Implementing a Terrestrial Timing Solution: Best Practices

Center for Alternate Synchronization and Timing (CAST)

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Prepared by:
OAK RIDGE NATIONAL LABORATORY
and
U.S. DEPARTMENT OF ENERGY, OFFICE OF ELECTRICITY

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ABSTRACT

This document is an overview and guide on the concept of precision time and how an alternative terrestrial timing solution to the Global Positioning System (GPS) can be implemented. What follows is a set of recommendations and best practices, derived from research at Oak Ridge National Laboratory (ORNL), across industry, and within the U.S. government, to implement a system of precision timing synchronization to support resilient operations for the U.S. grid. Precision time is a fundamental necessity for operating the grid today, and it becomes even more important as the grid modernizes with clean energy sources, microgrids, and precision sensors placed throughout the grid system to ensure failure-resistant operations. The Global Navigation Satellite System (GNSS), which includes (GPS), is currently the primary provider of precision timing today. A terrestrial-based system for time delivery and synchronization to augment GPS is outlined below and it would provide secure time, synchronized with Coordinated Universal Time (UTC), in the event of outages or other interruptions associated with time delivery.

1. The Timing System Operation and Its Components

1.1 INTRODUCTION TO PRECISE TIME

The explicit purpose of this alternative terrestrial timing solution is to deliver a wide-area synchronization (WAS) capability with precise traceability to Coordinated Universal Time (UTC) to U.S. Power Marketing Administrations (PMAs), Defense Critical Electrical Infrastructure (DCEI), and industry for the support of critical infrastructure and grid reliability, resilience, and security. Additionally, the creation of a "closed loop" network environment within the timing signal communications chain will reduce cyber vulnerabilities and the opportunity for "man-in-the-middle" attacks. The complementary timing capability described in this document can support WAS across multiple geographic regions to ensure coordinated and continuous operations.

Precise time needs to be distributed to many end points in an operating utility. Many other operational technology (OT) systems supporting bulk power, distribution, and transmission rely on precise and synchronized time, from supervisory control and data acquisition (SCADA) systems to protective relays to the array of traditional and new sensors supporting the transition to a smart grid [1]. The inherent time synchronization and correlation ensure each of the time-sensitive systems and devices perform their function at precisely the same instant. In addition to performance, there are regulatory requirements for sequence-of-event recording (SER) and fault-recording (FR) equipment to be synchronized with UTC [2]. While the Global Navigation Satellite System (GNSS) is currently the method of choice, and, when functioning correctly, a very capable source of time, an alternative source of time is necessary. It is well known that GNSS devices are inherently vulnerable to jamming and spoofing activities, which present a potential disruption to reliable and safe grid operations [3]. Building and implementing an alternative timing and synchronization capability will improve the resiliency of the PMAs, DCEI facilities, and the grid as a whole. The time delivery method of choice is the Institute of Electrical and Electronic Engineers (IEEE) standard 1588: Precision Time Protocol [4].

This document presents detailed technical information—the more detail on the process of time transfer over a terrestrial network to educate and inform the grid operator, the better. This detailed information will become important as the operators begin the process of implementing private total time transfer in their respective networks, both internal and external, including connectivity to the substation.

1.1.1 Precise Time

What is time? This concept does not exist in the physical world. The passage of time cannot easily be perceived, and we have created useful and precise measurement tools and methods to manage "time." The basic unit of time, the universal SI Second, was created on January 1, 1970, and is defined as 1/86,400th of a day, the number of seconds in a 24-hour period [5]. The signal that represents time is derived from the consistent number of transitions (9,192,631,770) of the single cesium atom when being bombarded at a specific microwave frequency. This atom movement is captured electronically in a digital counter, and once the count totals 9,192,631,770, the digital counter produces a single pulse: the 1 pulse per second (pps) signal. The machine that performs this function is the atomic clock (more specifically, for our purposes, the cesium clock). The "time" information in the context of hours, minutes, and seconds is, in fact, metadata, formatted digital data for use by people and machines, derived from this 1 pps signal.

The U.S. organizations responsible for the precise measurement of this time signal is the National Institute of Standards and Technology (NIST) in Boulder, Colorado, and the U.S. Naval Observatory (USNO) in Washington, D.C. These organizations, in collaboration with other Bureau International des Poids et Mesures (BIPM) timing centers around the world, develop UTC, a global, synchronized timing standard. As an example, the time derived from a Global Positioning System (GPS) receiver is correlated to UTC to determine its accuracy. This method ensures all GPS receiver outputs are synchronized to the same reference "time base," or Epoch, to create a universal time code across common industrial and commercial uses [6].

1.1.2 Introduction to Network Time

Network Time Protocol (NTP) is an Internet-based protocol that is used to synchronize devices connected to an Ethernet Network within a few milliseconds of UTC. NTP was developed in the 1980s and is the common method used by most systems to set their clocks [7]. The NTP Servers are usually geographically diverse, with a majority accessed thru public/private internet connections, while in many cases NTP Servers are using GNSS as the source to UTC. Systems can access Internet-based NTP Servers by using the NTP Pool Project addresses or any public NTP Server that is listening to requests. NTP can use authentication, which will allow the client to verify the authenticity of the NTP Server. This mode provides a means to prevent synchronization with rogue NTP Servers if provisioned correctly. As mentioned above, NTP is only accurate within milliseconds; however, the timing needs of the grid and event synchronization require 1 microsecond or better if the network is provisioned correctly for deterministic latency and the network is end-to-end controlled.

1.1.3 Precision Time Protocol

A more accurate method of time synchronization is Precision Time Protocol (PTP) as governed by the IEEE 1588 standard [4]. This method of time transfer has been in use since 2002 and, as of this writing, is on its third upgraded version. This protocol is used in telecom, finance, power grid, industrial, and other industries to transfer precise time from its generation point to its usage or consumption point. With a properly designed transport technology, time precision in the low nanoseconds is possible because of the ability to compensate for switching delays of network devices.

The basic operation of PTP is a communication between the timing master clock, or node, and a time slave. The timing master creates the Internet Protocol (IP) packets (8275.2) or Ethernet frames (8275.1) that carry the time value implemented as a timestamp. The time slave receives these packets and, from the time-value timestamp, produces a digital signal of 1 pps and a clock signal of a frequency used by the receiving application. The 1 pps signal is referenced to the time base, or Epoch (in a substation's usage, this is UTC), and measured in nanoseconds of precision relative to the original signal used by the timing master to create the PTP timestamp. The next few paragraphs will explain how the PTP protocol operates and will highlight critical best practices for its successful implementation.

The PTP protocol is composed of a simple communications syntax made up of synch messages (T-1), delay request messages (T-2), and delay response messages (T-3). Figure 1 below depicts this message exchange process.

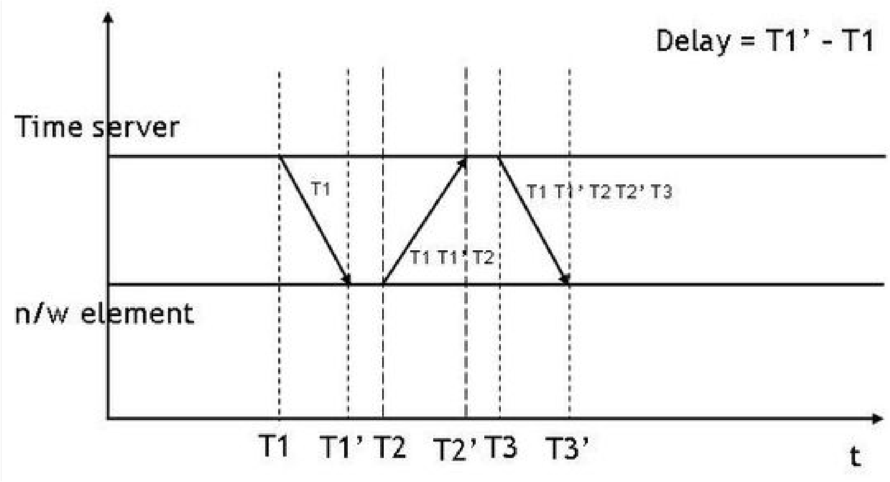


Figure 1. PTP message protocol.

The base premise of PTP is the paths from the time server to the target network element are identical in distance, and the time of flight of the messages are captured and measured as noted in Figure 1. This is called path symmetry, which guarantees the time slave can compute and replicate the value of time that the time master implemented in the timestamp it sends. The following describes this process.

To accurately synchronize to their timing master, clocks must individually determine the network transit time of the Sync T1 messages. The transit time is determined indirectly by measuring round-trip time from each clock to its master. The clocks initiate an exchange with their master designed to measure the transit time. The exchange begins with a clock sending a delay request (Delay_ReqT2) message at T2 to the master. The master receives and timestamps the Delay_ReqT2 at time T2' and responds with a delay response (Delay_RespT3) message. The master includes the timestamp T2' in the Delay_RespT3 message. Through these exchanges, a clock learns T1, T2, T3, T1', T2', and T3'.

If T1 is the transit time for the Sync message and T2 is the constant offset between master and follower clocks, then the time slave can use the timestamp placed in the T3 delay response message to calculate the offset in path flight time between the T1 and T2 paths. It then integrates this offset into its time calculation, and the clock now knows the offset during this transaction and can correct itself by this amount to bring it into agreement with the time master. This process is constantly repeated and requires almost no actual time to occur.

From the discussion of PTP operation, it is clear the closer the downlink and uplink path flight times, the more accurate the resulting time transfer will be. In the case of grid operations and time transfer, this calculation needs to resolve time alignment between the time master and time slave to as close to 100 nanoseconds as possible. The time error budget for the entire grid is 1 microsecond, the maximum time offset from UTC allowed for synchro phaser operation.

The best practice for implementing a PTP time transfer network between any pair of locations is to ensure the physical frame flight times in each direction are nearly identical and—most importantly—highly deterministic. Determinism in this context means very high repeatability over time. This practice will be discussed in much more detail later in this document.

1.1.4 Time Synchronization

NTP and PTP are the mechanisms by which multiple systems can achieve time synchronization. Synchronized time supports everything from basic alignment of IT and OT system time operations to switches and relays operating at the precise and appropriate times, to governing transactions across data-centric functions, to audit support, to ensuring information assembly and recovery in logs. If clocks across the network are out of synch or there is more than a microsecond of disagreement across different time-dependent systems, the consequences may range from minimal impacts to misoperation of protective relaying. Synchronization happens across time hierarchical stratums, wherein Stratum 0 is the authoritative source of time and Stratums 1, 2, and so forth are distribution tiers that preserve and serve time to downstream subscribers using NTP or PTP.

1.2 BASIC EQUIPMENT NEEDED TO IMPLEMENT PRESCISION TIME PROTOCOL

1.2.1 The Source of Time

At the root, or starting point, of the PTP time transfer system is a device that produces the time base, or Epoch, for the system to use. For the Center for Alternative Synchronization and Timing (CAST), this piece of equipment is a cesium clock (or atomic clock). This device will create the fundamental clock signals the timing master will eventually use to produce timestamps. The cesium clock will be synchronized to an external universal time reference with traceability to UTC. Traceability means the time output from this reference can be tracked back to the time source produced by NIST in Boulder, CO. The cesium clock will be synchronized from a signal emanating from the reference as either a frequency or a 1 pps signal. The cesium clock will align its internal electronics to mimic exactly the time source from the reference. Because the chosen cesium clock has an extraordinary stabilization capability, after synchronization it should be capable of outputting the time replica with 100 nanoseconds of accuracy for over 100 days. This activity is called holdover.

This precision and stability over a long time frame provides the grid operator a source of time that can augment or replace GPS, which is complementary to a GNSS time source. The cesium clock device is an off-the-shelf and readily available commercial product and is not susceptible to jamming or spoofing activity. The recommended components and specifications will be identified later in this document. CAST is continuing to define, refine, test, and evaluate best practices for the use and implementation of cesium clocks to ensure their continued operation at the level required for grid applications. These best practices will be discussed later in this document.

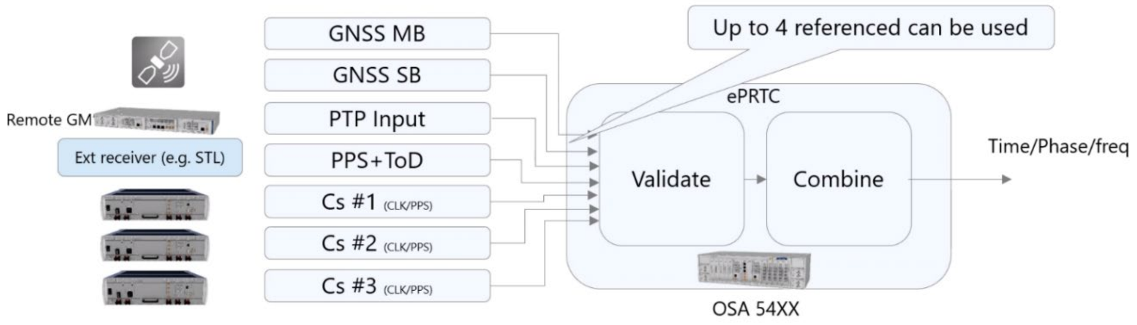


Figure 2. Example grand master PTP time scale.

1.2.2 The Master Source of PTP Time Transfer Packets

This device and the associated cesium clock are implemented in the central site determined by the grid operator. The output of the cesium clocks is injected into a device called a Grand Master (Packet) Clock (GMC). This device takes the output from the cesium clocks and disciplines its internal clock to synchronize with the cesium clock. It then creates the appropriate timing packet in the manner described earlier, generates a timestamp that is equal to the frequency of its internal clock, integrates the data message and timestamp into the appropriate packet type, and launches the packet onto the network.

This device performs many other PTP protocol functions, such as building a database of time slaves, formatting the output model to comply with whichever operating profile has been selected, performing a role in the Best Master Clock Algorithm used in a network to select the best master clock (if multiple cesium clocks are used to create timestamps), and reporting performance information to the network management system. In addition, for a PTP network to operate properly, a few general network requirements need to be in place. First and foremost, the PTP synchronization process requires a bidirectional network capable of transmitting IP packets from the master clock to the slave clock and back. This enables all devices to receive sync, follow-up, and delay response messages and to transmit delay requests. We recommend a device that has the capability to accept inputs from three cesium clocks, algorithmically compute the standard deviation, and select the best total output time quality. This feature, combined with the extremely long holdover times of the recommended cesium clocks, provide the grid operators the capability to operate in an independent mode at well under the error budget limit for up to 6 months. The recommended components and specifications will be provided later in this document.

1.2.3 The Remote Boundary Clock Master

This device is implemented in remote sites determined by the grid operator as intermediate locations with further sites downstream. Sometimes referred to as a Remote Synchronization Unit (RSU), this device receives the PTP packets created by the GMC and, using the PTP messages and time computation algorithm described earlier, synchronizes its internal clock to the GMC timestamp computed value. This function is a time slave function. This computed value of time is transferred to the internal master function in the boundary clock, and this remote GMC function now allows it to serve time slaves further along in the time distribution network chain. This device will generally have a Rubidium or Quartz oscillator as its local clock frequency source. This is because the PTP protocol will continuously service time to the boundary clock from its upstream GMC, so the holdover expectation is relaxed thus, a Rubidium or Quartz local clock, rather than a cesium clock, is acceptable. Time distribution requires messages in both directions to allow the system to compensate for the propagation message delay through the network. Some frequency recovery algorithms in slave clocks make use of both directions to deliver more accurate and stable timing results. Therefore, the PTP Profile permits both one-way and two-way operation.

PTP defines two types of clock behaviors: the one-step clock and the two-step clock. In a one-step clock, the precise timestamp is transported directly in the Sync message. In a two-step clock, a follow-up message is used to carry the precise timestamp of the corresponding Sync message. Follow-up messages were invented to facilitate timestamping at the hardware level, improving the accuracy of the timestamp. Their use means that the master does not have to modify the timestamp in the Sync message on the fly as the packet is being transmitted but can send it later in a separate, non-time-critical packet.

If the master can implement a one-step clock, this significantly reduces the number of PTP messages it has to send. However, some security mechanisms or architectural features in the master might require the two-step clock approach. Therefore, both one-step and two-step clocks are allowed in the profile. A PTP master clock compliant with the profile may use either a one-step or two-step clock.

1.3 BEST PRACTICES FOR THE TIMING SYSTEM EQUIPMENT

It is critical that environmental stability be maintained in and around the timing system equipment noted earlier. Equally critical is the knowledge and experience of the support staff responsible for this equipment. The environment, temperature, and vibration are critical elements to correct operation of the timing equipment. Oscillators of all types are subject to what is called an Allen Variance. This is the change in frequency that occurs because of the temperature surrounding the device. Cesium clocks are sensitive in this regard, as they provide the root frequency that drives this time-keeping process within the precision desired. The maximum target temperature change for these devices is less than 1 degree Celsius in a 24-hour period. The power source for these devices must be stable and have the AC noise filtered. This does not apply if DC power is exclusively used. Random noise on the input AC can have negative impacts on internal power supplies for these systems. It is best if they are connected to a protection-filtered power source with an uninterruptible power supply (UPS) capability. They are also well served if powered via a DC battery system.

Staff implementing such a system should have a good understanding of IEEE 1588 Precision Time Protocol [4] operations and network requirements. Knowing how to install and test the cesium clocks and PTP serving nodes is important. Using a GNSS PPS source to compare clock accuracy or knowing how to operate a Time Interval Counter to check frequency deviation is important. The CAST team can provide the necessary mentoring and technical assistance to build these competencies in a local timing solution operations team.

2. Interconnecting Timing System Locations

2.1 TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is the appropriate method to provide NIST-based precise time to the GMC node locations [8]. TWSTFT will implement satellite communications (SatCom) between NIST Boulder and the GMC root node location(s). In this approach, each location will have a minimum of a 2.4-meter satellite dish, a rack of satellite modems, and an agreement with SES Government Systems for a signal transponder to support time transfer (other satellite communications (SatCom)vendors may also be suitable for TWSTFT, subject to testing and verification).

This approach is well understood and is currently used to link NIST Boulder, USNO Washington, D.C., and BIPM France to coordinate UTC across these locations. The signal from the satellite transponder is a very precise 10 MHZ frequency received by the satellite modems for comparison to locally generated 10 MHz frequency signals. The offset or correction signal is passed over the satellite link for comparison to the NIST frequency source, this corrected signal is returned, and the local satellite modem updates its local clock with the correction value. The output from the satellite modems is fed into the cesium clock ensemble as the clocks lock to this signal. A 1 PPS signal can be integrated as well via GPS receiver into the GMC or cesium clock to establish UTC traceable time.

While SatCom has been used for many years to transfer precise frequency, operating this system requires significant knowledge and expertise. It is an expensive system to implement when considering the construction issues as well as the infrastructure components necessary for correct operation, but it is a needed component to establish an alternative timing system to GPS. The best practices for this type of technology implementation demands in-depth knowledge of the SatCom technology as well as the terrestrial equipment necessary for correct operation.

2.2 COMMON CARRIER LEASED OPTICAL TRANSPORT NETWORKSERVICE.

The recommended transport of PTP is the Optical Transport Network (OTN). This technology will facilitate communication of a WAS network that could connect master clocks to slave clocks (to include the substations). A common carrier-led OTN service is like what is known as “leased line.” Instead of a leased line, the client leases an optical path on a dense wavelength division multiplexing (DWDM) network with a digital wrapper technology known as OTN. OTN uses the *International Telecommunications Union’s* ITU-T standard G.709 [9]. The PTP protocol IEEE 1588 – 2019 annex b [4] specifies the method for mapping PTP onto the OTN path. This is a service available from any of the national telecom operators; however, the serving locations are typically found in major metropolitan areas. For example, the Oak Ridge National Laboratory (ORNL); in Oak Ridge, TN, was unable to secure an OTN link to the Western Area Power Administration (WAPA) in Loveland, CO, or Sandia National Laboratory (SNL) in Albuquerque, NM, for experiments. In circumstances in which OTN is not available, the ORNL team at CAST will work with a partner to conduct an evaluation of alternatives given the networks available and in place, anticipated network congestion, costs of establishing new networks, and required performance thresholds for the timing system.

The most important caveat to the OTN service is ensuring all node interconnect points along the path use Optical-Optical-Optical (OOO) switching instead of the more common (and easier) Optical Electronic Optical (OEO) switching method [10]. As noted earlier in the discussion about PTP operating characteristics, the need for path symmetry is crucial. In the case of the switching style, in an OEO system, the PTP packets are down converted from a serial optical signal frequency to an electronic byte-based method of moving the packets from the input port to the output port and then upconverted into a serial optical frequency again. This activity produces a subtle but definite change in the path flight time, creating an asymmetry and therefore negatively impacting the precision of time generated by the end clock. The 1588 annex b follows.

> [excerpted from IEEE 1588]
>
> **Transport of PTP over the Optical Transport Network (OTN)**
>
> **H1.1 General**
> This annex specifies those portions of the PTP standard that are specific to implementations that transport messages over the Optical Transport Network (OTN), as defined in the ITU-T Recommendations G.709 Amd.1, G.709.1 Amd.2, and G.7041 Amd.1. Several types of interfaces, Optical Transport Unit-k (OTUk), Optical Transport Unit-25 (OTU25), Optical Transport Unit-50 (OTU50), Optical Supervisory Channel (OSC) and Flexible Optical Transport Network (FlexO), are considered to transport PTP by the OTN. The support of Transparent Clocks is out of scope for the transport of PTP over the OTN.
>
> **H1.2 PTP message channel**
> ITU-T Recommendation G.709 Amd.1 defines the OTN synchronization messaging channel (OSMC) to transport PTP messages. Clause 15.7.2.4 of ITU-T G.709 Amd.1 (12/2020) specifies one byte in the OTUk, OTU25 and OTU50 overhead as the OSMC for the OTUk, OTU25 and OTU50 interfaces, respectively (see Figure 15-12 of ITU-T G.709 Amd.1 (12/2020)). Clause 14.1 of ITU-T G.709 Amd.1 (12/2020) defines support of the OSMC for the OSC interface, and Figure 15-1 of ITU-T G.709 Amd.1 (12/2020) shows that the OSMC is carried by the OSC payload. ITU-T Recommendation G.709.1 Amd.2 defines the OSMC to transport PTP messages for the FlexO interface. Clause 9.2.10 of ITU-T G.709.1 Amd.2 (12/2020) specifies two bytes in the FlexO overhead as the OSMC (see Figure 9-7a of ITU-T G.709.1 Amd.2 (12/2020)).
>
> **H1.3 PTP message encapsulation**
> ITU-T Recommendation G.7041 Amd.1 defines a Generic Framing Procedure, frame-mapped (GFP-F). This is used to encapsulate PTP messages as specified in clause 7.10 of ITU-T G.7041 Amd.1 (08/2019). To transport PTP over OTUk, OTU25, OTU50, and FlexO interfaces, the PTP messages shall be encapsulated into the GFP-F frames as specified in clause 7.10 of ITU-T G.7041 Amd.1 (08/2019). The GFP-F frames shall be inserted into the OSMC as specified by the normative references cited in H1.2 and H1.4. To transport PTP over the OSC interface, the encapsulation of PTP messages is implementation specific.
>
> **H1.4 Timestamp generation**
> To transport PTP over OTUk, OTU25, and OTU50 interfaces, the message timestamp generation shall be as defined in clause 15.7.2.4.1 of ITU-T G.709 Amd.1 (12/2020). To transport PTP over the FlexO interface, the message timestamp generation shall be as defined in clause 9.2.10.1 of ITU-T G.709.1 Amd.2 (12/2020). To transport PTP over the OSC interface, the message timestamp generation is implementation specific.

2.3 USING ETHERNET POINT-TO-POINT MICROWAVE RADIO

Another method, but not preferred, for transferring the PTP-based time packets is the use of point-to-point high-frequency Ethernet radio systems [11]. The systems are very common and used in the grid already to transfer data and control messages between locations. There are operational issues with these systems, which operators need to be aware of before using them to transfer time via PTP.

Because these systems are using free space environment (line-of-sight) between radio towers, they are susceptible to environmental disruptions such as fog, rain, and high winds. These systems have mitigation methods to ensure “some” data passes between radio locations in all these circumstances. The typical method used is controlled fade, a mechanism through which the radio reduces its data transfer rate until the measured error rate drops to an acceptable level. This is fine for normal data. However, for PTP, which is very sensitive to path symmetry, if the transfer rate changes to a lower value, the PTP algorithm will conclude the path between the radios suddenly got longer. In such a circumstance, the GMC will begin the process of recalibrating the timestamp flight times; thus, the resolution accuracy between the PTP nodes at each end of the radio will degrade. Once the environmental condition returns to normal, the PTP algorithm will normalize, and the desired precision can be recovered. It is important for the operator to understand this operating paradigm prior to implementing this type of system.

2.4 EMERGING ALTERNATIVE SOURCES OF TIME AND SYNCHRONIZATION

2.4.1 Digital Television Transmission

The National Association of Broadcasters (NAB) has released the new broadcast standard ATSC 3.0 [12]. While not yet fully implemented, this standard has the capability to carry a nanosecond-level timestamp and the geolocation data of the transmitter. When these are received, the timestamp can be used to "correct" the local clock. After several copies are received, the receiver can calculate the rate of change in the timestamp, which is directly related to the timestamp clock frequency. Using the timestamped geolocation data from other transmitters, combined with the receiver's own geolocation data, the direction and distance to each transmitter can be calculated. Once the local timestamp clock rate of change is aligned to the transmitter timestamp clock, the difference in received timestamp values represents the flight time of the received packet, which is used to advance the local timestamp clock to match the timestamping event time of the transmitter, as well as the flight time of the packet. These combined signals will allow the receiver and transmitter to correlate to approximately 50 nanoseconds of alignment, according to NAB engineers.

2.4.2 Multi-Source Common View Disciplined Clock

A future development of connecting multiple master clocks, is the Multi-Source Common View Disciplined Clock (MSCVDC), is a technique for synchronizing earthbound endpoints to a common clock without the requirement for large infrastructure investments or specialized personnel skill sets. MSCVDC is a recent NIST invention designed to support critical infrastructure timing systems that require a verifiably accurate and fail-safe clock [13]. A recent publication by Lombardi (2022) [13] introduces the MSCVDC, provides a technical description of how it works, and discusses its reliability, redundancy, security, and performance.

The technology background for MSCVDC is based on the NIST-developed Common View approach of synchronizing time at two different physical locations with very high correlation precision. The original system used high-accuracy GPS receivers with Rubidium oscillator companions. In this original embodiment, the two endpoints each received the 10 MHz and 1 pps clocks from a single satellite, the same one used for both ends. They would then compare themselves to these signals and, via a simple data exchange mechanism, exchange their local clock values.

The initial implementation of MSCVDC uses GPS as the Common View Signal (CVS) source. There are other CVS sources available, as noted in the following table. This is a partial list of direct broadcast satellites that deliver digital television signals to all 50 states and that could potentially provide a CVS source (sorted by longitude).

Table 1. Common View Signal sources to support MSCVDC.

Satellite	Year Launched	Longitude	Operator
T11 (DIRECTV 11)	2008	99° W	AT&T
T14 (DIRECTV 14)	2014	99° W	AT&T
T16 (DIRECTV 16)	2019	101° W	AT&T

Satellite	Year Launched	Longitude	Operator
T10 (DIRECTV 10)	2007	103° W	AT&T
T12 (DIRECTV 12)	2009	103° W	AT&T
T15 (DIRECTV 15)	2015	103° W	AT&T
EchoStar 105 (SES-11)	2017	105° W	EchoStar
EchoStar X	2006	110° W	Dish Network
EchoStar XIV	2010	119° W	Dish Network
EchoStar IX	2003	121° W	EchoStar

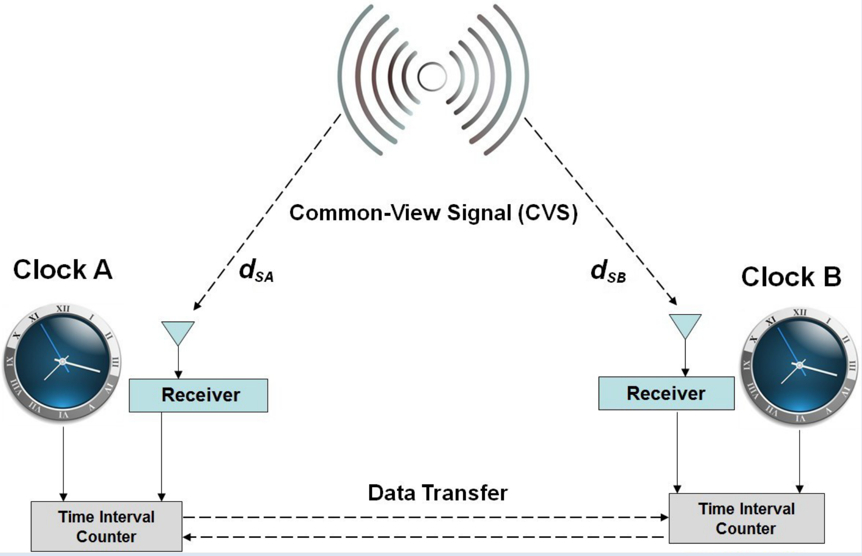
If the MSCVDC approach is of interest to a PMA, it is recommended they contact NIST Boulder. This technology can be “rented” from NIST for a nominal fee. It is also possible for the MSCVDC system to be purpose built for U.S. Department of Energy (DOE) use.

The following has been extracted and adapted from the above-referenced NIST publication for clarity:

[excerpted from Lombardi, 2022]

A common-view comparison can be arranged if there is a signal that can be simultaneously observed both in Chicago and in Boulder. If such a common-view signal (CVS) exists, then the clocks in Chicago and Boulder can each be simultaneously compared to the CVS. The difference between the two “indirect” comparisons effectively substitutes for a direct comparison and reveals the time difference between the Chicago clock and UTC (NIST). Even though the CVS signal originates from its own clock, the time signal it delivers does not have to be accurate, because it is cancelled out when the two indirect comparisons are subtracted from each other, if the propagation times are equal or if the differences in propagation time can be measured and corrected. In a common-view comparison, the CVS is not the reference clock used for synchronization, but instead just a vehicle that relays time information from one site to another.

The following figure shows a common-view time transfer system where a transmitter produces the CVS, and where the CVS is received at sites *A* and *B*. Both sites have a local clock and a receiver that each produce a 1PPS signal. At each site, the time difference between the received and local 1PPS signals is measured with a time interval counter (TIC). The site *A* measurement compares the CVS received over the path *dSA* to Clock A, producing the time difference *Clock A – CVS*. The site *B* measurement compares the CVS received over the path *dSB* to Clock B, producing the time difference *Clock B – CVS.*



2.5 SUGGESTED WIDE-AREA SYNCHRONIZATION NETWORK

The technologies described above can be used to transport time. Time transport can connect a slave clock to a master clock using terrestrial connectivity, i.e., OTN, Leased Lines (T-1), or microwave hops. In addition, master clocks, too, can compare their accuracy using the same terrestrial connectivity. For master clocks to receive a disciplined UTC clock, only OTN or MSCVDC will meet that requirement. Connecting various sites to a master clock using OTN, Leased Lines, or Microwave enables a WAS network. The various sites will need the path delay calibrations performed and added to maintain nanoseconds of accuracy. This is critically important for the power grid equipment as well as message/event handling during the analysis phase due to the nanosecond accuracy in the timing and event logs. Figure 3 below highlights an example tiered WAS network for timing, which could be established across the PMAs, regional utilities, and their respective infrastructures.

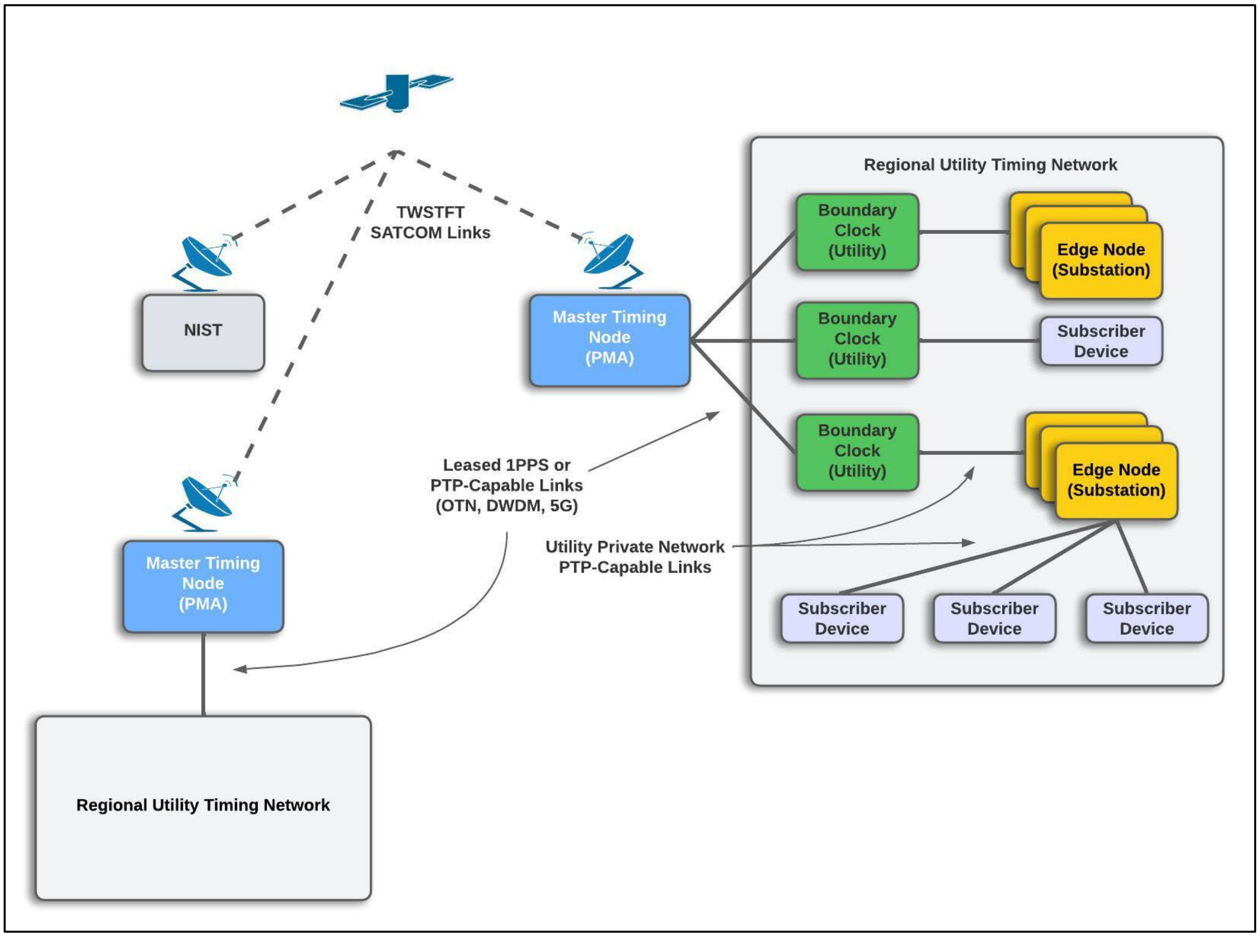


Figure 3. Example WAS network for inter-regional time synchronization.

3. Hardware Recommendations

Below are the recommendations for a grand master time scale. Various options are presented, starting with a highly available and highly accurate solution. The next solution is fault tolerant and less accurate than the former. The last solution is a basic solution without fault tolerance.

As displayed in Figure 4 below (and Figure 2 previously), it is recommended that one use the following for a fault-tolerant, highly available, and highly accurate grand master:

1. 3× optical cesium clocks that meet the Super ePRC (SePRC™) standard. Each cesium clock must have 4× pps outputs and 1× 10 MHz frequency output.
2. 2× Grand Master PTP Clocks that support majority voting (ensembling) that include a minimum of 2× 1 pps inputs as well as 2× 10 MHz inputs.
3. NIST MSCVDC and/or TWSTFT hardware components.

For the fault-tolerant mid-level accuracy grand master:

1. 2× optical cesium clocks that meet the ePRC+ standard. Each Cesium clock must have 4× pps outputs and 1× 10 MHz frequency output.
2. 2× Grand Master PTP Clocks that support multi-source combining that include a minimum of 2 each 1 pps inputs as well as 2 each 10 MHz inputs.
3. NIST MSCVDC and/or TWSTFT hardware components.

For a non-redundant grand master with basic accuracy:

1. 1× optical cesium clock that meets the ePRC+ standard. Each Cesium clock must have 4× pps outputs and 1× 10 MHz frequency output.
2. 1× Grand Master PTP Clock that supports 1× 10 MHz or 1× 1 pps input.
3. NIST MSCVDC and/or TWSTFT hardware components.

For the Grand Master PTP Clocks, it is recommended to have dual power supplies that support the target location's power type (AC/DC). Also, the recommended Ethernet connections should be 10 Gigabit Small Form-factor Pluggable (SFP) optics to prevent framing issues. The timing transmission paths should also be isolated from other traffic, if possible.

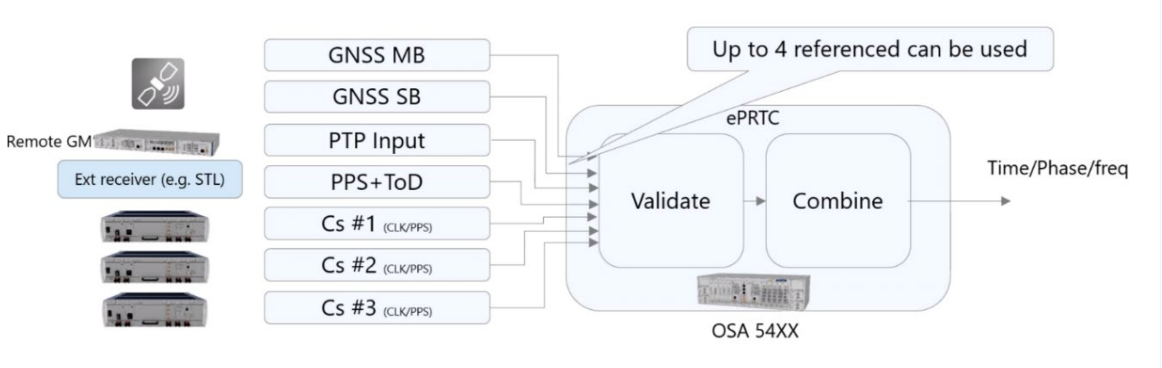
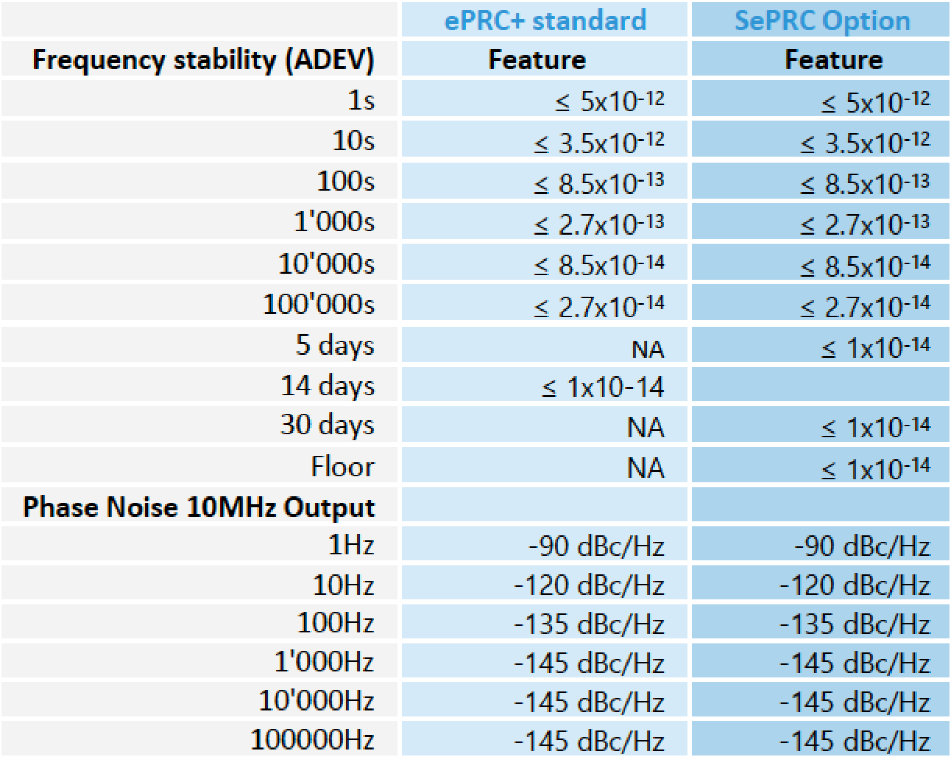


Figure 4. Example grand master PTP time scale.

3.1 CESIUM REQUIREMENTS

Below are the requirements for the types of optical cesium clocks described above. The SePRc specification is still in development, and the proposed values are listed below.



	ePRC+ standard	SePRC Option
Frequency stability (ADEV)	**Feature**	**Feature**
1s	≤ 5x10^{-12}	≤ 5x10^{-12}
10s	≤ 3.5x10^{-12}	≤ 3.5x10^{-12}
100s	≤ 8.5x10^{-13}	≤ 8.5x10^{-13}
1'000s	≤ 2.7x10^{-13}	≤ 2.7x10^{-13}
10'000s	≤ 8.5x10^{-14}	≤ 8.5x10^{-14}
100'000s	≤ 2.7x10^{-14}	≤ 2.7x10^{-14}
5 days	NA	≤ 1x10^{-14}
14 days	≤ 1x10-14	
30 days	NA	≤ 1x10^{-14}
Floor	NA	≤ 1x10^{-14}
Phase Noise 10MHz Output		
1Hz	-90 dBc/Hz	-90 dBc/Hz
10Hz	-120 dBc/Hz	-120 dBc/Hz
100Hz	-135 dBc/Hz	-135 dBc/Hz
1'000Hz	-145 dBc/Hz	-145 dBc/Hz
10'000Hz	-145 dBc/Hz	-145 dBc/Hz
100000Hz	-145 dBc/Hz	-145 dBc/Hz

Figure 5. Cesium stability and noise threshold requirements for grid-centric terrestrial synchronization operations.

3.2 GRAND MASTER REQUIREMENTS

Below are the requirements for the GMCs.

1. Multiband GNSS – If measuring accuracy is important. GNSS will not be part of time scale.
2. Rubidium (Stratum 2) oscillator that can hold up to 10 microseconds of accuracy over a 12-day period or 16 ppb over 5 years.
3. Graphical User Interface (GUI) for easier management and operation.
4. Timing accuracy probes built into the GUI.

4. Future Research through DOE's DarkNet Program

CAST has a close partnership with DOE's DarkNet Program, which is leading grid resilience R&D through research into complementary timing approaches, new secure communications pathways and protocols, distributed ledger technology, quantum encryption, and grid sensor analytics and artificial intelligence (AI). Through engaging with implementation partners, grid operators, and federal agencies, CAST helps DarkNet prioritize research needs. Additionally, CAST augments DarkNet research with testing and evaluation support and technical assistance services to understand scalability and implementation constraints within a particular partner's network.

Phase 3 of DarkNet research is currently underway, and includes the following tasks,

1. In partnership with WAPA, testing PTP performance from a GMC to three remote sites using Nokia hardware and WAPA's DWDM (OEO).
2. Establishing PTP viability over spacecraft SES-1 using Ethernet.
3. Establishing TWSTFT over spacecraft SES-1.
   a. In ORNL timing lab using two antennas.
   b. Between ORNL and NIST.
4. Demonstrating PTP (8275.2) using Juniper Original Equipment Manufacturer (OEM) devices over Dark Fiber, DWDM, and the Energy the Energy Sciences Network (ESNet).
5. Demonstrating PTP (8275.2) using Arista OEM.
6. Demonstrating PTP (8275.1) using Net Insight OEM.
7. Demonstrating PTP (8275.2) using Juniper OEM over Carrier Ethernet and OTN.

Phase 4 of DarkNet is currently being planned with multiple new research targets in mind. While this is subject to change based on feedback from DOE and program stakeholders, the following are priority research areas:

1. Demonstrating PTP transported over OTN using Generic Framing Procedure, frame-mapped (GFP-F) encapsulation.
2. Evaluating PTP transport over 5G cellular.
3. Evaluating PTP transport using a commercial satellite internet backbone.
4. Investigating a PTP-embedded security option to improve security while reducing timing packet latency.
5. Continuing collaboration with WAPA to evaluate TWSTFT over SatCom with NIST.
6. Partnering with NIST to evaluate and demonstrate MSCVDC, with potential integration with WAPA.

5. Summary

Our goal is to alleviate the GPS receiver from being the sole source of time within the power grid architecture. This document identifies the necessary systems and practices to implement a terrestrial complementary timing system to augment GPS/GNSS and provide resilience to disruptions in that time source. CAST will assist federal partners with the evaluation, installation, and operational expertise to implement these components within their local network environments.

The use of the standard PTP protocol ensures a properly designed and implemented network path can deliver the timing precision needed by the phasor measurement units (PMUs) and other time-sensitive applications. One very important item to consider is the ability to mix and match transmission techniques from the PTP root time source out to the RSUs (boundary clocks), as best served by the available transmission technologies. Those approaches identified as NIST-serviced technologies can be obtained through direct interface with the NIST Boulder Time and Frequency Division. Technical and implementation questions can be posed to the CAST team at ORNL

6. References

1. Department of Energy (DOE), Office of Electricity (OE), Response to NIST Request for Information (RFI) about Profile of Responsible Use of Positioning, Navigation, and Timing Services - https://www.nist.gov/system/files/documents/2020/07/14/pnt-0038.pdf

2. North American Electric Reliability Corporation (NERC) Reliability Standard PRC-002-2, Disturbance Monitoring and Reporting Requirements. https://www.nerc.com/pa/Stand/Reliability%20Standards/PRC-002-2.pdf

3. Improving the Operation and Development of Global Positioning System (GPS) Equipment Used by Critical Infrastructure - https://www.cisa.gov/sites/default/files/documents/Improving_the_Operation_and_Development_of_Global_Positioning_System_%28GPS%29_Equipment_Used_by_Critical_Infrastructure_S508C.pdf

4. "IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems," in IEEE Std 1588-2019 (Revision of IEEE Std 1588-2008), pp.1–499, 16 June 2020, https://doi.org/10.1109/IEEESTD.2020.9120376.

5. Bize, Sébastien. 2019. “The Unit of Time: Present and Future Directions.” *Comptes Rendus Physique*, The new International System of Units / Le nouveau Système international d’unités, 20 (1): 153–68. https://doi.org/10.1016/j.crhy.2019.02.002.

6. Lewandowski, W., and C. Thomas. 1991. “GPS Time Transfer.” Proceedings of the IEEE 79 (7): 991–1000. https://doi.org/10.1109/5.84976.

7. “History of Network Time Protocol.” n.d. Accessed January 5, 2023. http://www.ntp.org/ntpfaq/NTP-s-def-hist.htm.

8. “Two-Way Satellite Time and Frequency Transfer (TWSTFT).” 2016. NIST, May. https://www.nist.gov/pml/time-and-frequency-division/time-distribution/two-way-satellite-time-and-frequency-transfer.

9. “G.709 : Interfaces for the Optical Transport Network.” n.d. Accessed January 5, 2023. https://www.itu.int/rec/T-REC-G.709/.

10. Iqbal, M. Kaleem, M. Usman Iqbal, M. Bilal Iqbal, and M. Hassan Iqbal. 2012. “Optical Fiber Switches.” In 2012 International Conference on Open Source Systems and Technologies, 40–45. https://doi.org/10.1109/ICOSST.2012.6472825.

11. “Point-to-Point Microwave.” 2016. Federal Communications Commission. February 22, 2016. https://www.fcc.gov/wireless/bureau-divisions/broadband-division/point-point-microwave.

12. “ATSC 3.0 Technical Documents.” n.d. ATSC : NextGen TV. Accessed January 5, 2023. https://www.atsc.org/documents/atsc-3-0-standards/.

13. Lombardi, Michael A. 2022. “Multi-Source Common-View Disciplined Clock: A Fail-Safe Clock for Critical Infrastructure Systems.” NIST 126 (January). https://www.nist.gov/publications/multi-source-common-view-disciplined-clock-fail-safe-clock-critical-infrastructure.