer Jones, H., "The Rotation of the Earth, and the Secular Accelerations of the Sun, Moon, and Planets," *Monthly Notices Roy. Astr. Soc.*, Vol. 99, No. 7, 1939, pp. 541–558.

[2] Markowitz, W., Hall, R. G., Essen, L., & Parry, J. V. L., "Frequency of Cesium in Terms of Ephemeris Time," *Phys. Rev. Letters*, Vol. 1, No. 3, 1958, pp. 105–107.

[3] Seidelmann, P. K., & Fukushima, T., "Why New Times Scales?" *Astron. Astrophys.*, Vol. 265, 1992, pp. 833–838.

[4] Kaplan, G. H., *The IAU Resolutions on Astronomical Reference Systems, Time Scales, and Earth Rotation Models*, USNO Circular 179 (Washington: USNO), 2005.

[5] Her Majesty's Nautical Almanac Office & U.S. Naval Observatory Nautical Almanac Office, *The Nautical Almanac for the Year 2010* (Washington: GPO), 2009, p. 34.

[6] Gambis, D., & Luzum, B., "Earth Rotation Monitoring, UT1 Determination and Prediction," *Metrologia*, Vol. 48, 2011, pp. S165–S170.

[7] O'Malley, M., *Keeping Watch: A History of American Time* (New York: Viking Penguin), 1990.

[8] Finkleman, D., Allen, S., Seago, J., Seaman, R., & Seidelmann, P. K., "The Future of Time: UTC and the Leap Second," *American Scientist*, Vol. 99, No. 4, 2011, pp. 312–319.