Improvements of Indian standard time at NPL, New Delhi, maintained through GPS network

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The National Physical Laboratory (NPL), New Delhi, has been maintaining Universal Coordinated Time (UTC) through GPS network to keep it linked to UTC coordinated by International Bureau of Weights and Measures (BIPM) for more than ten years. Recent measures of housing of cesium clock in a controlled environment, the procurement of new receivers with prior calibration, maintaining the temperature of antenna at a fixed point and the adjustments of required phase and frequency from time to time, have been taken to improve the quality of UTC(NPLI). In view of this, the status of UTC(NPLI) has been studied analytically and exhaustively. The substantial improvement in the performance of the time scale UTC(NPLI) has been observed. This paper elaborates these observations.

Keywords: Indian standard time, UTC, GPS network, Atomic clock

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1 Introduction

The cesium atomic clock has the highest long term stability among the other commercially available atomic clocks. So, it is used as the primary standard of time and frequency parameters and is also used to maintain the national standard of time. But a clock, however precise and accurate it may be, defines its own time scale and no clock is perfect. Thus, the time scale initially synchronized on the conventional origin will depart from each other after some time. This very fact demands the necessity of internationally coordinated and recognized time scale which is hoped to be more uniform than the individual one. To realize a uniform time scale it has been felt necessary that all clocks maintained by the time keeping laboratories scattered around the globe, need to be compared with each other. International Bureau of Weights and Measures (Bureau International des Poids et Mesures, i.e. BIPM) in Paris, has been coordinating this activity. The scheme that is followed for this purpose compares the remote clocks to generate International Atomic Time (TAI), and Universal Coordinated Time (UTC) through the use of these inter-compared data. The link to compare the remote clocks employs normally two techniques, namely, common-view global positioning system (GPS) method and the two-way satellite time and frequency transfer (TWSTFT) technique. But most common time link is based on GPS satellite in common-view mode.

The National Physical Laboratory (NPL), New Delhi, maintains the time scale of Indian Standard Time (IST) with the help of a commercial cesium atomic clock (make HP and Model 5071A). The time scale maintained by NPL is designated as UTC (NPLI). The NPLI also makes use of GPS satellites in a common-view mode as the link to participate in the clock-comparison for contributing to the generation of TAI and UTC. The NPLI has undertaken few measures to improve UTC (NPLI).

This paper elaborates the scheme of inter-comparison of clocks. It also analyzes the data that are received as feedback from BIPM and evaluates the improvement in the performance of the clock of NPLI.

2 Concept of GPS time link

The GPS is a satellite-based radio positioning/navigation and also time transfer system. To use GPS for timing purposes one may make simultaneous measurements from four GPS satellites to get the solutions for four unknown parameters (i.e. three coordinates of the location of the receiving antenna and the time offset of the local clock of the receiver with respect to GPS time.). But if the precise
coordinates (i.e. three parameters) of the location is known in advance, the measurement from a single satellite would give the solution for time offset. All time keeping laboratories determine the precise clock coordinates of the respective locations in advance. So, a special GPS receiver, tracking only one satellite, is normally used for time link via GPS in common-view mode.

In a coordinated common-view time comparison method as illustrated in Fig. 1, a pair of stations observes one common satellite simultaneously. The time of local clock is compared with respect to the received GPS time. The differences between the simultaneous measurements of two locations determine quite accurately the time offset between two clocks of participating locations.

The BIPM computes TAI and UTC by using intercomparison data from atomic clocks kept at laboratories/institutions scattered all over the world. In GPS common-view mode, NPLI, like the most of the participating laboratories, has the set-up as shown in Fig. 2. The GPS receiver is connected to the 1pps (one pulse per second) signal delivered by the local standard clock [i.e. in this case, the particular cesium clock through which UTC(NPLI) is realized]. The internal software of the receiver computes, following a procedure as recommended by the Consultative Committee of Time and Frequency (CCTF), the clock offset between UTC(NPLI) and GPS time as realized by each satellite for conventional 13-min track.

All participating clocks will have to be compared with the time signals emitted by GPS satellites according to the scheme coordinated by BIPM. The scheme operates in a common-view mode as shown in Fig. 1. So, it is necessary that measurements of a particular zone should be made simultaneously with that of another zone through one common satellite. One way to achieve this with the help of a single channel (i.e. one satellite at a time) receiver is to schedule the measurement for each zone of the world judiciously so that the schedule of a particular time zone is always common with that of one (at least one) or more zones/regions of the world. A typical sample of the schedule for India is shown in Table 1 which had been followed by NPLI using a single channel receiver (Model TTR6) till recently. Table 2 indicates the zones of common view for a particular schedule. For example, at 0600 hrs UTC for satellite PRN No.08, the schedule is in common view with Middle East (ME), East Asia (EA) and Europe (E).

Now, new generation of timing receivers track many satellites simultaneously depending on the channel capacity of the receiver (e.g., eight-channel receiver is quite common). Thus, one gets more than one solutions (as many as number of satellites tracked) for GPS time corresponding to each time of measurement. So, in this case, “to follow a schedule” is no longer mandatory. The BIPM may easily sort out the data that correspond to common view with respect to the respective zone or laboratory. In fact, after procuring the TTS-2 receiver which is an eight-channel receiver, NPLI has also started to follow this method.

However, irrespective of the type of receiver or method, it is absolutely necessary to record the measurement in one common format (also conceived by BIPM) for the convenience of operation and coordination. The clock offsets are recorded by the
receiver in a particular format known as common GPS GLONASS time transfer standard (CGGTTS).

3 Experimental arrangements

The NPLI has recently procured two timing GPS receivers (model TTS-2), which are eight-channel receivers. Here, the eight-channel receiver implies that it can track eight satellites at a time. So, one may get eight timing solutions leading to simultaneous comparisons of eight GPS timing solutions with respect to the local time. The delays of the antenna cable supplied with the receivers have already been calibrated at the factory and have been taken into account in the software of the receiver. To finalize the set-up according to Fig. 2, the following arrangements have been made at NPLI.

3.1 Precise coordinate determination

3.1.1 Coordinate determination of one fixed point—It has been pointed out that the technique of time inter-comparison demands the prior knowledge of precise coordinates of the location. One fixed point of NPLI had been precisely determined earlier with respect to a location (i.e. IISc., Bangalore, India) which is linked to IGS network. The same fixed point has recently been re-determined with respect to another IGS station (i.e. NGRI, Hyderabad, India) for revalidation. The special GPS receiver that were used for this purpose is a 12-channel, dual frequency, geodetic advanced carrier technology (ACT) [Bench Mark Allen Osborne Associate (AOA), make GPS Receiver] receiver. The antenna is a choke ring antenna. The receiver has hyper-terminal software to download the acquired data. The data were acquired continuously for 7 days (from 16 Sep. to 22 Sep. 2004) round the clock. The raw data after conversion to RINEX format were downloaded from the receiver. The acquired data were processed at NGRI using

Table 1—Participating laboratories

<table>
<thead>
<tr>
<th>Area</th>
<th>Participating laboratories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe (E)</td>
<td>AOS, BEV, CAO, CH, DLR, DTAG, IEN, IFAG, IPQ, LDS, LT, Mad*, NIMB*, NMC, NPL, OHH, OP, ORB, PL, PTB, RAAI*, RIRT*, ROA, SMU, SP, SU, TP, UME, VSL</td>
</tr>
<tr>
<td>East North America</td>
<td>AO*, NRC, USNO</td>
</tr>
<tr>
<td>Hawaii (H)</td>
<td>WWVH*</td>
</tr>
<tr>
<td>East Asia (EA)</td>
<td>BIRM, CRL, JATC, KRIS, NAO, NIM, NIMT, NMIJ, NMLS, NTSC, SCL, SG, TL</td>
</tr>
<tr>
<td>Australia (A)</td>
<td>AUS, Can*, MSL</td>
</tr>
<tr>
<td>India (I)</td>
<td>NPLI</td>
</tr>
<tr>
<td>Middle East (ME)</td>
<td>INPL</td>
</tr>
<tr>
<td>South Africa (SAF)</td>
<td>CSIR</td>
</tr>
<tr>
<td>South America (SAM)</td>
<td>IGMA, Kou*, ONBA, ORNJ, TCC*</td>
</tr>
</tbody>
</table>

WWV, WWVH: NIST stations in Colorado and Hawaii.
AO: Arecibo Observatory.
Kou: CNES Kourou Center.
RIRT: Russian Institute of Radionavigation and Time, Saint Petersburg.
RAAI: Romanian Academy Astronomical Institute, Bucarest.
NIMB: National Institute of Metrology, Bucharest, Romania
TCC: TIGO, Conception, Chile.

Table 2—Sample of schedule decided by BIPM

<table>
<thead>
<tr>
<th>Class</th>
<th>PRN</th>
<th>Start h</th>
<th>Connects</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>08</td>
<td>0</td>
<td>ME,EA,E</td>
</tr>
<tr>
<td>A0</td>
<td>09</td>
<td>0</td>
<td>ME,EA,E</td>
</tr>
<tr>
<td>BC</td>
<td>07</td>
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</tr>
<tr>
<td>BD</td>
<td>07</td>
<td>1</td>
<td>SAF,ME,E</td>
</tr>
<tr>
<td>BD</td>
<td>28</td>
<td>1</td>
<td>ME,EA,E</td>
</tr>
<tr>
<td>38</td>
<td>11</td>
<td>1</td>
<td>H,EA</td>
</tr>
<tr>
<td>A0</td>
<td>07</td>
<td>1</td>
<td>ME,EA,E</td>
</tr>
<tr>
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<td>07</td>
<td>2</td>
<td>ME,EA,E</td>
</tr>
<tr>
<td>A2</td>
<td>07</td>
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<td>3</td>
<td>SAF</td>
</tr>
<tr>
<td>A4</td>
<td>24</td>
<td>3</td>
<td>SAF</td>
</tr>
<tr>
<td>AC</td>
<td>28</td>
<td>3</td>
<td>A,EA</td>
</tr>
<tr>
<td>BC</td>
<td>24</td>
<td>4</td>
<td>SAF,ME,EA,E</td>
</tr>
<tr>
<td>BC</td>
<td>09</td>
<td>4</td>
<td>SAF,ME,E</td>
</tr>
<tr>
<td>BD</td>
<td>09</td>
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</tr>
<tr>
<td>BD</td>
<td>24</td>
<td>5</td>
<td>ME,EA,E</td>
</tr>
<tr>
<td>A1</td>
<td>24</td>
<td>5</td>
<td>ME,EA,E</td>
</tr>
<tr>
<td>AC</td>
<td>07</td>
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<td>A,EA</td>
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<td>7</td>
<td>SAF,ME,E</td>
</tr>
<tr>
<td>BD</td>
<td>05</td>
<td>7</td>
<td>SAF,ME</td>
</tr>
<tr>
<td>BC</td>
<td>30</td>
<td>7</td>
<td>SAF,ME,E</td>
</tr>
<tr>
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<td>7</td>
<td>SAF,ME,E</td>
</tr>
<tr>
<td>D4</td>
<td>30</td>
<td>8</td>
<td>SAF,ME,E</td>
</tr>
<tr>
<td>A4</td>
<td>30</td>
<td>8</td>
<td>SAF</td>
</tr>
<tr>
<td>BC</td>
<td>23</td>
<td>9</td>
<td>SAF,ME</td>
</tr>
<tr>
<td>BC</td>
<td>18</td>
<td>9</td>
<td>SAF,ME,E</td>
</tr>
<tr>
<td>A4</td>
<td>18</td>
<td>9</td>
<td>SAF</td>
</tr>
<tr>
<td>A0</td>
<td>17</td>
<td>10</td>
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</tr>
<tr>
<td>AC</td>
<td>09</td>
<td>11</td>
<td>A,EA</td>
</tr>
</tbody>
</table>

Note: A=Australia & New Zealand; ME= Middle East; SAF= South Africa; EA=East Asia; E=Europe
versatile GPS data processing software, Bernese Version 4.2, after obtaining the precise orbit files from IGS data centre. To get more accurate results, global network solutions were adopted by including many other IGS stations (COCO, HRAO, HYDE, IISc, IRKT, KIT3, LHAS, POL2, SEY1, WTZR, YAR2) in and around India. In this process, the coordinates of the fixed point of NPLI was re-determined with respect to IGS station with an accuracy of better than 15 mm.

3.1.2 Transfer of coordinates to nearby points—
Coordinates of few other nearby locations were determined with respect to this point by the following method.

Incremental change in the coordinates of a nearby point (A) with respect to the pre-determined location (O) may be determined measuring the distance OA (say, $d$ metres) and the azimuth of the line OA (i.e. the angle $\alpha$) as shown in Fig. 3. The following approximate relations may be used to determine to the coordinates of nearby point without sacrificing the accuracy.

$$\delta \text{lat} = OM = d \cos \alpha \text{ (in metres)} = \frac{(d \cos \alpha)}{30.768} \text{ (in arc of second)}$$

$$\delta \text{long} = AM = d \sin \alpha \text{ (in metres)} = \frac{(d \sin \alpha)}{30.768 \times \cos(\text{lat})} \text{ (in arc of second)}$$

where,

$\delta \text{lat} = \text{Increment in latitude of A over that of O}$

$\delta \text{long} = \text{Increment in longitude of A over that of O}$

and

angle “lat” = Latitude of O.

Here, it is assumed that one arc of second is equivalent to distance of 1.85 km. It may be noted that value of $\alpha$ takes care of the polarity of the increment. In this method, coordinates of two additional points were determined with respect to the pre-determined location with the same accuracy of 15 mm. Two antennas of the receivers have been placed on these two points.

3.2 Calibration of antenna cable
Keeping in mind the aim of time accuracy of few nanoseconds, it has been felt necessary to measure carefully the delay of the cable used in the set-up for feeding 1pps from clock of NPLI to GPS receiver. To do this, two sets of measurements have been carried out as shown in Fig. 4[(a) and (b)]. Cable C is the cable whose delay is to be determined. Time interval counter (TIC) with a resolution of 150 ps has been used in these measurements.

One may write from Fig. 4[(a) and (b)]

TIC\(a\) = Delay B – Delay A
TIC\(b\) = (Delay B + Delay C) – Delay A

where

TIC\(a\) = TIC reading for set-up at Fig. 4(a)
TIC\(b\) = TIC reading for set-up at Fig. 4(b)
Delay A = Delay of cable A
Delay B = Delay of cable B
Delay C = Delay of cable C

So, combining the measurements of these two set-ups, one may write

Delay C = TIC\(b\) – TIC\(a\)

In the present case, the delay of cable C, thus determined, has been found to be 70 ns. This cable C has been used to feed 1pps of cesium clock to the receiver.

4 Morphology of data
4.1 Methodology of traceability of UTC(NPLI)
The NPLI along with about 60 other laboratories around the globe uses the scheme as shown in Fig. 2 to participate in the time comparison scheme of BIPM via GPS network. The precise coordinates of the
antenna and the delay of 1pps-feeding cable have been fed to receivers. Data recorded through the measurements carried out by the receivers follow strictly CGGTTS format. These data are sent to BIPM through internet/e-mail at regular interval of time. The BIPM uses all these data to generate a smooth time scale through robust software which is virtually the weighted average of clocks of all participating laboratories. Thus, this software generates the time scale (i.e. paper scale) combining all the received data. This time scale is named as Universal Coordinated Time (UTC). The software also evaluates the status of the time scale of contributing laboratories with respect to UTC. A circular T giving the status with respect to UTC is published by BIPM and is also available on BIPM website.

Thus, status of time scale of NPLI [i.e. UTC (NPLI)] is also available at the interval of 5 days through circular T. The records of UTC–UTC (NPLI) at the interval of 5 days as given in circular T are illustrated in Fig. 5(a) and Fig. 5(b). These data are to be analyzed systematically to evaluate the characteristics of the time scale. Practically, the feedback from BIPM cannot be on-line. It has a time delay of roughly one month. So, it is also necessary to predict the current status of UTC(NPLI). To analyze these data, the cesium clock [of NPLI that maintains UTC(NPLI)] may be assumed to have no drift in frequency. So the time scale of NPLI becomes a linear function of time, the slope of which determines the frequency offset with respect to UTC. Thus, to fit the data to a straight line the following model is used.

\[ x = A + Bt \]  \[ \text{... (1)} \]

where \( A \) (implying in this case as starting clock offset) is intercept, \( B \) the slope which is the relative frequency offset, \( x \) corresponds to UTC–UTC (NPLI) and \( t \) is the corresponding time of measurement (i.e. 0000 hrs of the corresponding MJD). The standard deviation (SD) of the fit is calculated through the equation

\[ SD = \sqrt{\frac{\sum_{i=1}^{N} (x_i - (A + Bt_i))^2}{N-2}} \]  \[ \text{... (2)} \]

Taking into account the last six months data of UTC–UTC(NPLI), \( B \) is determined to find the current offset of the time scale of NPLI. Six months are thought to be optimum as this period is not too short an interval to find the frequency offset of precise clock, like cesium atomic clock and also not too long a duration to get mixed up with any probable slow variation /drift that might occur by any unforeseen /unknown reason. This value of \( B \) may also be used to find out the current value of UTC–UTC(NPLI) using the method of extrapolation. The SD may be assumed to be the uncertainty of prediction of the current status of UTC(NPLI). Based on the data prior to July 2005, \( B \) has been found to be 10.6792 ns per day. Thus, the frequency offset has been found to be \( 1 \times 10^{-13} \). The SD of residual of the fit is 25 ns. Correlation coefficient is 0.99956.

\[ \text{The start of Julian era is defined as the beginning at noon on Monday, 1\textsuperscript{st} January of year 4713 B.C. A Modified Julian Day (MJD) which has been created by subtracting 2400000.5 from a Julian day number and thus represents the number of days elapsed since midnight (00:00) Universal Time on 17 November 1858, is usually referred as the date of observation time in timing experiment.} \]
Recently the following measures have been taken to improve the performance of the UTC(NPLI).

(i) Cesium clocks have been put in an environmentally controlled room. Temperature of the room is maintained at (23±2)°C and relative humidity at 50±5%.

(ii) Two antennas of new GPS receivers are maintained at a constant temperature of 50°C through heating. Further, these receivers have been supplied with a prior calibration by BIPM.

(iii) Proper frequency and phase adjustments have been applied to UTC (NPLI). A phase step to cesium clock may bring the UTC(NPLI) very close to UTC, but this closeness cannot be maintained unless the frequency is aligned to UTC as close as possible. So, the frequency step has been important. These phases of transitions have been elaborated in Fig. 5(b).

As a result of these measures, there has been substantial improvement in the uncertainty in UTC (NPLI) and the value of [UTC–UTC (NPLI)] is being maintained within 100 ns. These have been reflected in Fig. 5(b). One may note that the improvement of uncertainty from 20.6 ns to 7.6 ns has been observed since July 2005. It may also be noted that circular T has started giving the value of uncertainty only since December 2004.

4.2 Frequency stability of UTC(NPLI)

The random frequency stability of an oscillator, in time domain, may be estimated by several sample variances. The recommended measure is the two-sample standard deviation, which is the square root of the two-sample zero dead-time variance \( \sigma_y^2 \), also designated as Allan variance, defined as

\[
\sigma_y^2(\tau) = \frac{1}{2} \left\langle (\bar{y}_{k+1} - \bar{y}_k)^2 \right\rangle \tag{3}
\]

where \( \left\langle (\bar{y}_{k+1} - \bar{y}_k) \right\rangle \) denotes the average over large number of samples and \( \bar{y}_k \) may be estimated by

\[
\bar{y}_k = \frac{x(t_k + \tau) - x(t_k)}{\tau} \tag{4}
\]

The terms \( x(t_k+\tau) \) and \( x(t_k) \) are proportional to the instantaneous phase obtained from the comparison between two clocks at date \( t_k \) and \( t_{k+1} = t_k + \tau \) with \( k = 1,2,3,... \) and have the dimension of time. The term \( y_k \) is the average normalized frequency departure of one of the oscillator against the other one, estimated over the averaging time \( \tau \).

Allan deviation \( [\sigma_y(\tau)] \) is the representative of frequency stability (of a frequency source) over a particular averaging time \( \tau \). The status of UTC (NPLI) is updated by BIPM every 5 days. These values may be used as \( x_k \) in Eqs. (3)-(5) to find out the Allan deviation for averaging time of 5 days or more. These have been plotted in Fig. 6. As the status of UTC (NPLI) is updated by BIPM every 5 days, the Allan deviation of the respective cesium clock for the averaging time less than 5 days cannot be directly found out. However, it is well established that the Allan deviation of cesium clock for lower averaging time (less than 5 days) nearly follows a \( \tau^{-1/2} \)-law as, in this range, white frequency noise is predominant. Thus, “\( \tau^{-1/2} \) fit” may be applied to calculate the values of Allan deviation for lower averaging time. After applying “\( \tau^{-1/2} \) fit” into the observed Allan deviation, the extrapolated line gives the Allan deviation for lower values of averaging time \( \tau \). The estimate of Allan deviation for 1 sec to one day of averaging time has been shown in the inset Table of Fig. 6. It may be noted that up to the averaging value of 1000 s, the Allan deviation remains better than \( 10^{-13} \) as expected in the case of a cesium atomic clock.

\[
\bar{y}_{k+1} - \bar{y}_k = \frac{1}{\tau} \left\{ x(t_k + 2\tau) - 2x(t_k + \tau) + x(t_k) \right\} \tag{5}
\]
5 Conclusions

The NPLI has been maintaining UTC(NPLI) through GPS network to keep it linked to UTC for more than ten years. The status of UTC(NPLI) has been studied analytically. Housing of cesium clock in a controlled environment and procurement of new receivers with prior calibration, control of antenna temperature and judicious phase and frequency adjustment improved substantially the quality of UTC(NPLI). The NPLI has been processing the procurement of two cesium clocks. So, NPLI soon will have more than five cesium clocks. To optimally use these clocks, NPLI has already started working out an algorithm to generate a smoother time scale with the ensemble of available several cesium atomic clocks.

References


