“T” Aspect of PNT: Time, Time Transfer and Synchronization

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ABSTRACT

Time is an important phenomenon taking place in everything that changes. However, we tend to generally overlook the importance of it unless we are faced with a problem. This paper discusses the concept of time, clocks that is used to keep time and also the methods that are used to transfer and synchronize time/clocks for the common use of time. This paper presents the common understanding of the concepts and methodologies available in the open literature without going into technical details.

1.0 INTRODUCTION

Time is a concept experienced by everyone, but when asked it is not easy to explain what it is. It is a parameter in everything from daily life to science, in every action from getting around to waiting, from working to sleeping and regardless of whether we keep track, it dynamically progresses. Hence, it is important to keep such a dynamically changing phenomena synchronized across cities, countries and even continents. Clocks are the tools that tell us the time and the oscillator is the basic unit that clocks are built on. A clock comprises a suitable mechanism added to an oscillator which accumulates or counts the number of time intervals to measure elapsed time. However, oscillators are not perfect and various types have been developed for different requirements and applications. Performance of an oscillator (or a clock) depends on its frequency stability which is greatly affected by the oscillator noise. In general, frequency stability is the degree to which an oscillator produces the same frequency throughout a specified period of time. It is implicit in this general definition that the stability of a given frequency decreases if it is affected by noise and anything except a perfect sine wave [[1], Ch. 5].

If, due to poor oscillator stability, a clock’s performance is far from perfect, then it starts to drift and assume that you are the timekeeper of a large office building with the responsibility to keep all the clocks within the building synchronized. Despite the localized building example, this is in fact a universal problem within the time keeping community. Let’s extend the nature of the problem and assume that the location of the clocks may be local (an office building), region-wide (the branches of a bank recording the times of transactions), nationwide (telecommunications networks) or global (the time standards of different countries) [2]. There are three main issues to be addressed in this practice are,

- Quality of the clock (oscillator)
- Reference/source of time?
- Clock synchronization methodology?

Over the years, the clocks have become more precise and more accurate and today clocks with almost 10 ps/day drift are available. Coordinated Universal Time (UTC) is the most preferred reference time, thus the second issue is addressed. Many different techniques and systems ranging from MODEMs to direct radio broadcasts and from Loran-C/GPS to two-way satellite time transfer with varying performance and complexity are available for time synchronization. However, with the ubiquitous availability, GPS has become the most reliable source of time and it is also a reliable time-transfer system.

This paper will try to address the concepts and methodologies related to all these issues based on available literature and no originality claim is made. There are many books and papers that have addressed the issue of time and time transfer and this paper conveys the concept and methodologies through those publications. The paper is organized as follows, next section will talk about the concept of time and give details pertaining to different time sources. Then Section 3 will cover oscillators and clock technologies where in Section 4 time transfer and time synchronization will be discussed. Some concluding remarks will be presented at the end.

2.0 TIME

Time probably is the most under-appreciated concept by many that use it. Everyone experiences it but explaining is a difficult job. [[1], Ch. 2] presents a comprehensive coverage of time and reference systems. Most of this section follows the text on time given in [[1], Ch. 2], however the text is redacted and rephrased in some places to remain within the general frame of this paper. The perception of time is usually associated with change and for that one needs a unit and a starting point, moreover some sort of uniformity is also required for the unit. Defining a unit for time is not that hard as many of the changes that we relate to time are periodic. If the changing phenomenon varies with uniform period, then the associated time scale is uniform. Clearly, a desirable property of a description and realization of time is that its scale should be uniform at least in the local frame. In the past, Earth's rotation provided the most suitable and evident phenomenon to represent the time scale, with the unit being a (solar) day, however, Earth's rotation is not uniform (it is varying at many different scales: daily, bi-weekly, monthly, etc. In addition to scale or units, an origin must be defined for a time system, that is, a zero-point, or an *epoch*, at which a value of time is specified. Finally, whatever system of time is defined, it should be accessible and, thereby, realizable, thus creating a time frame.

Definition for the unit time, i.e., *the second,* was the first thing to be agreed upon for progressing with common time. Prior to 1960, a second of time was defined as 1/86400 of a mean solar day. Today, a fundamental time scale is defined by the natural oscillation of the cesium atom and all time, systems can be referred or transformed to this scale. Specifically, the SI (Système International) *second* is defined as follows [3]:

> *The second is the duration of 9.192.631.770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.*

This definition has been refined to specify that the atom should be at rest and at mean sea level then corrections are applied to actual measurements to comply with these requirements. The value of the SI second was set to the previously (in 1956) adopted value of a second of *ephemeris time* (ET), defined as 1/31.556.925,9747 of a mean tropical (solar) year, being computed for the epoch, 1 January 1900, on the basis of Newcomb's theory of motion of the Earth around the Sun [4].

Although the SI second now defines the fundamental time unit, one still distinguishes between systems of time that have different origins and even different scales depending on the application. Dynamic time is the independent variable in the most complete theory of the dynamics of the solar system. It is uniform by definition. Mean solar time, or universal time (UT), is the time scale based on Earth's rotation with respect to the Sun and is used for general civilian time keeping. Finally, sidereal time is defined by Earth's rotation with respect to the celestial sphere.

Dynamic Time

Dynamic time generally refers to the time variable in the equations of motion describing the dynamical behavior of the massive bodies of our solar system. The dynamic time scale refers to a coordinate system and thus represent a coordinate time. Common choices include the barycentric reference system (origin at the center of mass of the solar system) or the geocentric reference system. On the other hand, dynamic time has also been defined as a proper time, the time associated with the frame of the observer that a uniformly running clock would keep and that describes observed motions in that frame.

Atomic Time

Atomic time refers to the time scale defined and realized by the oscillations in energy states of the cesium-133 atom. The SI second thus is the unit that defines the atomic time scale. Atomic time was not realized until 1955 with the development of standardized atomic clocks. From 1958 through 1968, the Bureau International de l'Heure (BIH) in Paris maintained the atomic time scale. The origin, or zero point, for atomic time has been chosen officially as 0h 0m 0s, January 1, 1958. International Atomic Time was officially introduced in January 1972. It was determined and subsequently defined that on 0h 0m 0s, January 1, 1977 (TAI), the ET epoch was 0h 0m 32:184s, January 1, 1977 (ET).

TAI is realized today by the Bureau International des Poids et Mesures (BIPM), which combines data from over 400 high-precision atomic clocks around the world in order to maintain the SI-second scale as accurately as possible. TAI is published and accessible as a correction to each time-center clock. In the United States, the official atomic time clocks are maintained by the US Naval Observatory (USNO) in Washington, DC, and by the National Institute of Standards and Technology (NIST) in Boulder, CO, USA. Within each such center several cesium beam clocks are running simultaneously and averaged. Other centers participating in the realization of TAI include observatories in Paris, Greenwich, Moscow, Tokyo, Ottawa, Wettzell, Beijing, and Sydney, among over 70 others. The comparison and amalgamation of the clocks of participating centers around the world are accomplished by LORAN-C, satellite transfers, and actual clock visits. Time offsets of individual laboratories and their uncertainties are reported in the monthly issues of the BIPM Circular T [5].

Sidereal and Universal Time

Sidereal time represents the rotation of the Earth with respect to the celestial sphere and reflects the actual rotation rate of the Earth, plus effects due to the small motion of the spin axis relative to space. Reader is referred to [[1], pp 28-29] for more detailed explanation.

Universal Time (UT) is the time scale used for general civilian time keeping and is based approximately on the diurnal motion of the Sun. However, the Sun, as viewed by a terrestrial observer does not move uniformly on the celestial sphere. To create a uniform time scale requires the notion of a fictitious, or mean Sun, and the corresponding time is known as mean solar time (MT). UT is defined as mean solar time on the Greenwich meridian. The basic unit of UT is the mean solar day, being the time interval between two consecutive transits of the mean Sun across the meridian. The mean solar day has 24 mean solar hours and 86400 mean solar seconds. In comparison to sidereal time, the following approximate relations hold

$$1 \text{ mean solar day} = 24\text{h } 03\text{m } 56{:}5554\text{s in sidereal time} \tag{1}$$

$$1 \text{ mean sidereal day} = 23\text{h } 56\text{m } 04{:}0905\text{s in solar time :} \tag{2}$$

A mean solar day is longer than a sidereal day because in order for the Sun to return to the observer's meridian, the Earth must rotate an additional amount due to its orbital advance. Universal time as a scale derived from Earth's rotation has thus been separated into:

- UT1: Universal Time determined with respect to the meridian attached to the spin axis;
- UT2: Universal Time *UT1 corrected for seasonal vari*ations

UT2 is the best approximation of UT to a uniform time, although it is still affected by small secular variations. However, as a matter of practical utilization it has now been replaced by an atomic time scale. All civilian clocks in the world are now set with respect to an atomic time standard since atomic time is much more uniform than solar time and more easily realized through time transfer by satellite signals. Yet, there is still a desire (particularly, in the astronomic community) that civil time should correspond to solar time; therefore, a new atomic time was defined that approximates UT. This atomic time is called Coordinated Universal Time (UTC) and implemented in accord with Recommendation TF.460 of the International Telecommunication Union (ITU) [6]:

> *UTC is the time scale maintained by the BIPM, with assistance from the IERS, which forms the basis of a coordinated dissemination of standard frequencies and time signals. It corresponds exactly in rate with TAI but differs from it by an integral number of seconds. The UTC scale is adjusted by the insertion or deletion of seconds (positive or negative leap seconds) to ensure approximate agreement with UT1.*

Initially, UTC was adjusted so that |UT2 – UTC| < 0.1s. As of 1972, the requirement for the correspondence between UTC and UT was relaxed to |UT1 – UTC| < 0.9s. The adjustments, called leap seconds, are introduced either January 1 or July 1 of any particular year.

The international standard for Universal Time Coordinated is maintained by the Bureau des Poids et Mesures (BIPM) in Sevres, France. This UTC (BIPM) is the result of a weighted average of about 200 clocks distributed worldwide. The U. S. Naval Observatory (USNO) maintains a Master Clock (MC) that represents the time standard UTC(USNO-MC) that is kept within 100 nanoseconds of UTC(BIPM).

GNSS System Times

Satellite navigation systems provide user coordinates derived from distance measurements that are based on the propagation time of the transmitted signals. Thus, all these systems rely on very accurate clocks and time standards. To meet the needs of internal time synchronization and dissemination, each GNSS maintains a specific system time. The time systems of the four global navigation satellite systems, Global Positioning System (GPS), GLONASS, Galileo, and BeiDou, are all based on the SI second and atomic time similar to TAI. However, they are realized by different clock ensembles and have different origins and offsets with respect to TAI [7].

GPS time (GPST) is the system time employed by the Global Positioning System. Since 1990, it is formed as a composite clock from atomic clocks within the GPS Control Segment as well as the atomic frequency standards onboard the GPS satellites. Each of these clocks contributes to the resulting time scale with a specific weight based on the observed variance of the respective clock [8]. Using common view time transfer, GPS time is steered to deviate by at most 1s from UTC(USNO). In practice, the GPS – UTC(USNO) offset is much smaller than the specified range and achieves representative values at the level of 20 ns. In order to provide GPS users with access to UTC, a forecast value of the offset between both time scales is transmitted as part of the navigation message. GPS time is not adjusted by leap seconds to slow down with UT and it is thus permanently trails TAI by a constant amount

$$t\,(\mathrm{GPS}) = \mathrm{TAI} - 19\mathrm{s} \tag{3}$$

Note that (3) describes only the nominal (integer second) offset between GPS time and TAI, but neglects additional fractional offsets (typically at the level of tens of nanoseconds) related to different realization of the two time scales. GLONASS Time (GLST) is the only GNSS time scale that actually follows the ITU recommendation to align a disseminated time scale with UTC. Its origin is chosen as January 1, 1996 in the UTC (SU) time system, that is, the Russian (formerly Soviet Union, SU) realization of UTC maintained by the Institute of Metrology for Time and Space in Moscow. Besides incorporating leap seconds, GLST is always 3h ahead of UTC because of the time zone difference between Greenwich and Moscow. Thus,

$$t\,(\mathrm{GLONASS}) = \mathrm{UTC} + 3\mathrm{h} \tag{4}$$

Again, this relation does not account for fractional second offsets resulting from the independent realization of both time scales. GLST is obtained from an ensemble of hydrogen-masers in the GLONASS ground segment and synchronized to UTC (SU) using two-way time transfer with a specified tolerance of 1s. Following a consolidated effort to improve the alignment of GLST with UTC, the difference of the two time scales has improved from several hundred ns to a few tens of ns as of the second half 2014.

Both the Galileo System Time (GST) and BeiDou time (BDT) exhibit a constant offset from TAI. The origin for Galileo time, for consistency, is defined to be identical to that of GPS Time, but the origin for the BeiDou time system has been chosen as January 1.0, 2006 UTC. Thus

$$t\,(\mathrm{Galileo}) = \mathrm{TAI} - 19\mathrm{s} \tag{5}$$

$$t\,(\mathrm{BeiDou}) = \mathrm{TAI} - 33\mathrm{s} \tag{6}$$

Both time scales are generated from atomic clocks in the respective control segments and steered to UTC via time transfer and clock comparison with other UTC laboratories. GST is specified to differ by less than 50 ns (2σ) from UTC while a maximum offset of 100 ns applies for BeiDou.

Similar to Galileo, continuous time scales with a fixed −19 s offset from TAI are also adopted by the Japanese Quasi-Zenith Satellite System (QZSS) and the Indian Regional Satellite Navigation System (IRNSS/NAVIC) [[1], Ch. 2].

3.0 CLOCKS

Similar to the previous section, discussions by another comprehensive text [[1], Ch. 5], this time on clocks, is followed as a reference. Clocks and oscillators are needed by reference timescale centers such as those that contribute to the international time scale, UTC. This specialized area requires the most highly stable and accurate time standards that are maintained under controlled environmental conditions. Their outputs are processed with special ensembling algorithms designed to produce an absolute reference for all systems. For example, the current suite of clocks used at the USNO consists of many commercial cesium beam frequency standards and hydrogen masers, and specially built rubidium fountain standards. These clocks are physically separated and operated in a tightly controlled environment. Size, weight and power are not issues pertinent for these clocks; primary emphasis is on performance, mostly for intervals of days and much longer.

Clocks used in mobile applications are typically crystal oscillator-based devices and small atomic clocks or oscillators used for positioning, communications or internal to other remote sensing systems. The requirements for mobile devices typically emphasize size, weight and power rather than time and frequency performance so their performance requirements are not particularly demanding or rigorous.

Devices used in handheld applications are the most demanding in terms of size, weight and power. They commonly use small quartz crystal oscillators. However, in recent years there have been several efforts to develop extremely small atomic standards. These small atom standards offer better accuracy and stability than crystal oscillators in an extremely small package.

3.1 Clock Technologies

Clocks are based on oscillators that generate a periodic signal of a given frequency. The stability of this frequency and the resulting time count depends on the underlying physical principals and design properties and may vary widely between different classes of oscillators. Key types of oscillators presented in this section include quartz crystal oscillators as well as cesium, rubidium, and hydrogen maser atomic clocks, which constitute the conventional atomic clock technology available today. An overview of the stability that can be expected from the different clock types is shown in Figure 1.

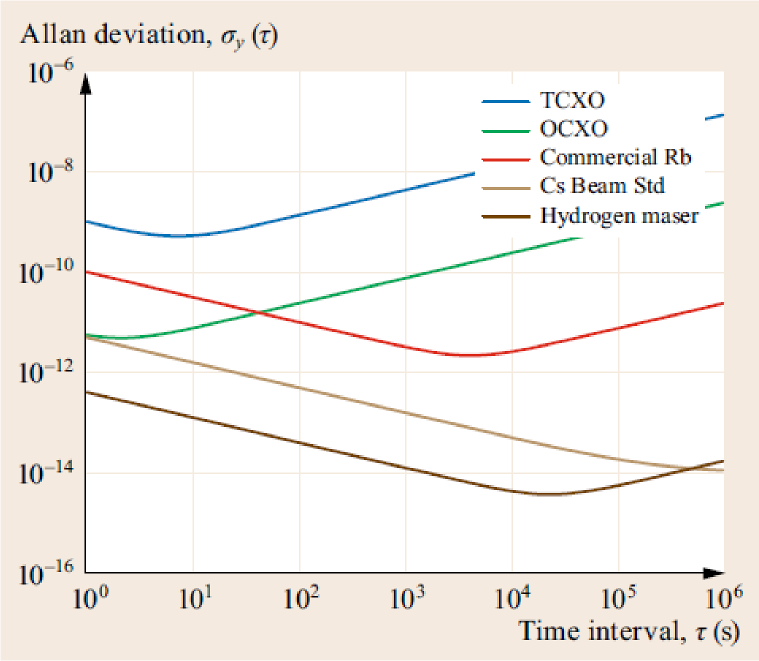

Figure 1: Performance of the classical microwave atomic frequency standards compared with temperature-compensated (TCXOs) and oven-controlled (OCXOs) crystal oscillators [[1], Ch. 5]. [1]

3.1.1 Quartz Crystal Oscillators

The most common and ubiquitous oscillators available are those made with quartz crystals. They are a basic form of harmonic oscillator beyond the simple electronic oscillators based on resistor-capacitor (RC) and inductor-capacitor (LC) circuits. Crystal oscillators are used in many forms of electronics and all GNSS receiving equipment operates with these devices to provide the necessary frequencies for radio frequency (RF) signal processing and to form an actual clock.

Quartz is a piezoelectric crystal material that can produce electrical signals by mechanical deformation of the material. Conversely, electrical signals can produce mechanical deformation. Crystal oscillators have a

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[1] The Allan variance, also known as two-sample variance, is a measure of frequency stability in clocks, oscillators and amplifiers. The Allan deviation, also known as sigma-tau, is the square root of the Allan variance. The M-sample variance is a measure of frequency stability using M samples, time T between measurements and observation time τ.

higher quality factor (i.e., ratio of resonance frequency and resonance bandwidth) than the simpler RC and LC circuitry. They have better temperature stability but do use some of the same circuit designs as the LC oscillators with a quartz resonator replacing the tuned circuit portion. Other types of physically mechanical oscillators are implemented with microelectro-mechanical system (MEMS) techniques that use devices made from silicon processed through microelectronic fabrication techniques. The advantage in the MEMS devices is that they are simpler to manufacture and more compatible with modern microelectronic circuitry.

Crystal resonators are available to cover frequencies from about 1 kHz to over 200 MHz. At the low frequency end, wristwatch and real-time clock applications operate at 32:768 kHz and powers of two times this frequency. The conventional BAW resonators range from 80 kHz to 200 MHz. The frequencies of SAW devices range from above 50 MHz to the low GHz range. The quartz crystal material is comprised of silicon dioxide and can occur naturally or can be grown synthetically. Oscillators are cut from these crystals in a variety of shapes. The shape, size and orientation within the crystalline structure determines the mode of vibration, its resonant frequency and properties of the oscillator. A voltage applied to the crystal will cause it to vibrate and produce a steady signal dependent upon the way the crystal is cut.

The types of crystal cuts and the method of mitigating the environmental effects on the crystal determines the category of the oscillator. Three configurations in most common use are the room-temperature crystal oscillator (RTXO), the temperature-compensated crystal oscillator (TCXO), and the oven-controlled crystal oscillator (OCXO). The RTXO typically uses a hermetically sealed crystal and individual components for the oscillator circuit. The TCXO encloses the crystal, temperature-compensating components and the oscillator circuit in a container. The OCXO adds heater elements and controls to the oscillator circuit and encloses all the temperature-sensitive components in a thermally insulated container.

3.1.2 Conventional Atomic Standards

Conventional atomic frequency standard designs are passive devices that are functionally illustrated in Figure 2. The basic principle is to coherently excite transitions between two energy levels in the atom selected and detect that the transition has occurred. The frequency of the atomic transition is given by ν_0 in Figure 2, where ΔE is the difference in energy levels of the atom and h is the Plank's constant.

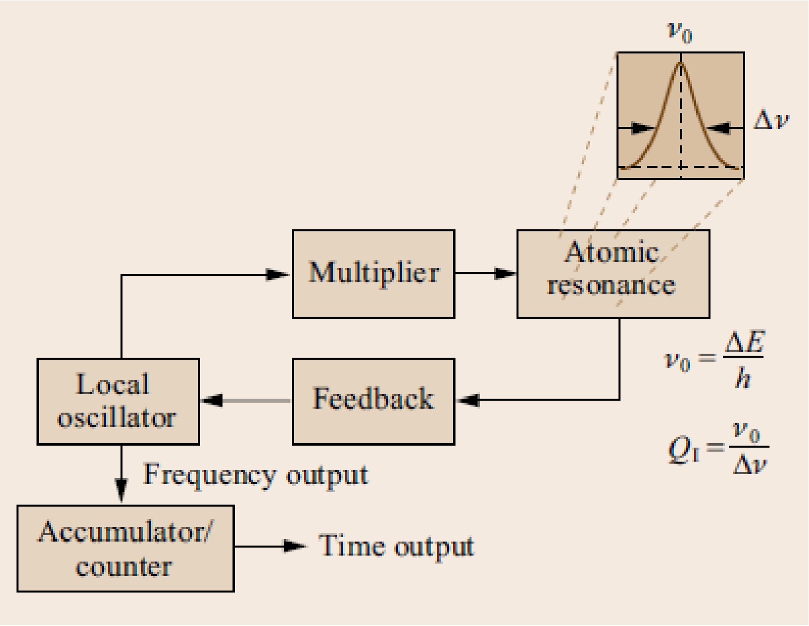

Figure 2: Generic atomic standard block diagram [[1], Ch. 5].

Rubidium Frequency Standards

Rubidium gas cell standards are the most commonly produced commercial atomic clocks. They are small, consuming relatively low power and are inexpensive in general. They are widely used in the telecommunications industry as frequency references for cellular telephone systems. They are also often found as internal frequency standards in laboratory instrumentation such as frequency counters, signal generators, and signal analyzers. Rubidium clocks were the first atomic clocks used in orbiting spacecraft and have become the primary clock technology used in the GPS satellites.

Cesium Beam Frequency Standards

Cesium beam frequency standards are commercially available clocks and have been widely used for time-keeping and precise frequency generation, particularly in the telecommunications industry where they are used for clocking high-rate data streams. They are inherently much more accurate in frequency than rubidium clocks with accuracies as good as $5x10^{-13}$. They also have an inherently very low frequency drift and reduced sensitivity to environmental effects, although the associated electronics in the units may be somewhat affected by environmental conditions, primarily temperature. Specially built cesium beam clocks with large long tubes designed for high accuracy have also been used as primary laboratory standards. Considering the small frequency shifts and the accuracy that can be maintained by a cesium beam frequency standard it is the most accurate device that is easily and commercially available.

Hydrogen Maser Frequency Standards

Hydrogen masers are the most stable frequency standards commercially available for use in laboratory and ground station environments. They have been developed for scientific, timekeeping and GNSS applications. There are two basic designs of hydrogen masers in use, the active maser where the maser cavity actually oscillates and produces a signal actively and the passive maser whose cavity is passively interrogated in a similar manner to the rubidium and cesium devices just discussed. A third design of hydrogen maser known as the Q-enhanced maser that can operate in either mode.

3.1.3 Timescale Atomic Standards

Commercial cesium clocks are still the most prevalent standard for timekeeping in other than national time-keeping centers. Second is the active hydrogen maser that is in limited commercial availability. Both of these commercial devices are expensive with the hydrogen masers being about an order of magnitude more expensive than the cesium. The capability of GNSS timing receivers to disseminate time is increasing and many systems are using them to replace precise frequency and time standards as reference standards in timing applications.

Within national timing centers, such as the National Institute of Standards and Technology (NIST) in the United States, the laser cooled cesium fountain has largely replaced the large thermal beam standards that were used as primary standards for determination of the SI second and contribution to the international atomic time scale. Unlike these other standards, cesium fountain clocks are not commercially available so that each center has built their own version. A number of different cesium fountain clocks are now in use throughout the world and in 2012 some 21 timing centers used cesium fountain clocks as their primary frequency standard. These primary standards serve as the metrologic reference and their performance is therefore determined by comparison and coordination with the Bureau International des Poids et Mesures (BIPM).

4.0 TIME TRANSFER AND SYNCHRONIZATION

By definition, transfer is sharing a reference information across multiple users and synchronization is the coordination of multiple separate units to operate in unison. Time transfer is the transmission of time from a reference time source to other clocks in a network, Figure 3, so that the client/slave clocks can compute the offset of their local clocks from the reference clocks and adjust their clocks accordingly to achieve and maintain network time synchronization. Time synchronization, on the other hand, is the process of setting two or more clock in a network to "exactly" the same time where the ultimate goal is to minimize the offset between a local time and a reference time to achieve the finest accuracy. Thus, both terms, i.e., transfer and synchronization, are often used interchangeably when the information being shared/synchronized is time as it is transferred to synchronize units in terms of their internal clocks. Time can be transferred via direct cable connection or wirelessly by means of navigation and communication systems. As discussed in the previous sections, due to ubiquitous availability and highly precise time information GPS has become the main tool for time transfer. However, regardless of the method employed, the goal is to minimize the clock error (ε) as much as possible.

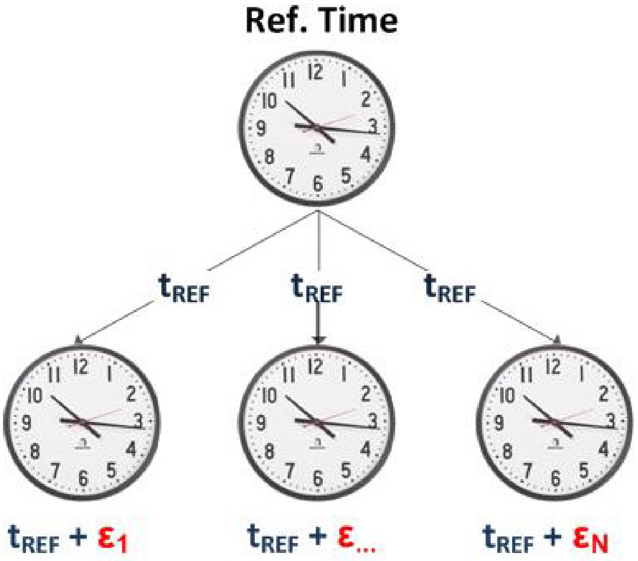

Figure 3: Concept of time transfer [9].

4.1 GPS Time Transfer

GPS Time Transfer is a method based on the principle of transferring time via GPS signals. GPS time is a continuous measurement of time from an epoch started at January 6, 1980 at midnight (0 hours 0 minutes 0 seconds) Universal Time Coordinated (UTC). GPS-Time is often stated in a number of weeks and seconds from the GPS-Time epoch. GPS-Time does not introduce leap seconds and so is ahead of UTC by an integer number of seconds (10 seconds as of 1 July 1994, 11 seconds at 1 January 1996). GPS-Time is steered by the Master Control site to be within one microsecond (less leap seconds) of UTC. The GPS Navigation Message contains parameters that allow the GPS user to compute an estimate of the current GPS-UTC sub-microsecond difference as well as the number of leap seconds introduced into UTC since the GPS epoch. GPS-Time is derived from the GPS Composite Clock (CC), consisting of the atomic clocks at each Monitor Station and all of GPS Satellite Vehicles (SV) frequency standards. Each GPS SV signal is transmitted under control of the atomic clocks in that particular SV. SV-Time is monitored and the difference between GPS-Time and the SV-Time is uploaded into each satellite for transmission to the user receiver as the SV Clock

Correction data [10]. GPS-Time is controlled so that it maintains a close relationship to UTC, so that the time available from a GPS timing receiver is traceable to global time standards. When required by the application, GPS-Time can be converted to UTC employing the GPS-UTC parameters sent in the Navigation Message.

GPS Time Transfer is accomplished through communication between a GPS receiver and a time receiver. The GPS receiver receives signals from GPS satellites and outputs time information. The time receiver receives the time information from the GPS receiver and provides the accurately synchronized time. Most GPS time receivers are one channel C/A-code devices because such devices are simple and of reasonable cost. Several different methods are used to transfer time from a reference standard through GPS to the user receiver. Real-time systems usually depend on some form of direct-reference time transfer. A GPS receiver can track the GPS satellites and recover precise time from one or a set of satellites using the direct-reference technique. If the position of the receiver is accurately known, one SV signal will suffice for setting GPS-Time in a receiver. For a receiver without a previously known position, position from a GPS navigation solution can be used but the resulting time estimate will reflect any errors in the GPS-derived position solution. For a C/A-code receiver operating under SA the position can dither by 100 meters (95%) resulting in GPS time accuracies of around 330 nanoseconds (95%) [10].

4.2 Time Transfer Methods

Any time-transfer algorithm must be designed with its purpose in mind. For example, if a time-transfer method is being used to discipline a local oscillator to a remote standard, the free-running stability of the local oscillator must be considered when designing the time-transfer procedure so that the resulting algorithm will make the best possible use of the calibration data. There are several methods used in transfer time which will be described briefly in this section. Readers are referred to many publications, such as [11], available in open literature for detailed discussion of the methods.

4.2.1 One-Way Method

In a one-way time transfer system, time is transmitted through some communication channel to one or more receivers. It is most applicable to the dissemination of time and frequency and is characterized by dissemination of standard time and standard frequency using standard radio waves. After reception, the receivers will decode the message, and either report the time, or adjust a local clock which can provide hold-over time reports in between the reception of messages. The advantage of one-way systems is that they can be technically simple and serve many receivers, as the transmitter is unaware of the receivers. The principal drawback of the one-way time transfer system is that propagation delays of the communication channel remain uncompensated however, there are a number of systems where the delay from the transmitter to the receiver can be determined (either in whole or in part) by the use of ancillary data. For instance, the signals transmitted by the satellites of the global positioning system (GPS) are in this category where many contributions to the path delay can be estimated by the use of parameters transmitted from the satellite in the navigation message.

4.2.2 Common View Mode

The common-view method is a simple but elegant way to compare two clocks or oscillators located in different places. The time difference between two clocks may be determined by simultaneously comparing each clock to a common reference signal that may be received at both sites. Unlike one-way measurements that compare a clock or oscillator to GPS, a common-view measurement compares two clocks or oscillators to each other. As long as both end stations receive the same satellite signal at the same time, the accuracy of the signal source is not important. The nature of the received signal is not important, although widely available timing and navigation systems such as GPS or LORAN [13] are convenient, TV broadcast signals could also be used for this purpose [14].

4.2.3 Melting-Pot Method

The Melting-Pot method, also known as All in view mode [15], can be used to synchronize clocks over widely separated distances. Unlike the Common view mode, the Melting-Pot mode does not require simultaneity in the observations by both stations, it only requires that each station observe as many satellites as possible during the day that its receiver can track. The individual GPS time versus the local standard's time comparisons are put together over a period of time. The linear fit solution of these points is considered the offset of the GPS time from the local standard's time. Subtracting one local standard's offset time from the other yields the time difference between the two locations. This method is more robust than the Common View method, because it observes significantly more satellites during the day. Therefore, it is more suitable for unattended synchronization systems because the offset values are more stable and the system is more robust to occasional data gaps since the offset is computed from several measurements.

4.2.4 Two Way Method

The two way method involves a system of performing time transfer through simultaneous transmission of a time/frequency signal between two remote sites (or among multiple remote sites). In a two-way time transfer system, the two peers will both transmit, and will also receive each other's messages, thus performing two one-way time transfers to determine the difference between the remote clock and the local clock. The sum of these time differences is the round-trip delay between the two nodes. It is often assumed that the path delay is symmetric between the directions between the peers. Under this assumption, half the round-trip delay is the propagation delay to be compensated. A drawback is that the two-way propagation delay must be measured and used to calculate a delay correction. That function can be implemented in the reference source, in which case the source capacity limits the number of clients that can be served, or by software in each client. The two-way satellite time and frequency transfer (TWSTFT) system being used in comparison among some time laboratories uses a satellite for a common link between the laboratories. The Network Time Protocol (NTP) uses packet-based messages over an IP network [16].

4.2.5 Other Methods [12]

Other highly precise time transfer methods are available in addition to the foregoing, including the LASSO (Laser Synchronization from Stationary Orbit) system (in which a laser pulse and a radio wave are shared) and the ground-based optical fiber system. The former method aims at time transfer with sub-nanosecond precision by measuring the intervals between arrival times of laser pulses synchronized with atomic time issued from multiple points on a single satellite. However, since the required ground facilities are very costly and the lasers are susceptible to weather variations, this system has not been put to practical use.

As telecommunication speeds increase, time transfer and time synchronization using ground-based optical fibers is becoming subject to greater development and broader implementation. Further, a new method of providing reference signals over relatively short distances (from a few to several dozens of km), has been advanced; under the proposed plan a stabilized reference signal is transmitted in the optical range and applied as a local signal in astronomic observations.

4.3 Time Synchronization

Time synchronization is critical for the operation of distributed systems in networked environments. The requirement for precision time synchronization has become more and more pertinent as communication technologies have moved from inherently synchronous networks, such as time-division multiplexing networks and traditional bus-driven and fieldbus architectures, toward packet-based networks. Time synchronization is one of the key issues for successful operation of communication networks. It enables network nodes to maintain an accurate and precise time. As a result, accurate time-stamping and meaningful ordering of transmitting messages become possible. Packet-based networks have eventually led to the use of

Ethernet as the basis for communication between distributed devices in automation networks. One limitation of Ethernet has been its inability to support real-time communication. To introduce a sense of timeliness in communication and control over Ethernet, time synchronization support by means of dedicated network messages and protocols has been a prerequisite. At first, existing time synchronization protocols for computer networks such as the network time protocol (NTP) have been used for this purpose, but their limitation in accuracy and precision has led to the design of customized protocols better suiting the needs for distributed real-time systems [17].

One of the expectations from time synchronization is to eliminate the latency in critical data transmission. This is achieved through scheduling a traffic lane for transmitting packets. The traffic lane is a commonplace in a wireless network, regardless of a synchronous or asynchronous transmissions. Along with channel scheduling, various network applications also rely on time synchronization. In some network applications, network nodes only need relative time synchronization for ordering various network events. In this case, the clocks of the nodes are synchronized with each other irrespective of the high accuracy of the synchronization. In many other network applications, all network nodes need their clocks to be synchronized with a highly accurate clock [18].

Comprehensive analysis and detailed discussion of time synchronization techniques are beyond the scope of this paper, however, open literature offers plethora of resources for those interested in further information.

5.0 CONCLUSIONS

This paper covers the "T" aspect of PNT and discusses the concepts and methodologies related to time transfer and time synchronization. GPS (or more commonly GNSS) is the most used tool for efficient time transfer to users, however, it requires to fully understand the GPS operation in order to grasp the related time transfer techniques. Details of how GPS operates are omitted here and a brief discussion of the methodologies are presented.

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