The future of

Coordinated Universal Time (UTC)

Elisa Felicitas Arias

Seminario de la UIT para la Región de las Américas
(Manta, Ecuador, 20-21 de septiembre de 2012)
Outline

- Historical background

- Evolution towards the adoption of atomic time
  - Motivations
  - Applications

- UTC with leap seconds
  - Still necessary?
  - Conflicts with present applications
    - Case of global navigation satellite systems (GNSS)

- Solutions

- Role of the BIPM
The second and the time scale, a little bit of history

- **International Astronomical Union (IAU)**
  - 1/86400 mean solar day

- **CIPM (1956), IAU, CGPM(1960)**
  - 1/31 556 925.9747 of the tropical year 1900

- **Universal Time (UT)**
  - Based on Earth Rotation (apparent daily motion of the Sun)

- **Ephemeris Time (ET)**
  - Based on the orbital motion of the Earth around the Sun
  - ET was a timescale used only by astronomers, the practical timescale remained UT

- **CIPM (1964), CGPM(1967)**
  - 9 192 631 770 periods of radiation corresponding to the transition between two hyperfine levels of the ground state of the Cs 133 atom

- **CCDS, CIPM (1970), CGPM (1971)**
  - Definition of TAI

- **International Telecommunication Union (ITU)**
  - Definition of UTC

- **CGPM (1971)**
  - Endorses UTC
Some useful concepts

- The rate of rotation of the Earth is not uniform
  - The length of the day changes
  - The seconds do not have the same duration
  - UT1 (a form of UT corrected for polar motion but affected by the irregular rotation of the Earth)

\[ D(t) = \frac{\omega_0}{\omega(t)} \times 86400 \text{s} \quad \frac{d(UT1)}{dt} = \frac{\omega(t)}{\omega_0} \]
• “Rotational” second defined as a fraction of the day
Some useful concepts

• **Ephemeris time ET**
  - Formally defined as the argument (t) in the dynamical equations of the apparent annual motion of the Sun;
  - Such argument represents uniform time;
  - Can be determined in post-real time only, from the difference between the observations and calculated positions of the Sun (Moon in the practice);
  - The second of ET was determined as ~ to the average duration to the second of mean solar time over the century; at the moment of its adoption, the ET second was shorter than the mean solar time second by $1.4 \times 10^{-8}$;
  - The principle of continuity when a unit is redefined was violated, and
  - Consequences came later at the adoption of atomic time.
The adoption of atomic time

• The atomic second was defined to keep continuity with the ephemeris second, so shorter than that derived from the mean solar day;

• TAI can be considered as an average of clock readings, all on the rotating geoid and realizing with some approximation the SI second;

• By « averaging » the scale unit of TAI is realized, but the problem of fixing the origin (arbitrary) remains, necessary for providing a timescale capable of measuring time intervals;

• TAI was fixed by considering it equal to UT (a particular form) on 1 January 1958, at 0 h UT.
• Changing from UT to TAI meant that

\[
\text{since } \omega \text{ decreases in the long term } \Rightarrow \\
1 \text{ rotational day } > 1 \text{ « atomic day »}
\]
Improved dynamical theory required a revision of ET

Essen had developed the caesium frequency standard

UK, USA operated Cs standards

The BIH already included these standards in the calculation of the reference timescale

Any modification involved a major change
Reasons for not changing

Astronomical time was « the time of God »

Decorrelation with the solar rhythm of human activities

Need of accessing UT1 with some precision

Defining different timescales for different applications

Defining a unique timescale adapted to all applications
Astronomical navigation | Determination of longitude by observing celestial objects at known positions | Need to access UT1 with 1 s precision

Astronomers | Telescope pointing | Need to access UT1 with 1 s precision
Compromise to satisfy all users

• Adopt TAI, whose unit interval is the atomic second;
• Define UTC, as derived from TAI, with the atomic second as unit but modified for rendering it close to UT1;
• Establish a tolerance adequate to maritime navigation and astronomical observation:

\[|\text{UT1} - \text{UTC}| < 0.9 \text{ s}\]

• Maintaining the two scales within the tolerance by addition of a second (leap second, positive or negative) to UTC whenever decided by the organization monitoring the Earth rotation (IERS today);

• The ITU-R approved a recommendation (ITU-R, TF-460.6, 1970) establishing the procedure for the application of leap seconds to UTC.
From BIPM Annual Report on Time Activities

Before adoption of TAI and UTC

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>UTC</th>
<th>[TAI - UTC] / s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>Jan. 1 - Aug. 1</td>
<td>1.422 8180 + (MJD - 37300) x 0.001 296</td>
<td></td>
</tr>
<tr>
<td>1961</td>
<td>Aug. 1 - Jan. 1</td>
<td>1.372 8180 +</td>
<td></td>
</tr>
<tr>
<td>1962</td>
<td>Jan. 1 - Nov. 1</td>
<td>1.845 8580 + (MJD - 37665) x 0.001 1232</td>
<td></td>
</tr>
<tr>
<td>1963</td>
<td>Nov. 1 - Jan. 1</td>
<td>1.945 8580 +</td>
<td></td>
</tr>
<tr>
<td>1964</td>
<td>Jan. 1 - Apr. 1</td>
<td>3.240 1300 + (MJD - 38761) x 0.001 296</td>
<td></td>
</tr>
<tr>
<td>1964</td>
<td>Apr. 1 - Sep. 1</td>
<td>3.340 1300 +</td>
<td></td>
</tr>
<tr>
<td>1964</td>
<td>Sep. 1 - Jan. 1</td>
<td>3.440 1300 +</td>
<td></td>
</tr>
<tr>
<td>1965</td>
<td>Jan. 1 - Mar. 1</td>
<td>3.540 1300 +</td>
<td></td>
</tr>
<tr>
<td>1965</td>
<td>Mar. 1 - Jul. 1</td>
<td>3.640 1300 +</td>
<td></td>
</tr>
<tr>
<td>1965</td>
<td>Jul. 1 - Sep. 1</td>
<td>3.740 1300 +</td>
<td></td>
</tr>
<tr>
<td>1965</td>
<td>Sep. 1 - Jan. 1</td>
<td>3.840 1300 +</td>
<td></td>
</tr>
<tr>
<td>1966</td>
<td>Jan. 1 - Feb. 1</td>
<td>4.313 1700 + (MJD - 39126) x 0.002 592</td>
<td></td>
</tr>
<tr>
<td>1968</td>
<td>Feb. 1 - Jan. 1</td>
<td>4.213 1700 +</td>
<td></td>
</tr>
</tbody>
</table>

After adoption of TAI and UTC, following the ITU recommendation

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>UTC</th>
<th>[TAI - UTC] / s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>Jan. 1 - Jul. 1</td>
<td>10 (integral number of seconds)</td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>Jul. 1 - Jan. 1</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>1973</td>
<td>Jan. 1 - Jan. 1</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>1974</td>
<td>Jan. 1 - Jan. 1</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td>Jan. 1 - Jan. 1</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>
35 leap seconds
• **DUT1**

The value of the predicted difference UT1 – UTC, as disseminated with the time signals is denoted DUT1. The values of DUT1 are given by the IERS in multiples of 0.1 s.

The magnitude of DUT1 should not exceed 0.8 s.

The departure of UTC from UT1 should not exceed ±0.9 s.

A positive or negative leap-second should be the last second of a UTC month, but first preference should be given to the end of December and June, and second preference to the end of March and September.

A positive leap-second begins at 23h 59m 60s and ends at 0h 0m 0s of the first day of the following month. In the case of a negative leap-second, 23h 59m 58s will be followed one second later by 0h 0m 0s of the first day of the following month.

The IERS should decide upon and announce the introduction of a leap-second, such an announcement to be made at least eight weeks in advance.

FIGURE 3
Positive leap-second

Designation of the date of the event
30 June, 23h 59m 60.6s UTC

30 June, 23h 59m —— 1 July, 0h 0m

FIGURE 4
Negative leap-second

Designation of the date of the event
30 June, 23h 59m 58.9s UTC

30 June, 23h 59m —— 1 July, 0h 0m
Are clocks prepared for beating the second 60 in a minute?

Is a stepped UTC adapted for modern applications?

• The leap-second event (artificial injection of a second in a device not adapted for a second named « 60 ») provokes system interruptions, affecting:
  • Synchronization of networks
    • Communications
    • NTP (network time protocol)
    • Computers
    • Electrical power distribution and control
    • …
  • Satellite synchronization
    • GNSS times
  • Space operations
    • Vehicles launching
  • Air traffic control, airport operations
  • Time dissemination in general
Negative points of UTC with leap seconds

- Breaks the essence of time: continuity
- Impredictable occurrence at irregular intervals
- Need of keeping archives manually updated
- Forced operation of clocks
  - Simplified today, Cs clocks can be programmed for leap second application
- Positive or negative?
  - Risk of 2 s offset
- Simultaneous all over the world, so at different local times
  - Impact is different depending on local times and of the date of application
- Non-respect of procedure of application
  - Applied on the first working day of the year (the lab is closed…)
  - Second 60 distributed over a number of seconds around midnight (steered seconds …)
Arguments to defend UTC with leap seconds

• Accomodates (uniform) atomic time to (non-uniform) Earth rotation time
  • But who really cares today?
• Gives acces to UT1 to better than 0.9 S
  • Predictions of UT1-UTC by the IERS give a more precise access
• Can be considered equal to UT1, so equal to GMT
  • GMT was abandoned in the 1950s by the IAU, replacing it by UT;
  • It was recommended not to use GMT or its acronym to avoid confusion with UTC since 1972
• Many people believe that by preserving UTC with the leap seconds they strictly follow solar time
  • What about legal times following time zones?
  • Good exemples: European Central Time, China without time zones, daylight saving times where 1-h offsets are applied between Summer and Winter times (people do not care…)
The vertical black thick lines show the possible values depending on:
- season (summer time, equation of time)
- extent in longitude

Additional shift if leap seconds are abandoned in 2012
Typical problems and ambiguities arising from the LS

**Timescales differing by seconds**
http://leapsecond.com/java/gpsclock.htm

- **Change of day problem**
  - Some systems have time tagging on different timescales for different services;
  - At the leap second occurrence the change of day is not simultaneous for the timescales;
  - Happens in some GNSS, when the GNSS time and UTC are used.

- **Change of week problem**
  - Analogous to the change of day;
  - Dating in weeks is typical of GNSS

- **MJD counting**
  - Measure of time intervals by the number of days of 86400 s elapsed between the extremes of the interval
Elimination of the leap second application in UTC

- Decorrelation with UT1 (1 h in many hundreds of years…)
- Software not prepared for an unlimited difference UT1 – UTC
- Hardware not prepared for supporting DUT1 bigger than 1 digit
- Time is necessary for adapting the systems to the new definition

- Continuos reference timescale UTC
- No loss of time in leap second application (human resources, money)
- No more outages of systems affected by leap seconds
  - GLONASS is an example
- Interperability of GNSS facilitated, UTC will provide the direct reference for steering

- Probable disparition of TAI (offset with UTC will remain constant)
- Will stop proliferation of timescales and thus avoid confusion and minimize risks.
GNSS and the leap second

- GNSS define internal timescales for allowing system synchronization, they are necessary to achieve the navigation solution.

- GNSS timescales are continuous, constructed from clock ensembles, and steered to and external reference.

- The external reference is UTC as realized in a laboratory.

- UTC is stepped, so most GNSS steer to UTC(k) modulo 1 second.

- GLONASS follows exactly UTC(SU).

- The choice of the number of integral seconds from UTC is arbitrary.

- Conflict with interoperability.

<table>
<thead>
<tr>
<th>GNSS time</th>
<th>Reference for synchro</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>UTC(USNO)</td>
</tr>
<tr>
<td>GLONASS</td>
<td>UTC(SU) [VNIIFTRI]</td>
</tr>
<tr>
<td>Galileo</td>
<td>UTC(k), k in Europe</td>
</tr>
<tr>
<td>BeiDou</td>
<td>UTC(k), k in China</td>
</tr>
<tr>
<td>EGNOS</td>
<td>UTC(OP)</td>
</tr>
</tbody>
</table>

Bureau International des Poids et Mesures
Relationship between TAI, UTC and the GNSS times
Without considering the integral nb of seconds, amounting 16 s since July 2012.

Is it clear for users that the scales are different?
Redefining UTC, the process

- The ITU has a very heavy process for approving/modifying recommendations (Working Party → Study Group → WRC)

- The discussion has been in the WP7A for 12 years, strong opposition of one administration blocked the progress of the proposal. Three other administrations opposed in 2012.

- Arguments against the change have no technical support
  - Decorrelation to the Sun
  - Confusion of people, of nature in general, religious dates (the adoption of the Gregorian calendar for accommodating the dates of Easter implied the elimination of 10 days, 4 October 1582 has followed by 15 October, but was not adopted by all the world, only that linked to Rome)
  - UTC approximates UT1, and UT1 approximates GMT (legal time in UK); without leap seconds UTC and GMT will diverge (in fact there is no physical realization of GMT, it is the name given to UTC realized at UK by NPL)
The draft recommendation TF-460.6 proposing a new definition of UTC without leap seconds was submitted to the Radiocommunication Assembly in January 2012.

- Considering the need of adapting software, hardware and procedures, it would not be in force until at least 5 years after approval.

A questionnaire sent by the ITU-R to the administrations previous to the RA was answered by about 15 members, only three opposing. In a previous survey, the IAU and the BIPM manifested their support to the elimination of the leap second.

The RA took into consideration that there was some balance between the administrations with a clear opinion (either positive or negative) and those requesting for some analysis and information. In consequence the decision on the adoption of a continuous timescale was differed to the World Radio Conference in 2015.

- The BIPM delegates to the ITU continue working on this direction…
Helping to the process, promoting discussion, educating

- A Special Issue of Metrologia, « Modern Timescales ». Published in July 2011
  - Guest editors are F. Arias (BIPM) and W. Lewandowski (BIPM) both delegates from the BIPM to the ITU-R

- Discussion at the Royal Society of London on 3-4 November 2011
  - Invited contributors only
  - Participation by invitation
  - T. Quinn, F. Arias organized

- Putting the discussion to the International Committee for GNSS (ICG)

- Promoting a reflexion on the responsibility for the definition of the world time reference,
  - ITU rules on the dissemination by signals, but is not the metrological authority
  - The well-established world metrology structure CGPM-CIPM-BIPM-NMIs should naturally take the responsibility
Last (?) leap second

End of June 2012
TAI-UTC = 35 s