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Time Synchronization in the Electric Power System

NASPI Technical Report

NASPI Time Synchronization Task Force

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NASPI North American SynchroPhasor Initiative

Disclaimer

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Executive Summary

The power system uses precision timing for grid monitoring and situational awareness, to coordinate the operation and integration of a variety of grid assets, and for grid protection and operation. Because power systems are so large and often geographically separated, power data acquisition systems need to share a common time source. In some advanced applications, clocks need to be precisely synchronized to a common reference to enable the integration of diverse data types and sources and assure that decentralized, parallelized analysis and control actions are effectively coordinated and implemented. Information about time is used to understand how relationships and conditions change over time, to identify and understand specific events (whether an individual lightning strike or the sequence of events for a system collapse), and to understand dynamic and transient grid events.

Members of the North American Synchrophasor Initiative (NASPI) work with synchrophasor technology, one of the principal timing-dependent technologies used on the power system today. Synchrophasor technology uses phasor measurement units (PMUs) to measure voltage and current waveforms and calculate phasors at high speeds in real-time, time-stamping those measurements against a time source such as the Global Positioning System (GPS). PMU data can be used for real-time situational awareness and operator decision support, generator model validation, forensic event analysis, and to provide additional visibility into system stability and oscillations.

In this paper, NASPI's goal is to identify and articulate what power system engineers and operators need to know about the role and emerging importance of high-quality timing sources in routine and mission-critical grid applications. We articulate architectures and guidelines for how to get timing right and adopt best practices for timing, systems, and equipment that provide the correct, consistent time needed for emerging mission-critical applications, such as closed loop wide-area controls and real-time operator decision support.

PMUs need access to reliable Coordinated Universal Time (UTC) to allow synchrophasor applications to time-align the voltage and current time series data for analysis and coordinated activity over a wide geographical area. Most of the PMUs in North America acquire timing data from GPS. Since GPS signals are weak, they are inherently vulnerable to both human-caused and natural disruptions. Today, disruptions in GPS signal or other precision time sources will complicate grid operations by raising false alarms, increasing costs, delaying operational actions, and lowering system efficiency – but should not cause major grid failures. At this time, PMUs should not be used for automated controls and other mission-critical purposes until timing challenges have been resolved and time and measurement integrity can be assured. Significant improvements in timing system provision and timing distribution reliability are needed before synchrophasor technology can become fully effective and reliable for increased reliance on automation in wide-area monitoring, protection, and control systems for smart grid applications.

This paper reviews the ways that synchrophasor technology and other power system applications use precise, accurate time signals for wide-area device and data synchronization. It explains the timing delivery requirements – which include the timing resolution and time signal delivery – for those applications. The paper offers definitions and explanations of timing (basic topics such as clocks, frequency, synchronization, and UTC), timing measurement characteristics (such as accuracy, resolution, and precision) and timing sources and systems (such as GPS and master clocks). It documents the problems of current positioning, navigation and timing solutions. It identifies and reviews a number of specific, near-term solutions and mitigations that can address multiple failure causes (redundant timing sources, better installation and maintenance practices, detection of bad or anomalous time signals, specifications for good-quality equipment, etc.).

Last, the paper closes with some longer-term recommendations (e.g., timing problem detection, equipment interoperability, and standards updates) within the grid sector and beyond. Those include the following points:

- **Accuracy** – While accuracy requirements are achievable with today's technology, the mechanisms to provide it are too costly and too large physically if sources beyond GPS are employed. GPS-only solutions are vulnerable to interference, jamming, loss of signal, and spoofing, and so cannot be used as the sole source of timing for a mission-critical application. We also need better methods to identify when time signals have become corrupted due to events such as a leap second or spoofing.
- **Resiliency and reliability –** Tomorrow's timing sources must be able to function with high availability in the event of the loss of one time signal method (i.e., by failing over to a back-up timing system such as an on-board oscillator), and should work during power outages.
- **Security –** Since we cannot count on physical security to completely protect access to timing sources and the networks that transport their information, we must find new ways to ensure the integrity of our timing sources.
- **Flexibility –** There are many ways to use time-synchronized, PMU-like sensors for smart grid coordination and protection functions. This will require having small, highly accurate time-synchronized sensors that can be deployed cheaply and easily. The timing source should support "smart grid" capabilities (e.g., flow data with feedback from residences and businesses, and enable distributed, decentralized analysis and control) as well as improved support for advanced user/applications, better interoperability with other timing sources and grid components, and better inter-sector coordination.
- **Costs** – The industry is eager for manufacturers to develop small, inexpensive sensors that can collect high-speed, high-accuracy, time-synchronized grid data. But to deploy a time-synchronized sensor such as a PMU, the users need to buy the device, install it, and provide secure high-speed communications to collect and use the data. All of these elements need to become easy and low-cost to enable full utilization of time-synchronized sensors.
- **Standards and testing** – There is still work needed to fully incorporate clear, consistent timing performance requirements into standards and conformance testing, and to ensure interoperability between different timing methods and time-using devices.
- **Applications** – Given the many ways in which time signal delivery may fail, applications need to be more sensitive to whether incoming data is accurate and accurately time-stamped, and should be able to work around data gaps and losses where possible. Applications should warn users if data problems such as bad time-stamps are compromising the quality and trustworthiness of the application's analytical results.

1. Introduction

The power system uses precision timing for grid monitoring and situational awareness, to coordinate the operation and integration of a variety of grid assets, and for grid protection and operation. Because power systems are so large and often geographically separated, power data acquisition systems need to share a common time source. In some advanced applications, clocks need to be precisely synchronized to a common reference to enable the integration of diverse data types and sources and assure that decentralized, parallelized analysis and control actions are effectively coordinated and implemented. Broadly speaking, information about time is used to understand how relationships and conditions change over time, to identify and understand specific events (whether an individual lightning strike or the sequence of events for a system collapse), and to understand dynamic and transient grid events.[1]

The North American Synchrophasor Initiative (NASPI) is a North America-based collaboration between electric providers, vendors and consultants, government, and academics to foster the understanding, value, and use of synchrophasor technology to improve power system reliability and efficiency. NASPI has over 1,000 members worldwide who share information and insights, solve problems, and develop guidelines, standards, and technical reports pertaining to synchrophasor technology. The NASPI Work Group holds two meetings per year, and its task teams and task forces meet more frequently to advance specific projects. NASPI archives and work products can be found at www.naspi.org.

Members of the power sector have been working with experts in the timing community to identify and address the timing provision and distribution issues relevant to synchrophasor technology. NASPI's goal is to identify and articulate what power system engineers and operators need to know about the role and emerging importance of high-quality timing sources in routine and mission-critical grid applications. We articulate architectures and guidelines for how to get timing right and adopt best practices for timing, systems, and equipment that provide the correct, consistent time needed for emerging mission-critical applications, such as closed loop wide-area controls and real-time operator decision support. We anticipate that our work products (for instance, documentation of leap second associated time-stamping problems) will have value for the entire power system industry, and may be exportable to other industries as well.

1.1 Synchrophasors

Synchrophasor technology is a maturing technology being deployed now across the North American electric transmission grid. Synchrophasor technology is being used for wide-area monitoring and situational awareness, verification of grid models, event analysis, and for analysis of a variety of grid phenomena. Because the effective operation of synchrophasor technology requires highly precise, fully reliable, and secure monitoring, timing, and communications systems, it embodies the timing and synchronization challenges involved for successful deployment and coordination of the distributed networks in the Smart Grid and

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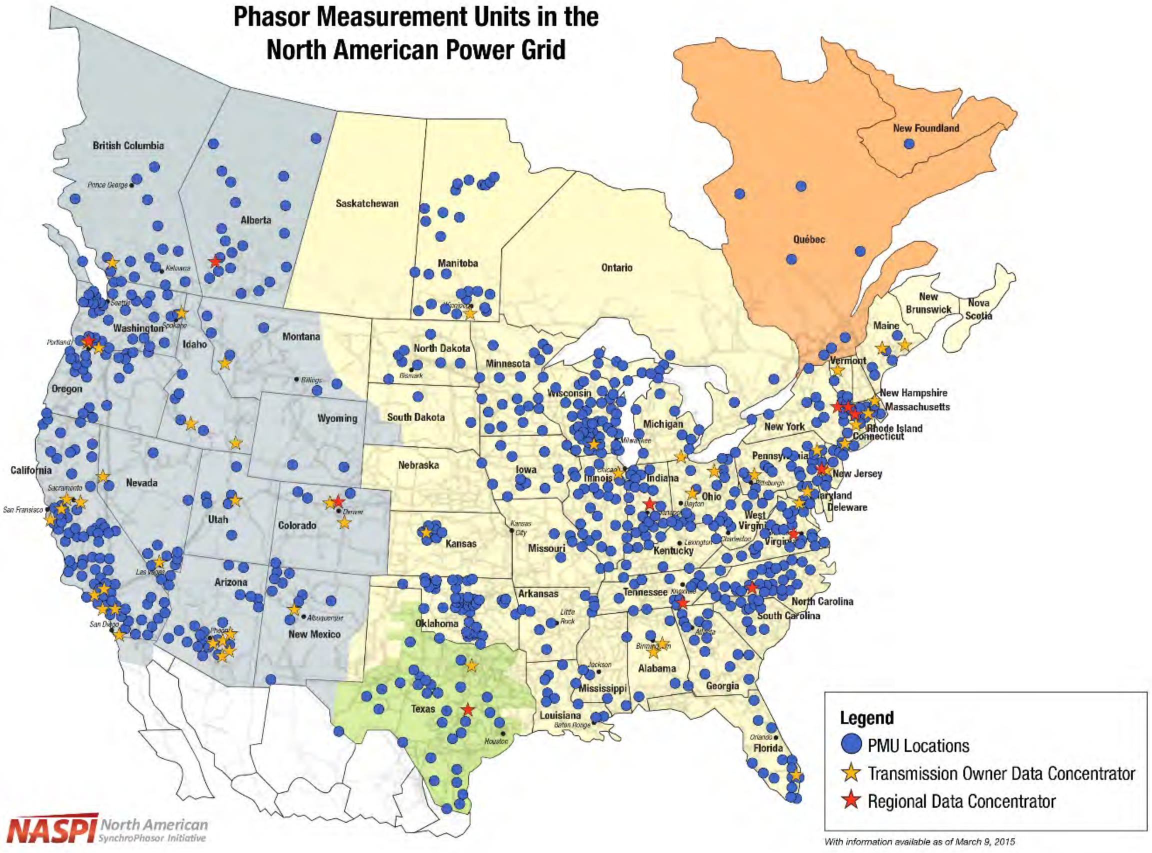
[1] U.S. National Institute for Standards & Technology, "Precision Timing for Smart Grid Systems," website at https://www.nist.gov/programs-projects/precision-timing-smart-grid-systems, and NIST Special Publication 1500-08, "Timing Challenges in the Smart Grid" (January 2017).

Internet of Things. Within five years, synchrophasor technology could become mission-critical for bulk power system operation and be at the early stages of use at the electric distribution level.

Synchrophasor technology uses PMUs to measure voltage and current waveforms and calculate phasors. Each measurement is time-stamped and thus synchronized against Coordinated Universal Time (UTC) using a time source such as the GPS. PMU data is collected at 30 to 120 samples per second and sent to data concentrators and archives. Synchrophasor applications have among the most stringent precision time and time interval requirements of all timing uses on the electric power system, due to high-frequency reporting, phasor precision needs, and the wide geographic distribution of PMUs.

Figure 1 shows the locations of networked PMUs (i.e., those which can deliver real-time data to reliability coordinators and active archive and applications sites) installed across North America in 2015; many more have been installed since.



Courtesy of the North American Synchrophasor Initiative () and the U.S. Department of Energy.

Figure 1. Almost 1,800 PMUs were installed across North America in 2015 [NASPI 2015]

The present grid is primarily managed using technologies like Supervisory Control and Data Acquisition (SCADA), which at a refresh rate of 4 to 6 seconds provides only quasi-static visibility. As the level of distributed resources and bi-directional (transactive) market operations make the overall system less predictable, the level and types of risk associated with maintaining grid reliability and security become higher. The dynamics and variability of distributed resources and loads reduce the time and tolerances to handle operational problems. The promise and value of synchrophasor technology lies in its ability to provide real-time visibility of the power system. This helps operators and engineers better understand current and emerging conditions on the grid and develop better predictive and actionable information from tools such as big data analytics. PMU data will be used to operate the grid more efficiently, using real-time grid conditions and phase angles to push more electricity through existing capital assets, and getting earlier warning about asset condition problems and capabilities.

Synchrophasor data from PMUs can be used for generator model validation, forensic event analysis, reducing and eliminating generator-caused oscillations, and to provide additional visibility of power flows, including stability and oscillations across key interfaces. They can be used for generator synchronization, islanding detection, system black-start restoration, and micro-grid management enabling power systems operations to optimize energy and cost efficiency.

PMUs need access to reliable Coordinated Universal Time (UTC) to allow synchrophasor applications to time-align the voltage and current time series data for analysis and coordinated activity over a wide geographical area. Most of the PMUs in North America acquire timing data from GPS. Since GPS signals are weak, they are inherently vulnerable to both human-caused and natural disruptions. Today, disruptions in GPS signal or other precision time sources will complicate grid operations by raising false alarms, increasing costs, delaying operational actions, and lowering system efficiency – but should not cause major grid failures. Time synchronization-enabled technologies such as synchrophasor-based applications can be used for protection and control purposes, but losing GPS signals could potentially lead to grid failures, especially if systems do not recognize and test against possible timing vulnerabilities. At this time, PMUs should not be used for automated controls and other mission-critical purposes until timing challenges have been resolved and time and measurement integrity can be assured. Significant improvements in timing system provision and timing distribution reliability are needed before synchrophasor technology can become fully effective and reliable for increased reliance on automation in wide-area monitoring, protection and control systems for smart grid applications.

1.2 The NASPI Time Synchronization Task Force goals

Power system owners and operators use primarily GPS as the source for timing and determining asset position. Today, GPS disruptions complicate (with higher cost, longer duration, and lower efficiency) but do not kill grid operations. For mission-critical time-synchronized applications in the future, however, GPS and alternate time sources (and the ways they are delivered and used) will need to become more reliable.

NASPI seeks to help the user community implement consistent, reliable time across a substation and synchronized across a power system. The methods for this are well-established and effective in other industries, so the challenge is not so much to create new solutions as to identify those methods and practices and help migrate them into the power sector. NASPI is working to:

- Identify the options for reliable delivery of precise, accurate time signals for wide-area device and data synchronization
- Document problems of current position, navigation, and time (PNT) solutions

- Identify specific, near-term solutions and mitigations that can address multiple failure causes (redundant timing sources, better installation and maintenance practices, detection of bad or anomalous time signals, specs for good-quality equipment, etc.)
- Identify and share how-to information for these solutions
- Recommend longer-term research needs (timing problem detection, equipment interoperability, standards updates, etc.) within grid sector and beyond

Timing errors from the time source can cause incorrect synchrophasor data that can create false analytical conclusions. In the future these errors could drive undesirable and possibly dangerous automated grid operations with synchrophasor-based controls. The power sector needs to protect future grid operations with better timing tools and practices to improve robustness and resilience. It must assume that PNT could be unreliable at both source and receiving points, and must start implementing measures to assure that PMU data receives accurate, reliable time-stamps despite multiple time signal delivery failure modes.

GPS, timing and the grid are having their “moment” – in addition to this NASPI effort, the U.S. Department of Homeland Security (DHS) is looking at how the grid and other critical infrastructures use timing and the vulnerability of GPS to spoofing and jamming and working on better timing awareness and solutions,[2] EPRI is surveying some timing uses and their vulnerabilities,[3] NIST is examining the use of precision timing for the smart grid,[4] and the telecommunications community is documenting timing delivery options.

Until now, there has been little work in specifying or detailing the timing requirements for power system applications – timing, time quality, and synchronization have been afterthoughts, not deliberately designed into applications. Based on the data that does exist, synchrophasor technology will need 1 microsecond interval measurements, but it will be necessary to identify and specify other timing requirements.

Some of the ideas and work products that NASPI hopes to develop on behalf of our power system colleagues include the following, most of which are addressed in this paper:

- Articulating why good timing delivery systems matter for grid reliability (especially in synchrophasor space).
- Explaining the terminology and definitions to understand timing ideas, standards, and protocols (borrowing as much as possible the conventions and terms already used within the timing community).

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[2] The DHS effort is described in Sarah Mahmood’s presentation, “GPS Timing in Critical Infrastructure,” at the IEEE/NIST Timing Challenges in the Smart Grid Workshop (October 26, 2016). To enhance critical infrastructure resiliency, DHS’s new Positioning, Navigation & Timing group is working on mitigation through GPS vulnerability and impact assessment, increasing awareness of GNSS threats and needs, working with manufacturers to improve GNSS equipment, and develop complementary PNT sources such as eLoran, Iridium, fiber and more.

[3] The EPRI research effort is described at Chason, Glen, “Timing Security Assessment and Solutions,” presentation at NIST Tiing Challenges in the Smart Grid workshop (October 26, 2016).

[4] See the NIST report, “Timing Challenges in the Smart Grid,” NIST Special Publication 1500-008 (January 2017).

- Expanding our understanding of how different power system applications use timing now and begin articulating how and why timing requirements (including accuracy, reliability, redundancy, and other timing-related and SLA-type (Service Level Agreement) performance expectations and metrics) might be strengthened for different applications, to raise the bar for developers and vendors.
- Explaining what timing delivery options are available and whether and how each is suitable relative to our emerging applications requirements.
- Developing recommendations for what power system people need to do to assess and improve timing system quality, including installation, redundancy, test methods, good practices, and more.

Timing and data quality are the next level in our expanding understanding of synchrophasor technology basic elements (which is building over time from PMUs, to applications and analytics, to standards, to data networks and handling, and now to timing and data quality).

2. Synchrophasor Technology Overview

2.1 Synchrophasor technology and precise timing

Time-synchronized measurements are needed to enable the calculation and comparison of multiple phasors at different locations and gain a wide-area view of the power grid. Therefore, synchrophasor applications need reliable access to a stable time source such as UTC to time-align power system data for analysis and coordinated activity over a wide spatial expanse (see Figures 2 and 3). Phasor data concentrators (PDCs) aggregate and time-align the phasor data from multiple PMUs.

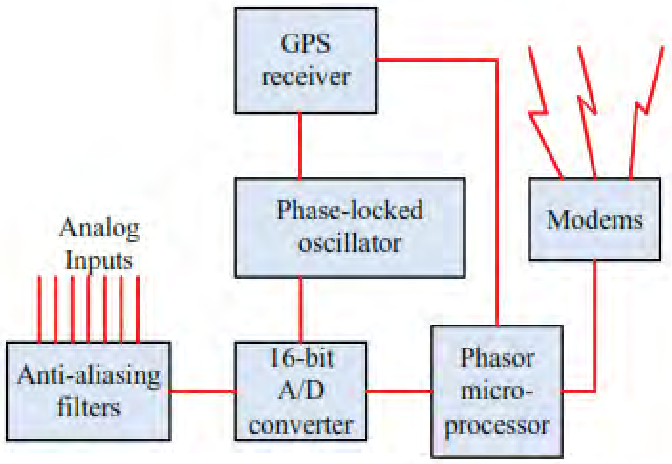

Figure 2. Block diagram of PMU showing GPS receiver and oscillator [J. Dagle]

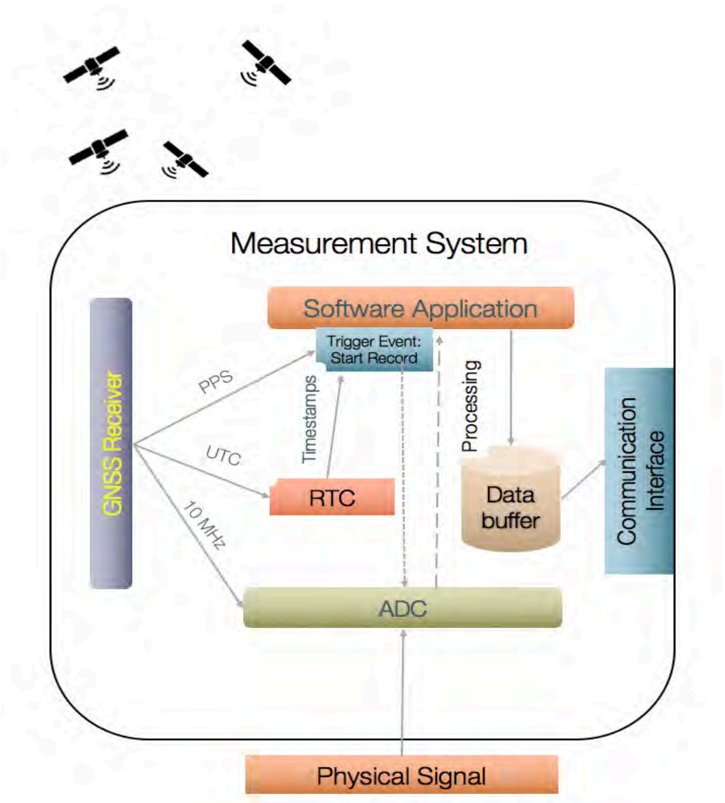

Figure 3. How precision time is used in a distributed measurement system (ADC = Analog to Digital Converter, RTC = Real-time Clock) [NIST]

A PMU sends data frames composed of synchrophasor, frequency and rate of change of frequency (ROCOF) measurements at a specified rate of *N* times per second. Synchrophasor reporting times are required to be evenly spaced with frame 0 being sent at the top of each UTC second. Within a one second interval, each frame is uniquely identified by a time-stamp, which is zero for the first frame in a given second, and $1/N$ for the next and so on up to $(N\text{-}1)/N$ for the last frame.

As illustrated in Figure 2, the Global Navigation Satellite Systems (GNSS) receiver typically provides a variety of time and frequency signals, including UTC, pulse per second (PPS) and 10 MHz. The 10 MHz signal serves as a reference for the Analog to Digital Converter (ADC) for consistent sampling of the electrical signal. UTC provides a synchronized time-stamp for the data, and the PPS can be used to trigger frame 0 at the top of a second.

2.2 Time Vector Error and its implications for timing accuracy

Power system quantities are usually represented by sinusoids. In equation 1, $x(t)$ is a representation of a voltage or current as a sinusoidal waveform as used in alternating current (ac) power system analysis, where t represents an instant in time, ω is the angular frequency, X_{m} is the magnitude of the waveform (110 volts, for example), and ϕ is the angle evaluated at time 0 between the signal being observed and a reference signal, as defined in IEEE C37.118.1-2011.

$$\mathrm{x(t)} = \mathrm{X_m}\cos(\omega\mathrm{t} + \phi) \tag{1}$$

Power system engineers commonly assume that the frequency is at its nominal value, and refer to just the magnitude, X_m, and phase, ϕ, as a *phasor.* These two quantities, as measured by a PMU, are referred to as a *synchrophasor.* The frequency (also measured by the PMU), is also reported. For the purposes of measuring ϕ, the time may be taken as a "local zero" at the UTC second rollover, and therefore at the top of every cycle of the reference signal.

Often, a different representation is used, based on Euler's equation. For a time-varying complex number $Ae^{j(\nu t+\varphi)}$ the relationship

$$Ae^{j(\nu t+\varphi)} = A\cos(\nu t + \varphi) + jA\sin(\nu t + \varphi) \tag{2}$$

allows us to regard the projection of the sinusoidal quantity onto the horizontal axis as being represented by the real part of the quantity. That is, an equation of the form of Equation (1) is given by

$$A\cos(\nu t + \varphi) = \mathrm{Re}[Ae^{j(\nu t+\varphi)}] \tag{3}$$

For our purposes

$$\mathrm{Re}\left[X_\mathrm{m}e^{j(\omega t+\phi)}\right] = X_\mathrm{m}cos(\omega t + \phi). \tag{4}$$

We can separate this into two parts. $X_\mathrm{m}e^{j(\omega t+\phi)}$ can be written $X_\mathrm{m}e^{j(\phi)}e^{j(\omega t)}$. The time-dependent unit-sized part $e^{j(\omega t)}$ is called by mathematicians the *rotating phasor*, or the *rotator*.[5] The part $X_\mathrm{m}e^{j(\phi)}$is called the *stationary* phasor. We could write that as $X_\mathrm{m}e^{j\phi} = \boldsymbol{X}_\mathrm{m}$ so that the complete expression $X_\mathrm{m}e^{j(\omega t+\phi)}$ is $\boldsymbol{X}_\mathrm{m}e^{j\omega t}$.

The complex number $\boldsymbol{X}_\mathrm{m}$ gives the position of the rotating phasor at time $t = 0$, that is, it corresponds to the part of (4) that power engineers call the *synchrophasor*. Some have interpreted this mathematics to mean that *only* the exponential notation can be used to describe the phasor, but that is a misinterpretation. Equation (3) shows that the sinusoidal and exponential representations are equivalent.[6]

The stationary phasor has for decades been called simply the phasor by power engineers. The expression $X_\mathrm{m}e^{j(\omega t+\phi)}$, evaluated at time $t = 0$, results in the two quantities that define the stationary phasor, and power engineers are taught that since the power system frequency is

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[5] See Clement, P., & W. Johnson, Electrical Engineering Science (1960); Scharf, L. & R. Behrens, A First Course in Electrical and Computer (1990); and Moura, L., & I. Darwazeh, Introduction to Linear Circuit Analysis and Modelling (2005).

[6] It may also be noted that if the parameters of Equation (1) are not constant, Euler's equation itself becomes an approximation, and the exponential model is therefore also an approximation. We know this will sometimes be the case. The amplitude of the current signal is quite variable, and since the PMU is expected to report a value for the rate of change of frequency, it is evident that this is expected to change, too. Since the equations are approximations, the results of the measurement cannot be interpreted as representing "true values."

constant, power system signals can be represented by just these two quantities. The representation brings significant simplification to the problem of analyzing power systems, because it allows the use of geometrical solutions to the equation representing the signal, instead of the more complicated trigonometric ones. Further, it allows the use of what are called phasor diagrams, an invaluable aid to visualization.

A phasor diagram representing (1) is shown on the right side of Figure 4. The left side shows how it is derived. Some power engineers do not draw the arrow indicating rotation.

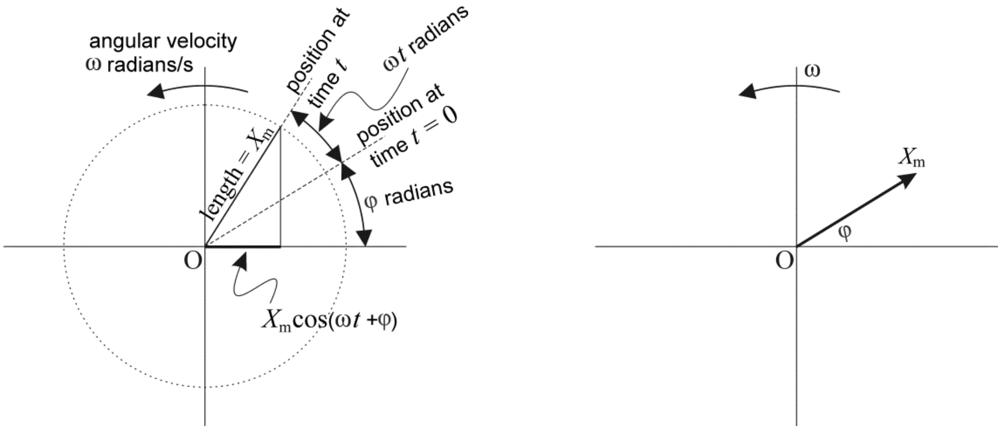

Figure 4. Rotating phasor whose projection on the horizontal axis is $\mathbf{x(t) = X_m \cos(\omega t + \varphi)}$

In summary, a PMU reports the values of a *synchrophasor* (the result of the measurement of the magnitude, X_m, and phase angle, ϕ, relative to a cosine function at the nominal power frequency), along with the frequency. These quantities are evaluated over an interval of time defined by the IEEE standard (IEEE C37.118.1, 2011). Time in the PMU is synchronized to UTC.

The time accuracy requirement in IEEE C37.118.1-2011 is indirectly determined by the need to meet the requirement for a maximum 1% of a value called the Total Vector Error (TVE). TVE is a way to express the uncertainties in the result of the measurement that are due to a component in the measurement of amplitude and a component due to the measurement of the phase. If there is no uncertainty in the result for phase, a maximum of 1% is allowed in the result for amplitude. The question is how to put a percentage error number on phase.

The question must be asked because phase is somehow “different” from magnitude. The quantities that are standardized by the SI system are what are now called *rational* in the classification scheme of Stevens.[7] The term implies something about the kind of mathematical operation that can be done on the result of the measurement: it is possible to take *ratios*, because

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[7] See Stevens, S., “On the theory of scales of measurement,” Science, 103, 677-680 (1946); Ellis, B. Basic concepts of measurement (1966); and Luce, R., & J. Tukey, “Simultaneous conjoint measurement,” J Math Psych, 1, (1964).

all the SI quantities have a single natural zero and a linear scale. Angle is a fundamentally different kind of quantity.

The allowable uncertainty in phase is determined as follows. To cope with the difference in kind, it may be conjectured that at some point in the history of the PMU it was decided that if the 1% uncertainty of amplitude were regarded as a small phasor added to (or subtracted from) the phasor that represents the power system quantity being measured, angle uncertainty and amplitude uncertainty could be combined, much as the uncertainties in rational quantities were combined: as the square root of the sum of the squares.[8]

For two variables, this combination method, the root of the sum of the squares, results in the equation of a circle. Recall that the equation of a circle whose center is the origin is

$$r^2 = x^2 + y^2. \tag{5}$$

A circle whose center is (a, b) is described by

$$r^2 = (x-a)^2 + (y-b)^2. \tag{6}$$

Added to a phasor diagram, the terms a and b are the horizontal and vertical offsets of the center of the circle, so that to put the circle at the end of the phasor in **Error! Reference source not found.**, equation (6) becomes

$$r^2 = (x - X_\mathrm{m}\cos(\omega t + \varphi))^2 + (y - X_\mathrm{m}\sin(\omega t + \varphi))^2. \tag{7}$$

The circle thus described is not a phasor, though it is sometimes drawn as if it were, in order to illustrate the size of the circle. It is simply a circle that moves along with the tip of the phasor, and there describes a region within which the TVE is defined as being acceptable.

Figure 5 illustrates the situation, exaggerating the size of the TVE circle for clarity.

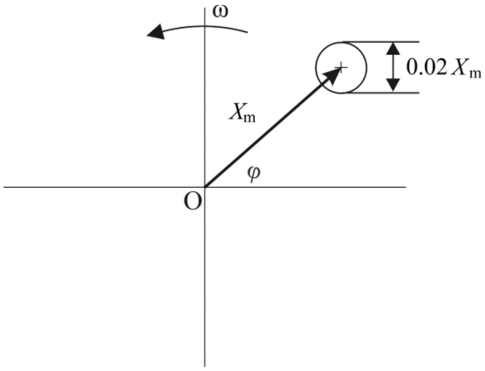

Figure 5. TVE as a circle

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[8] This method of combining is actually justifiable only under a restricted set of conditions that were not taken into consideration in this development. Nevertheless, the method seems to have produced a measure of uncertainty that applies to angle with a size that seems quite appropriate to our situation.

If we further exaggerate the size of the TVE circle, we can see that the geometry of the situation indicates that the maximum permissible phase error is given by

$$\epsilon_{\varphi} = \sin^{-1}\left(\frac{1}{100}\right) = 0.573°. \tag{8}$$

where ϵ_{φ} is the phase error, as shown in Figure 6.

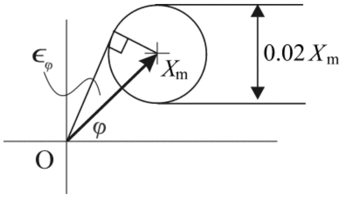

Figure 6. TVE as circle (close-up)

It may be observed that the fact that the value is a constant supports the observation made earlier that angle is somehow “different” from magnitude. A 1% error in magnitude depends on the size of the quantity being measured. A “1% error in angle” is always just over half a degree, whatever the value of the phase being measured.[9]

While the origin of the TVE presented above is speculative, the result is not. Because the error is independent of the angle being measured, it is possible to say that, regardless of the angle being measured, at 60 Hz a 1% angle error corresponds to a timing error of 26.5 μs. If the clock signal is delayed, the phase will be reported as advanced from its proper value.

However, the standard suggests a maximum timing uncertainty of 1 μs, rather than 26.5. That gives some allowance for sources of uncertainty other than angle. The IEEE standard gives graphs showing the interrelationship between magnitude error and phase error for a given TVE.

2.3 Timing delivery requirements

Timing requirements stem from the temporal concepts of *determinism*, *fast*, and *now*. In *determinism*, the application is looking for predictable and often constant time intervals. The application may expect reports of measurement samples to arrive at a deterministic rate. An application may also have the temporal requirement of being *fast*, so that the data arrive and can be analyzed before some event that is characterized in those data triggers a cascading effect on the system. *Now* is the minimum possible interval in the system; applications are looking for data to arrive quickly, but with a wider tolerance than *now*. Commercially available communication and computing systems can meet users’ and applications’ needs for many levels of *fast* and *deterministic* data speeds, but customized hardware, systems, and service performance agreements may be required to meet the most stringent performance requirements. Efforts such

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[9] The value, just over 34 minutes of arc, seems to pass a “reasonableness test.” The IEEE Standard for instrument transformers (C57.13-2008) has three classes of accuracy. They allow a magnitude error of 0.3, 0.6 and 1.2 percent. The maximum angle error corresponding to each of these classes is 30, 60 and 120 minutes. One might reasonably infer that a 1% transformer would be allowed 100 minutes of phase error, just three times the amount allowed in the PMU.

as Time Sensitive Networking (TSN) are underway to create standards and interoperability of systems using precision time to enable a greater degree of determinism.

While the time-synchronized aspect of PMU data enables many analytical and awareness applications, not all of these applications have the same message-rate and message delivery timing requirements. Figure 7 shows, conceptually, the actions that must be performed through the process of physical measurement through message delivery and handling (referred to here as “message transfer”).

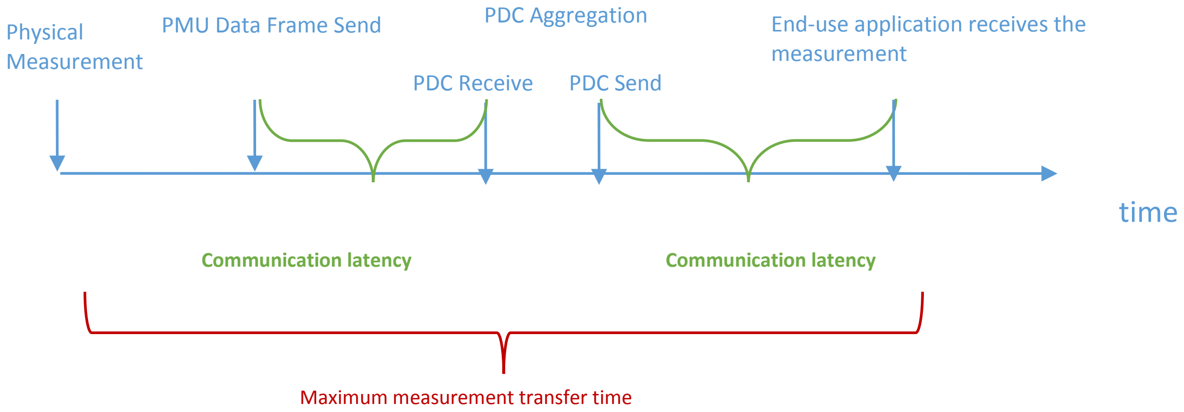

Figure 7. Maximum measurement delivery time [Weiss, Silverstein et al., 2017]

NASPI is working to document the message transfer (delivery) speed requirements of different types of power grid analysis applications.

In general, the different timing requirements are associated with what the application needs to do or needs to be able to extract from the data. If it is observing a high-speed, dynamic behavior like oscillations from generators, it needs very precise, accurate time at very high reporting rates and within a specified time interval for the data to be applicable. Ideally, the measurement will remain an accurate representation of grid conditions from the time of physical measurement until the time when that measurement is delivered to the end-use application. The measurement transfer time is comprised of processing and communication latencies. For other monitoring and visualization aspects, the data can be slower with less stringent data transfer requirements, to suit human operators’ limitations. Most synchrophasor systems collect high-speed PMU data for use in all applications, but down-sample the data as appropriate to support slower applications such as wide-area system monitoring or system frequency monitoring.

3. Definitions

Members of the utility community do not always use terms about timing to mean the same things (or the correct things). Since this is a complex technical topic, the NASPI TSTF offers this terminology discussion to enable the synchrophasor community and the broader electric industry to use accurate timing terminology in appropriate ways.

The following are some of the key terms that metrologists and others who work on timing systems use to describe, characterize, and evaluate the capabilities and appropriateness of alternative timing delivery systems for various purposes. Most of the definitions below are taken from the ITU-R TF.686.3 2013 Glossary (indicated by "—"), with additional information and explanation added as appropriate. The terms and definitions are divided into three sections:

- *Timing* covers basic topics such as clocks, frequency, synchronization and UTC.
- *Timing measurement* characteristics defines topics such as absolute versus relative time, accuracy and precision.
- *Timing sources and systems* addresses topics such as GPS and NTP.

3.1 Timing

Absolute time/synchronized time – Events are recorded to absolute time when they are time-synchronized and time-stamped against a common time source such as GPS network-distributed time. This is distinguished from relative time, which counts time passed from an initiating event (such as from a lightning strike to a relay action).

Atomic clock – "An atomic clock keeps time using an oscillator based on an electronic transition frequency in the microwave, optical or ultraviolet region of the electromagnetic spectrum of atoms." Atomic clocks based on cesium (Cs-133) atoms are often used as a timing source.

Clock – "A device for time measurement and/or time display." Modern clocks for devices such as PMUs contain harmonic oscillators (such as a quartz crystal) or use quantum step energy differences (vibrations) of atomic transitions, which vibrate or oscillate repetitively at a precisely constant frequency.

Clock ensemble – "A collection of clocks, not necessarily in the same physical location, operated together in a coordinated way either for mutual control of their individual properties or to maximize the performance (time accuracy and frequency stability) and availability of a time-scale derived from the ensemble."

Clock signal – A particular type of signal produced by a clock generator, used to coordinate and synchronize actions.

Clock time difference – "The difference between the readings of two clocks at the same instant." Two clocks that are effectively synchronized to a good time source such as GPS should have no clock time difference, but two clocks that are not synchronized will show clock time difference.

Coordinated clock – "A clock synchronized within stated limits to a reference clock that is spatially separated."

Frequency – "If T is the period of a repetitive phenomenon, then the frequency $f = 1/T$. In SI units the period is expressed in seconds, and the frequency is expressed in hertz." A periodic wave is defined to have the same frequency over all time. The PMU is expected to measure "frequency" over a much shorter time, and successive measurements are not required to furnish the same result.

Frequency drift – “A systematic undesired change in frequency of an oscillator over time. Drift is due to ageing plus changes in the environment and other factors external to the oscillator.” In the case of atomic clocks, it has been established that ambient temperature differences may cause drift in clock frequency.

Frequency standard – “An accurate stable oscillator generating a fundamental frequency used in calibration and/or reference applications.”

Greenwich Mean Time (GMT) – Mean solar time as measured with reference to the meridian passing through the Royal Observatory, Greenwich. GMT was adopted as the world’s first global time-scale in 1884. However, “GMT is no longer maintained and has been replaced by universal time (UT) and coordinated universal time (UTC) for precise applications. GMT […] in common parlance is used most often to indicate UTC, the time-scale broadcast in standard time signals.”

Leap second – “An intentional change in the number of seconds per minute, to extend a designated minute by one extra second (a positive leap second) or to finish the minute early by one second (a negative leap second). The leap second is used to adjust coordinated universal time (UTC) to ensure approximate agreement with the rotation of the earth (UT1).” The leap second procedures are documented in Recommendation ITU-R TF.460.

Local time – The time at a specific location within a zone that observes a uniform standard time for legal, commercial, and social purposes (for instance, daylight savings versus standard time within the United States). In most cases, time zones on land are offset from UTC by a whole number of hours.

Period – The duration of time for one cycle of a repeating event; the reciprocal of frequency. Table 1 shows examples of the relationship between frequency and period.

Table 1 – Frequency and Period

Frequency (cycle)	Period (time)
1 millihertz, (mHz, 10^{-3})	1 kilosecond (ks, 10^{3})
1 hertz (Hz, 10^{0})	1 second (s, 10^{0})
1 kilohertz (kHz, 10^{3})	1 millisecond (ms, 10^{-3})
1 megahertz (MHz, 10^{6})	1 microsecond (µs, 10^{-6})
1 gigahertz (GHz, 10^{9})	1 nanosecond (ns, 10^{-9})

Phase – “A measure of the fraction of the period of a repetitive phenomenon, measured with respect to some distinguishable feature of the phenomenon itself.” In PMU terminology, phase has two meanings. It may be the entire argument of the cosine in the equation $v(t) = Vcos(2\pi ft + \varphi)$, so that the derivative of the phase is the frequency. The word is also used to describe φ alone. This is the parameter the PMU measures as the difference between the signal being observed and a reference wave. The value returned is the principle value, the one closest to the time $t = 0$. This phase wrap is defined on the interval $(-\pi, \pi]$ (in radians), meaning its value includes –180° but not +180°. Unwrapped phase plots can go significantly outside of this range.

Pulse per second (PPS) – A pulse that is created once every second. Some utility timing applications use PPS.

Synchronization – "The relative adjustment of two or more frequency sources with the purpose of cancelling their frequency differences but not necessarily their phase difference." Outside the ITU-R Glossary, synchronization means that devices are coordinated to operate in unison using time propagation means such as GPS.

TAI – "The time-scale established and maintained by the BIPM on the basis of data from atomic clocks operating in a number of establishments around the world. Its epoch was set so that TAI was in approximate agreement with UT1 on 1 January 1958." International Atomic Time (TAI) is a coordinated atomic time scale based on the SI second. TAI is defined in ITU-R TF.460-6.

Time Interval Error – "TIE is a measure of wander and is expressed in units of time. It is defined as the phase difference between the signal being measured and a reference clock. TIE is conventionally set to zero at the beginning of a total measurement period and therefore is a measure of the phase change since the measurement began." Wander and TIE are characteristics of a clock, and the measurement referred to on this definition is one performed when characterizing a clock. The PMU standard IEEE C37.118.1 has no specific requirements on TIE. The maximum TIE for a PMU probably should be specified, since the device is applying time-stamps to reported measurement results.

Time-stamp – "An unambiguous time code value registered to a particular event using a specified clock." Most PMUs in North American time-stamp their measurements using GPS as the time transfer method.

Time synchronization – The coordination of disparate events according to time in order to operate a system in unison, and track comparable data and events based on consistent time-based records. This often requires either the availability of consistent, accurate, widely distributed clocks and/or the transport of physical timing signals such as those delivered by GNSS timekeeping systems.

Time transfer – A scheme where multiple sites share a precise reference time, often accurate down to one nanosecond. One-way time transfer systems may suffer from propagation delays on the communication channel, which apply to radio clock signals such as LORAN and GPS. This requires compensation at the receiving point to maintain consistency relative to the source time, requiring calibration for precision or accurate estimation. Two-way time transfer systems such as NTP (Network Time Protocol) use two peer clocks transmitting and receiving timing messages to enable precise determination of the difference between the source and local clock to correct the round-trip signal delay. The precision and stability achieved depend on the noise of measurements and signal path, which can be significant for particular applications.

Traceability – "The property of the result of a measurement or the value of a standard whereby it can be related to stated reference, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties." PMU measurements should be traceable to a specific time propagation source.

Universal Time – "Universal time is a measure of time that conforms, within a close approximation, to the mean diurnal motion of the sun as observed on the prime meridian.

UT is formally defined by a mathematical formula as a function of Greenwich mean sidereal time."

UTC (Coordinated Universal Time) – "The time-scale maintained by the *Bureau Internationale des Poids et Mesures* (BIPM) and the International Earth Rotation & Reference Systems Service, which forms the basis of a coordinated dissemination of standard frequencies and time signals." UTC was chosen as the abbreviation specifically because it is neither the French *Temps Universel Coordonné*, nor the English *Universal Coordinated Time.* It is the primary time standard by which the world regulates clocks and time. UTC is defined by the International Telecommunications Union Radio (ITU-R) Recommendation TF.460-6. It is based on TAI and has leap seconds inserted as necessary to keep time consistent with the slowing of the Earth's rotation, leap second insertions are decided by the International Earth Rotation and Reference Systems Service (IERS) and announced by IERS Bulletin C. UTC is close to, but no longer matches, GMT. UTC has replaced GMT and GMT usage is discouraged.

3.2 Timing measurement characteristics

Absolute time – Time that is measured and stamped against an international time scale such as UTC or TAI, delivered by a method such as GPS or NTP. When a PMU time-stamps a grid measurement using GPS, it is using absolute time as one of the descriptors for the grid conditions at the moment of measurement.

Accuracy – The definition in the Guide to the Expression of Uncertainty in Measurement (GUM) [Joint Committee, 2012] is "closeness of the agreement between the result of a measurement and the true value of the measurand." However, GUM discourages the use of "true value," at the same time giving it the following definition: "This is a value that would be obtained by a perfect measurement." A measurement system that has systematic bias will produce inaccurate measurements, and a clock that has drifted will yield inaccurate time signals.[10]

Coverage – The geographical area where timing signal delivery is feasible.

Differential accuracy – The capacity for the equipment to employ *differential* strategies. For instance, a differential GNSS approach relies on three elements: the GNSS satellite, a reference station at a known location, and a roving GPS receiver. This scheme allows the roving receiver to make an improved calculation using the GNSS signal together with a second signal from the known location through a difference calculation of the two signals.

Jitter – "The short-term phase variations of the significant instants of a timing signal from their ideal position in time (where short-term implies here that these variations are of frequency greater than or equal to 10 Hz)."

Precision – VIM [Joint Committee, 2008] defines precision as the "closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions." A measurement is precise if

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[10] It is worth noting that for many purposes, most utilities want their time signals to be accurate relative to local time (relative to UTC) rather than GPS or some absolute time.

repeated measurements under identical conditions produce the same result, i.e., it is repeatable and/or reproducible. A clock ensemble may yield precise yet inaccurate time signals.

Relative time – Many actions on the grid are timed relative to a triggering event such as a fault or lightning strike, rather than to absolute (synchronized) time. Relative time is calculated such that the zero point is when the initiating event occurred, rather than relative to synchronized UTC (or local) time. Relays may be time-synchronized using GPS (“absolute time”), but their job is to identify a triggering event, effect calculations about the event, and act to protect grid assets within a necessary time relative to the triggering event. A PMU may have an interval of time for which it considers the message delays acceptable relative to the arrival of a first message.

Resolution – “The smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.” In the case of grid measurements and timing, a millisecond (10^{-3} second) is a higher level of resolution than a microsecond (10^{-6} second) or a nanosecond (10^{-9} second).

3.3 Timing sources and systems

GNSS (Global Navigation Satellite System) – “Systems of satellites providing autonomous geo-spatial positioning and time/frequency recovery with global coverage, allowing receivers to determine their latitude, longitude, altitude and time using time signals transmitted line-of-sight by radio from the satellites.” Current GNSS include the United States’ GPS, European Union’s Galileo, Russia’s GLONASS, and China’s Beidou systems.

GPS (Global Positioning System) – GPS is the USA NAVSTAR GNSS system, which uses a network of typically 30 satellites (although only 24 are necessary to meet the specification) that transmit multiple microwave signals from which receivers can establish position, speed, and time to aid in PNT. GPS is operated by the United States government as a public service. The GPS system issues open civilian signals as well as encrypted military signals. Good GPS receivers enable improved stability and precision in addition to improved resilience.

Master clock – A highly accurate clock that obtains and maintains time information from an external time source, such as GPS or radio time broadcasts. The master clock shares these time signals with client slave clocks across a communications network, enabling time synchronization and consistent time-stamps within the network.

Network time server – A network device that synchronizes its internal system time to an external time source, and distributes that time to clients across a computer network using NTP.

NTP (Network Time Protocol) – “The network time protocol is used to synchronize the time of a computer client or server to another server or reference time source, such as a terrestrial or satellite broadcast service or modem. NTP provides distributed time accuracies on the order of one millisecond on local area networks (LANs) and tens of milliseconds on wide-area networks (WANs). NTP is widely used over the internet to synchronize network devices to national time references.” NTP uses a hierarchical, semi-layered system of time sources to synchronize servers to reference clocks. The current version, NTPv4, is documented in Internet Engineering Task Force (IETF) RFC 1305.

NTP server – An NTP server uses NTP to circulate accurate time information to sub-devices for synchronized time.

Oscillator – "An electronic device producing a repetitive electronic signal, usually a sine wave." Common oscillators use a quartz crystal or cesium as the oscillation source.

Reference clock – Another term for master clock, which uses a timekeeping standard or source to synchronize and regulate the accuracy of other clocks.

Signal delivery method – Also known as time transfer or time propagation. GPS and NTP are both time signal delivery methods.

Slave clock – A clock that is controlled by and connected to a master clock. There may be multiple slave clocks operating with the same time-stamp provided by a single master clock.

4. Power System Uses of Timing

The electric meters used for over a century have reported electric usage (kilowatt, kilovolt-ampere or kilowatt-hours) every 24 hours, while the time-of-use meters installed starting around 2011 report customer energy demand (kW) and consumption (kWh) at intervals of 15, 30, and 60 minutes. Clock accuracy errors can lead to billing and demand profile errors.

Starting in the 1960s and 70s, grid SCADA systems have monitored power systems at a rate of one report every four to six seconds. Historically, most power system timing uses have relied on relative time, because the task of devices such as line protection relays is to determine whether a problem exists and respond to it within a specific time period relative to some prior event, rather than absolute time (as linked to UTC or International Atomic Time [TAI]).

Figure 8 shows some of the key power system timing uses in relative terms.

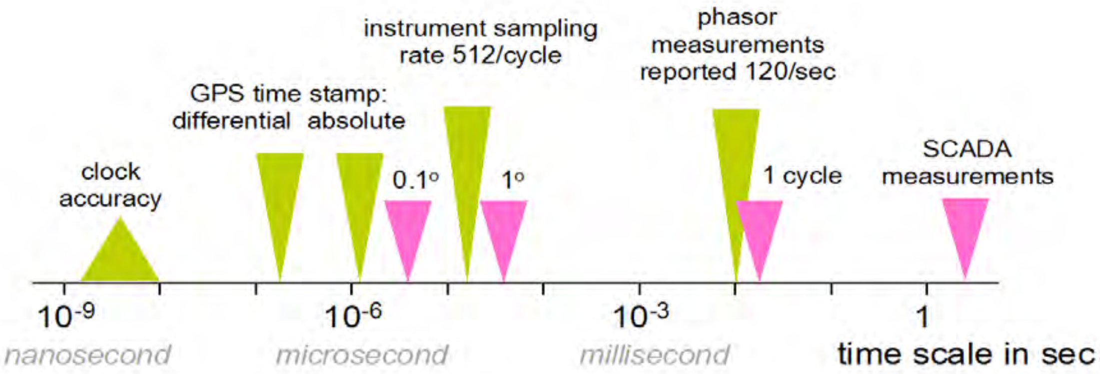

Figure 8. Time and power measurement resolution [von Meier 2017]

Four relatively recent technology advancements have made synchrophasor technology possible: the emergence of widely distributed, sufficiently accurate UTC through GPS; high-speed communications networks; growing data storage and handling capabilities; and advanced data processing and analytics capabilities. Synchrophasor technology enables monitoring of the grid at 30 to 120 time-tagged samples per second – broadly, at least 100 times faster than SCADA – providing higher resolution insights into aberrant grid behavior. Since these reports must be time-aligned for effective meaning and analysis, this creates the power system's emerging need for reliable, accurate and precise timing sources.

4.1 Key grid timing uses

Most current uses of precise time on the electric transmission grid are in applications that do not affect grid security or reliability. This will likely change in the future as more applications use synchrophasor data for automatic control. Some of the more prominent uses of timing on the grid today are described below.

Relays are the workhorse devices used for power system protection. They monitor local grid conditions down to the microsecond and actuate control operations (including breaker operation) for line trips and other system protection measures. Although relays and system protection actions may be time-synchronized with GPS or SONET over fiber, they calculate time relative to some triggering event such as a fault – the point of protection schemes is to respond quickly (as by opening a line or isolating a power plant) to address a problem and protect assets.

PMUs do high-speed grid monitoring, time-synchronized to UTC with microsecond accuracy, and are used mostly at the transmission level. They now sample at 30 to 120 samples/sec; timing must be accurate within 1 µs. When timing delivery mechanisms become more reliable, synchrophasor technology can become a mission-critical tool.

Digital fault recorders (DFRs) and protective relays

Virtually all new substation equipment today accepts a time sync signal and uses it to time-stamp data. The data can be sequence of event type data where a logic bit or external contact input changes state and the device attaches a precise time-stamp to the state change information. In the following example a change of state of a circuit breaker is shown.

```
2017-02-19 17:56:22.561 CB 372 Open
2017-02-19 17:56:32.572 CB 372 Close
```

The time-stamp can also be applied to point on wave measurements. When microprocessor relays or DFRs detect a fault, they can record waveform data that includes the voltages and currents measured before, during, and after a fault. This precise time-stamp can be used to correlate events across a wide area. See Figure 9 for an example of time-stamped waveform data.

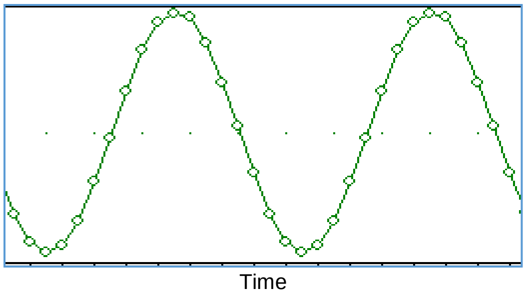

Figure 9. Each point on the waveform has an associated precise time-stamp (time-stamps indicated by green circles)

In virtually all cases, protective relays do not rely on precise time to make decisions to trip circuit breakers and clear faults from the system. Timing is used for recorded data so that post-mortem event analysis is simplified. There is a regulatory requirement (NERC PRC-002-2) that certain DFRs and/or relays have time synchronization that is accurate to within 2 milliseconds of the UTC time scale.

Lightning correlation

When faults occur on the transmission lines, it is helpful to the utility to know if the fault was caused by lightning. If lightning strikes a line or line support structure it can cause physical damage as well as an electrical fault. Often the line will trip for the lightning event and then reclose several seconds later and remain energized. However, there may be damage to the insulators or conductor due to the lightning strike. Because of this, it is a good idea to inspect in the area of the strike. There are companies that provide lightning data for a fee. These companies have sensors placed around a large geographical area and can detect the location, intensity, and polarity of lightning strikes. The strikes are time-stamped to one millisecond or better and utilities can compare the strike data from the lightning service to the fault inception time measured from the point on wave time-stamps from DFRs or relays. This comparison gives the utility a good location to inspect as well as an idea of what to look for based on the magnitude of the strike. Accuracy to one millisecond with respect to absolute time is good enough for reliable lightning correlations.

Traveling wave fault location

Traveling wave fault location is a method of locating faults on transmission lines that is independent of voltage, current, and line impedance. This method is based on the principle that a traveling wave is generated at the point of the fault. The voltage collapse at the fault creates a high-frequency pulse that travels down the transmission line at nearly the speed of light. The arrival time of this pulse is measured at each end of the line. With a precise arrival time, usually time-stamped to 0.1 microseconds, the fault location can be determined within a few hundred feet. This method requires very accurate relative time at each terminal that measures the wave arrival time.

Synchrophasor data

Synchrophasor data consists of time-stamped voltage and current vector values sent very quickly to an operating center, typically 30 to 120 samples per second. Data from many stations are sent to a centralized PDC, and the PDC can compare readings from across the grid. These comparisons can give power system operators and engineers a near real time indication of the health of the grid. This same data can be used to provide inputs to wide area control systems that can make decisions and initiate control actions. When the data is used to provide automatic control actions, the accurate, reliable, and secure timing is essential. This data requires an absolute time accuracy of 1 microsecond. Section 2 of this document explains synchrophasor data and its uses in greater detail.

Power quality monitors

Power quality monitors are most often used on the distribution system to monitor the power that is delivered to customers. If a customer is having issues with their power, then having time-synced data can help the utility correlate events with the customer's measurements as well as events possibly recorded from multiple PQ monitors. It is also possible for transmission-level events to create voltage problems on the distribution system. In this case, have time-synced data from the PQ monitors makes it easy to correlate with the events recorded from the transmission DFRs or protective relays.

SCADA measurements

SCADA measurements provide data to grid operators about the condition and state of equipment in the field. Breaker status (open or closed), transformer temperature readings, voltage, current, and power measurements all come to the operators via the SCADA system. The data that is sent to the operators can be time-stamped so that the actual time of the event is known, as opposed to the time that the reading arrived at the operating center. The scan time of SCADA systems can be anywhere from one or two seconds to 10 seconds or more. A lot can happen between scans, so it is helpful to know the time of each of the events, rather than the time the data arrived. The accuracy requirement will vary depending on the source of the data in the field; breaker operation times need better accuracy than a temperature alarm, for example.

4.2 Grid application timing requirements

A key issue for grid timing applications is, given how quickly electricity moves and how quickly the grid can fall apart, how sensitive a specific application needs to be – and therefore its timing source needs to be – to effectively address and achieve its intended purpose.

Figure 10 illustrates why high-frequency sampling of a grid event enables the measurement device to capture transient events, by showing daily generation from a 2.5 MW solar photovoltaic plant for three specific days with varying insolation patterns. The slower measurements from daily meter data show limited variations in power output, while the high-speed PMU data reveal significant, frequent changes in output on days that appeared more stable from the metered measurements.

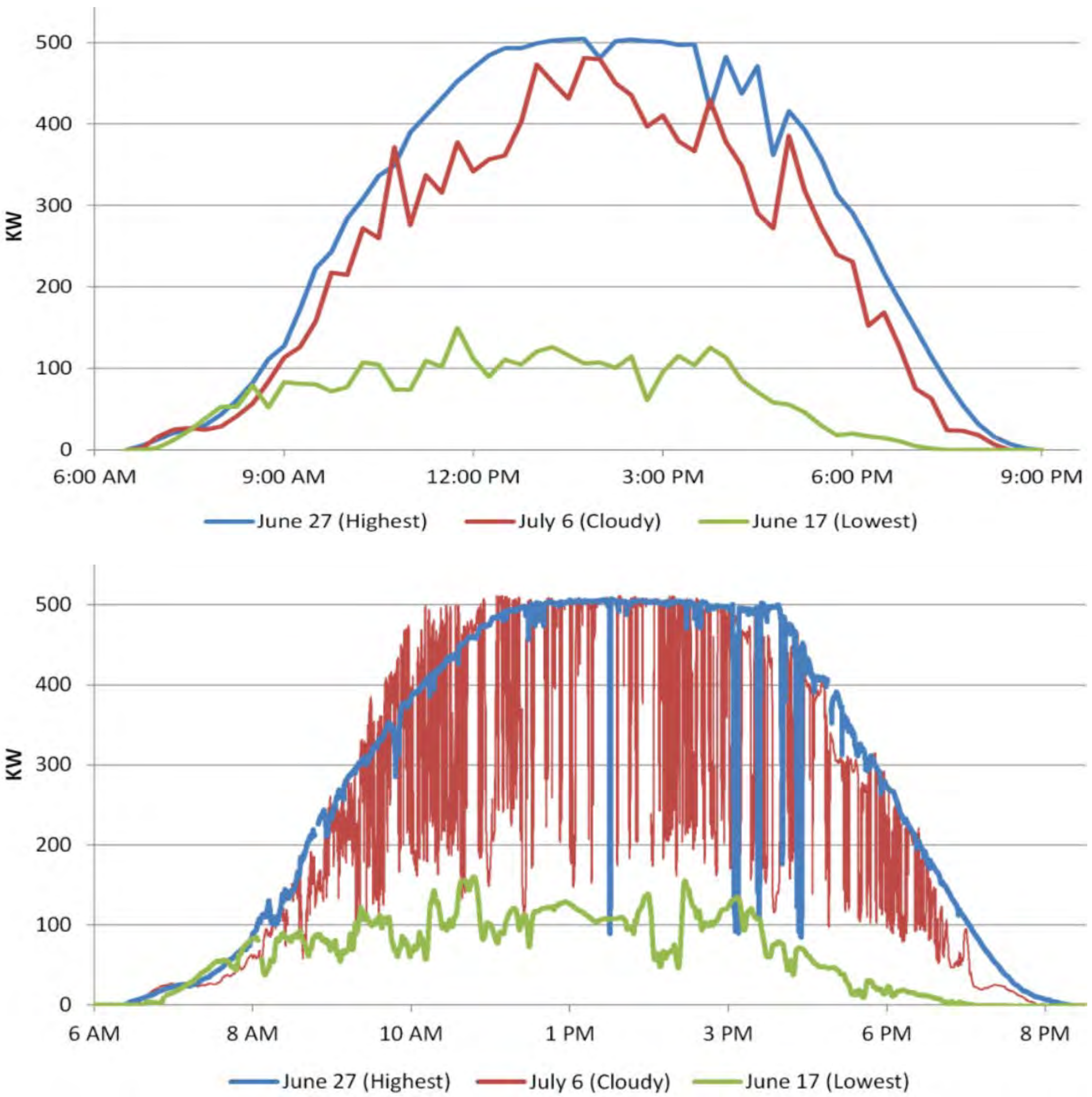

Figure 10. Photovoltaic production comparison, Mustang 2.5 MW PV plant. Top graph = meter data, bottom graph = PMU data [White, Oklahoma Gas & Electric, 2016].

These high sampling speeds enable unprecedented identification and analysis of local and inter-area oscillations, as well as rapidly changing conditions. Oscillations on the system can lead to preliminary equipment failure, or even contribute to a large-scale blackout, as occurred on August 10, 1996 [WSCC 1996]. The ability to capture and analyze these oscillations, as well as changing conditions associated with intermittent renewable and distribution generation, enables the grid to detect transient system events and respond dynamically for more efficient and reliable operations. The ability to rapidly detect and take remedial actions in the presence of dynamically varying generation sources and loads is especially pertinent in evolving energy distribution from a centralized system to a more economical and energy efficient localized, mesh network of systems, capable of bi-directional power flow.

Table 2 lists some of the dominant grid timing uses and their timing requirements. Some of these applications are discussed in further detail below this table, explaining why specific time resolution levels are required for different applications. Most of these requirements have been incorporated into industry requirements and technical interoperability standards such as IEEE C37-118.1 (Standard for Synchrophasor Measurements for Power Systems) and IEC/IEEE 61850 (Electric Substation Automation standards). The requirements are also part of system reliability standards such as North American Electric Reliability Corporation (NERC) PRC-002-2 for disturbance monitoring and reporting.

Table 2. Power system uses of time-dependent data

Grid application	Timing requirements (minimum reporting resolution and accuracy relative to UTC)
Advanced time-of-use meters	15, 30, and 60 minute intervals are commonly specified (ANSI C12.1)
Non-TOU meters	Ongoing, with monthly reads or estimates
SCADA	Every 4-6 seconds reporting rate
Sequence of events recorder	50 µs to 2 ms
Digital fault recorder	50 µs to 1 ms
Protective relays	1 ms or better
Synchrophasor/phasor measurement unit (30 - 120 samples/second)	Better than 1 µs 30 to 120 Hz
Traveling wave fault location	100 ns
Micro-PMUs (sample at 512 samples/cycle)	Better than 1 µs
Communications protocols	
Substation local area network communication protocols (IEC 61850 GOOSE)	100 µs to 1 ms synchronization
Substation LANs (IEC 61850 Sample Values)	1 µs

4.3 Problems with current precision time delivery

Synchrophasor data are time sensitive, and must be time-stamped accurately and delivered swiftly, which in turn requires PMUs to have UTC delivered to them accurately and reliably. A real-time UTC(x) signal comes from a laboratory (x), generally a national lab, that participates directly with the International Bureau of Weights and Measures (*Bureau International des Poids et Mesures* – BIPM) in generating UTC. Each participating lab generates its realization of UTC in terms of its UTC(x), and then reports its clocks and observations of other labs to BIPM.[11] Similarly, any GNSS receiver will have a local approximation of the actual UTC, but often to a precision sufficient for PMU usage rather than perfect, actual UTC.

Legal traceability of a time source requires traceability to a recognized lab. No GNSS receiver achieves true traceability on its own. The user should understand that even receivers with good stability and precision do not automatically provide traceability to TAI or UTC time-scales, but only provide good uncalibrated time without traceability. Some clock manufacturers test their devices against the clock in a recognized lab to verify the traceability of timing signals against a trusted absolute time scale. In the field, traceability can be provided using a calibrated combined antenna, antenna cable, and receiver system, though the calibration of any such system degrades with time.

Delivery of accurate time is at odds with typical communications systems, as accurate time delivery requires compensation for network delays (which include transmission delay, propagation delay, queuing delay, and processing delay), and correction of network asymmetry. Asymmetry in using a two-way time transfer protocol such as NTP or Precision Time Protocol (PTP) can result in a constant bias in the time transfer value that can only be measured with an independent time transfer system. The most common means of time distribution that is able to synchronize to the IEEE C37.118 requirement of 1 μs is via GNSS; GPS is the primary constellation used in North America for acquiring traceable UTC time. GPS and other GNSS deliver UTC by predicting the time of the satellite clocks and the signal propagation delays from the satellites to the receiver and adjusting for the predicted delays.

PMUs can have an integrated GNSS receiver or rely on other time signals, most commonly IRIG-B with IEEE C37.118.1 extensions or 1 pulse per second (PPS) with Time of Day information. Clocks providing the time signal output typically rely on GPS to receive UTC time. There can be anomalies of various types in these operations ranging from unintentional errors, receiver configuration or antenna installation, and sources of interference to manipulation denying the system of the correct time signals. In addition, the delays incurred from the receiver time, to the hardware clock and the actual time-stamp event of the synchrophasor must be taken into account as sources of time uncertainty.

Timing errors from the time source – or between the time source and the point of time-stamping – can create incorrect synchrophasor data, and lead to missing data and/or the failure to create data frames. The failure to deliver data to concentrators and applications within acceptable latency periods causes data gaps that could obscure early warning information about dynamic grid conditions. Data from offline testing and from actual field experience with the 2015 leap second[12] and the 2016 GPS UTC transmission error[13] show that such events cause real PMU data errors. Such errors can create false analytical conclusions, and in the future could drive

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[11] None of these labs have the actual UTC, since it is a post-processed time scale, but they each have a prediction of UTC. The most accurate labs typically stay within 10 ns of true UTC.

[12] See Silverstein, Alison, "Leap Second Effects on Synchrophasor Systems – Recent Leap Second Experiences," *NASPI Technical Report NASPI-2016-TR-008* (November 2016).

[13] Divis, Dee Ann, "GPS Glitch Caused Outages, Fueled Arguments for Backup," *Inside GNSS News* (January 29, 2016),

undesirable and possibly dangerous automated grid operations with synchrophasor-based controls.

Although the GNSS systems have high reliability and integrity, anomalous timing events such as leap second insertions have created synchrophasor data quality problems. While the electric industry is not the only sector and user group affected by such problems, it will be necessary to find ways to eliminate or mitigate the adverse impact of timing delivery problems before synchrophasor technology can be used with confidence for mission-critical grid operations.

Given the potential vulnerability to intentional and unintentional failures in GPS, synchrophasor and other precision timing-dependent systems should use multiple timing sources to improve timing redundancy and reliability. With the trend of Ethernet-based measurement and automation systems in the power grid, the electric industry is beginning to integrate network-based time protocols, such as the IEEE 1588-2008 Precision Time Protocol (PTP) with the IEEE C37.238 PTP Profile for Power Systems and IEC 61850-9-3 PTP Profile for Utility Automation. The industry is also applying and experimenting with the ITU-T PTP Telecommunications Profiles for wide-area clock synchronization. PTP is a two-way, packet-based time distribution protocol that transmits packets both from and to the master. This makes it possible to cancel the networking delay from the master clock, assuming the symmetry of the delay (i.e., that the delay is approximately the same in both directions). However, there are a number of sources of error, most notably asymmetry of the delay and packet delay variation (PDV).

Other sources of satellite and ground-based radio propagation methods, such as eLORAN and LORAN-C, are also being explored. An industry test is planned in early 2017 of how eLORAN performs in noisy substation environments.

In addition to time synchronization, industry synchrophasor communication standards such as IEEE C37.118.1-2011 and IEEE 1588 PTP Power Profiles, IEC 61850-9-3 and the current draft of IEEE C37.238 revision, all require and/or communicate a time uncertainty. Dynamic measurements of time uncertainty can be a challenge in a network environment, but are necessary in making accurate phasor representation estimates and understanding the confidence of the estimates when used in downstream applications.

As in many cyber-physical systems (CPS), data in the smart grid must be delivered in a timely manner, i.e., the *latency* of the data must meet requirements for operation. For managing latency, the delay through networks provides a different challenge than for synchronization. In most cases, the latency must meet a *not-to-exceed* specification. While timeliness is different from synchronization, verifying the latency requirements over distributed systems requires synchronized clocks in order to minimize the contribution of clock uncertainty on the latency measurement error. There are cases where it is advantageous for latency to be further managed, such as for the value of the latency to be predictable, for applications having a critical dependence on the transmission of measurement and control commands. Thus, latency predictability can be used to help verify the integrity of the communications, as well as invoke local control actions on the grid to prevent a data delay or drop from causing a larger outage.

4.4 Consequences of incorrect time-stamps and late-arriving data

Timing errors cause false conclusions about grid conditions, which may lead to the misdiagnosis of system problems, incorrect responses to address those problems, and shutdown or mis-operation of grid assets. The Bonneville Power Administration reports that in one instance, "A bad GPS signal and cheap receiver led to the loss of two 500 kV lines, one 40 miles, the other 80 miles long."[14] Whether incorrect time-stamps are caused by errors such as a clock problem (as has occurred from leap second events) or from spoofing or jamming, incorrect time-stamps can cause a variety of problems for synchrophasor data analysis, including:

- Data that is time-stamped incorrectly in the PMU may be flagged as having an erroneous time-stamp and dropped from the data stream used for analysis. If there are too many dropped or lost data points, the application may be less effective and trustworthy.
- If data with an incorrect time-stamp is not flagged as erroneous, it may have the same time-stamp as a correct data point, in which case the PDC may drop both data points as erroneous or choke on a buffer overload from too many time-stamps reported for the same instant for the same channel and PMU. If the PDC chokes, it will stop feeding data to the application, which may lose the ability to operate.
- If data with an incorrect time-stamp is synchronized with data that actually characterizes a different time and grid condition, then the application will produce incorrect results – this has been observed in connection with leap second events.
- PMU data that are delayed by excessive latency (slow delivery) to a PDC and application may be dropped by the PDC because of late arrival, and not aggregated and delivered to the application for analysis.

Many of the situations above have been demonstrated in PMUs and PDC handling of the 2015 and 2016 leap second events.[15] For instance, ISO New England reported that none of the online streaming PMUs in its system applied the 2015 leap second properly, taking from one sample to one full second to add the leap second. The resulting erroneous time-stamps caused calculated phase angles to bounce back and forth, and angle data were not correct until all PMUs had applied the leap second correctly.[16] Similar occurrences have caused more than one utility to freeze its synchrophasor applications until it could verify that all of its PMUs and PDCs were receiving correct clock signals and that all of the incoming time-stamps were accurate.[17]

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[14] Aaron Martin, BPA, comments at the NIST-IEEE Timing Challenges in the Smart Grid workshop, quoted in the Resilient Navigation & Timing Foundation blog (October 27, 2016), at http://rntfnd.org/2016/10/27/timing-smart-grid-quotes-fm-nist-workshop/. Martin's presentation is located at https://www.nist.gov/sites/default/files/documents/2016/11/02/02_martin_timing_needs_for_power_industry_final.pdf. In this case, the Air Force was testing the GPS satellite, causing the broadcast of bad GPS data which caused BPA to respond to an erroneous line current differential reading. BPA is now tracking planned GPS testing, using GPS receivers that detect test modes, and using different methods and thresholds to monitor differential phase.

[15] Silverstein, Alison, "Leap Second Effects on Synchrophasor Systems – Recent Leap Second Experiences," *NASPI Technical Report NASPI-2016-TR-008*, November 2016

[16] Zhang, Frankie Quang et al., "Leap Second Report Summary and Recommendations," ISO New England, October 19, 2015, and P.K. Agarwal, H. K. Rathour et al., "Encounter with Leap Second – Experience in Indian WAMS," NASPI International Synchrophasor Symposium, March 23, 2016.

[17] Silverstein, "Leap Second Effects on Synchrophasor Systems," op. cit.

5. Alternative Timing Sources and Options

This section surveys and explains the available and emerging timing options (such as GNSS, network, and local clocks) and indicates which are suitable for meeting expected synchrophasor timing and security requirements.

This addresses two closely related topics, as screening and explaining how existing and emerging timing options suit timing and security requirements requires specifying both current and anticipated timing and security requirements. Section 4.1 covers synchrophasor timing and security requirements (a 5 to10 year time horizon into the future) and Section 4.2 describes whether the available and emerging timing options can meet those future requirements

5.1 Timing source considerations and requirements

Timing sources suitable to feed time signals to PMUs must be accurate enough to meet the PMU's timing performance standards, be able to deliver the signal to a widely distributed set of PMUs, and must be reliable and secure. Many of the synchrophasor systems today use satellite clocks, accessing a GNSS, as their timing source. Satellite clocks used in the electric utility sector consist of several components, and understanding how these components work and interact is helpful to understand how best to interpret timing.

The clocks consist of a GPS receiver chip that interfaces with custom electronics and an oscillator to generate the precise time. The GPS receiver chip is usually manufactured by a GPS specialty company. The output of the chip is then fed into the clock components to be translated in accordance with clock settings. As shown in Figure 11, substation clocks interpret the GPS signal, convert it into various protocols (such as IRIG-B, NTP, PTP or PPS) that can be used inside the substation, and deliver the time signal to various uses within the substation. It is important to understand that *the GPS receiver has a distinct firmware that is separate from the firmware used by the electronics that decode the GPS receiver's output*. While these two pieces of software work in conjunction with each other, they are independent software provided by separate entities, and are not always designed, implemented and tested to be fully interoperable under all circumstances.

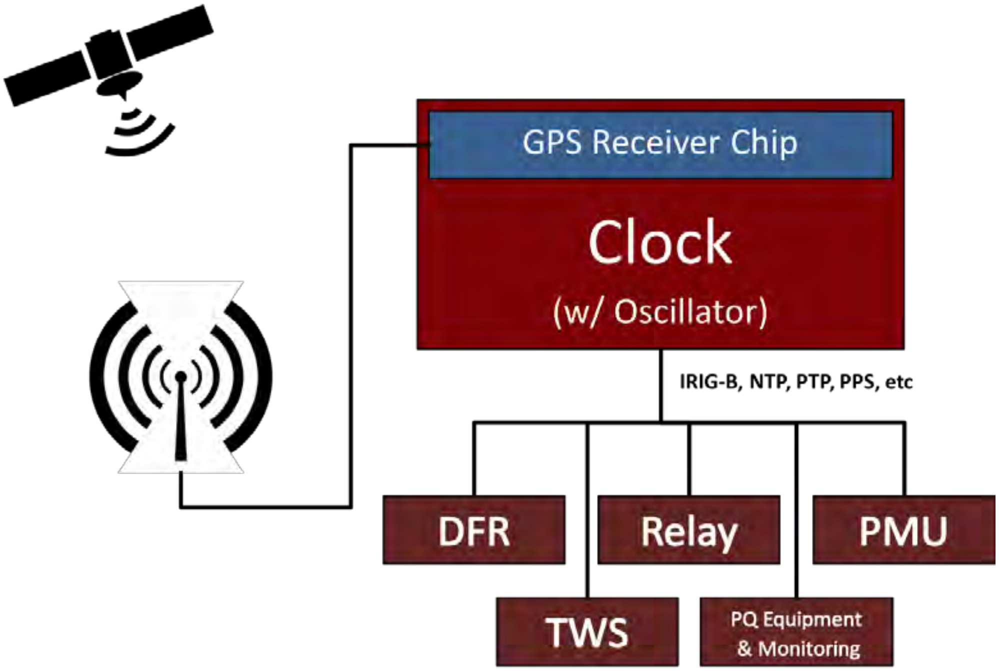

Figure 11. Schematic of GPS clock in a substation [Orndorff]

5.2 Timing systems and characteristics

Relevant timing system characteristics include:

- **Coverage** – This addresses how broadly the timing signal can be distributed from the point of origination, and whether there are any geographically or technologically caused points that the signal cannot reach. Most of the timing distribution services reviewed here are intended to cover North America.
- **Accuracy** – Accuracy refers to the closeness of the time signal distributed to the absolute or perfect time. It can be characterized in terms of an uncertainty bound from a time source (e.g., ± 1.0 µs from UTC). If the time signal comes from a biased source, or from a clock that has drifted, it will distribute inaccurate time signals.[18]
- **Signal delivery method** – Signal distribution methods include wired (as from a network-distributed time), wireless (as from satellites or terrestrial transmitters), or clocks located within or next to the point of timing use.
- **Stability** – Timing stability refers to an oscillator's skew from a reference oscillator. Skew may be non-linear and non-monotonic.
- **Comparative reliability** – This includes three aspects: **R** (Reliability, or the ability of the component to consistently perform according to its specifications); **A** (Availability, or the ability of the component to avoid downtime); and **S** (Serviceability, or the ability to easily maintain and repair the component).

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[18] IEEE standard C37.118.1-2011, which defines the standard for PMUs, directs that the total error associated with measurements must fall within a tolerance of ±26 µs with a recommended accuracy of 2.6 µs.

- **Susceptibility to interference, jamming, and spoofing** – See Section 6.2 below for reasons why false or missing timing signals can harm PMU effectiveness.

Table 3 summarizes key information about the principal sources of precision timing signals, including GNSS, eLoran, NIST's WWVB, public telecommunications networks using optical transport networks (OTN, including SONET), and the Iridium satellite time service from Satelles. Those time sources are discussed below.

Table 3. Summary of Timing Source Characteristics

	Accuracy	Coverage	Signal delivery method	Notes
GNSS	60 – 80 ns	Worldwide	Wireless / satellite	Includes GPS, Galileo, GLONASS & Beidou; often used as primary timing source.
eLoran	± 1 µs (± 100 ns if 71 stations)	Transmitters at Dana, IN Wildwood, NJ Boise City, OK Fallon, NV (1MW for Lower 48 states)	Wireless / terrestrial tower	Same timing source as GPS (Stratum-1). Can provide timing for 70-90 days without an external reference, completely independent of satellites. When integrated with GNSS, can provide "Trusted Time and Frequency". eLoran signals can penetrate deep inside buildings, underground, and to some distance under water.
NIST WWVB	100 µs if disciplined with GPS	Transmitter in Fort Collins, CO. (100 µV/m over most of the continental United States and Southern Canada during some portion of the day)[19] Differential accuracy 1 µs over 80 km	Wireless / terrestrial tower	Makes good hold-over source if sufficient signal. Good penetration of buildings, can hold-over if local GNSS is lost.
Optical Transport Network (OTN)	Frequency accuracy of optical channel transmitter clock is ± 20 ppm[20]	Typical residential and commercial coverage provided through public telecom network	Wired	Provided via multiple standards including SONET, 10 Gbit Ethernet, Fibre Channel, and 100 Gbit Ethernet.
Iridium STL	100 ns (differential accuracy 50 ns)	Worldwide	Iridium satellite	Robust capability 30 dB gain over GPS. In development by US DHS as alternative for GPS.

A GNSS provides PNT service by transmission of signals from a constellation of satellites orbiting the Earth. For dynamic position and navigation, four or more satellites are needed; for

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[19] Source: https://en.wikipedia.org/wiki/WWVB .

[20] Source: http://www.ieee802.org/3/ae/public/mar01/garner_1_0301.pdf .

time-reception on a fixed location, a single received satellite is needed to maintain operation once the position has been averaged and locked. Multi-channel receivers are used to track as many signals as possible, allowing the excess of signals to eliminate false results and through that improve the precision and accuracy.[21]

Multiple GNSS exist, including:

- **GPS** – The Global Positioning System (GPS) or NAVSTAR is a U.S. GNSS for which the L1 C/A signal is the traditional civilian signal, as part of GPS Standard Performance Service (SPS). Keyed receivers also have access to the L1 and L2 P(Y) signals as part of GPS Precision Performance Service (PPS). Modernized GPS also provide L2C and L5 signals for civilian use and the new M code on L1 and L2 for military use. Precision receivers can utilize the L1 and L2 P(Y) signals in pseudo-codeless form, which is used for surveying purposes and precision navigation.
- **GLONASS** – The GLONASS system is a Russian GNSS for which the L1 signal is the traditional civilian signal. Military/precision receivers also use the L1 and L2 precision signal.
- **GALILEO** – The GALILEO system is a European system providing a large set of services, among those open service and Public Regulated Service (PRS) which is encrypted but provides a verified timing service.
- **BEIDOU** – The Beidou system is a Chinese system providing civilian and military signals, including a regional satellite based augmentation system (SBAS) enhancement.

Efforts have been made to ensure that the GNSS signals, and in particular new GNSS signals, are complementary such that users can rely upon multiple GNSS signals and switch between GNSS sources if one fails. GPS- and GLONASS-capable receivers are starting to be relatively commonplace, and several are now GALILEO and BEIDOU ready.

Since there can be several error sources in the accuracy of PNT, several means to augment them have been developed. Differential GPS (DGPS) provides correction over short distances by transmission of corrections, often for naval use, using transmitters on 300 kHz frequency. Larger areas are covered with SBAS such as the Wide Area Augmentation System (WAAS) for North America and EGNOS for Europe. Finer networks of receivers are used to support survey measurements.

eLORAN: (Enhanced Long Range Navigation) is a low frequency (100 kHz) terrestrial PNT system whose signals are generated from one or more transmitters that can operate independently, in a sovereign network, or across borders. This system is currently not operational in North America, but is under study. eLoran signals are easily received at distances of 800 or more miles from the transmission source on land, and over 1200 miles at sea. The current technology is a significant evolutionary improvement over various predecessor Loran systems, including Loran-A, -B, -C, and -D. eLoran can coexist with Loran-C or -D, as well as its Russian equivalent, Chayka. Besides timing, time-of-day, and frequency, eLoran provides positioning, azimuth/heading, and one or more low-rate Loran Data Channels (LDC). eLoran has built-in

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[21] The RAIM and T-RAIM are sets of algorithms that improve the result.

integrity, and its base signal and/or data channel(s) can be encrypted. eLoran PNT can be augmented with differential capability or hyperfine additional secondary factor (ASF) surveys that improve positioning and timing accuracies within a pre-defined region. eLoran can provide UTC time, though the accuracy is strongly dependent on the distance from the transmitter, or from an ASF station, as well as on environmental factors. Differential signals are broadcast on one or more of the LDCs alongside the primary PNT signal.

WWVB: The NIST radio station WWVB transmits at a very low frequency (VLF) of 60 kHz and effectively distributes standard time information to about ± 100 microseconds throughout the North American continent. If WWVB stations are co-located with GNSS, WWVB can be used differentially if GNSS is lost over about 80 km to about 1 microsecond. NIST has proposed a "differential WWVB" ground-based radio signal system with broadcast beacons capable of propagation accuracy similar to GNSS.[22]

Other VLF time standard transmitting sites are in the Far East (JJY in Japan)) and Europe (MSF in the United Kingdom). NIST WWV also transmits time information in the high-frequency (HF) radio spectrum. Devices that use WWVB as a timing source need a dedicated receiver to pick up the WWVB signal. The lack of inherent delay compensation requires calibration to improve phase accuracy. Variation in propagation delay is usually a limit to achieved precision.

Public Telecom OTN: The low-level protocol called the Optical Transport Network (OTN) on a public telecom network has been shown to have a stability of under 100 ns indefinitely, if the circuit is not interrupted. This can deliver UTC directly from NIST, assuming a direct link to NIST. If there is a method to calibrate it, the circuit can maintain accuracy under 100 ns. This could work well as a back-up timing source if GNSS were available most of the time.

Iridium: Iridium is a global constellation of 66 cross-linked Low Earth Orbit (LEO) satellites that provide voice and data connections over the planet's entire surface, including oceans and polar regions. Each satellite can project 48 spot beams approximately 250 miles in diameter onto the Earth's surface. All spot beams and satellite footprints overlap, with the satellite's full 48-beam footprint approximately 2,800 miles in diameter. A time service is available from a company alliance between Satelles and Orolia, with accuracy specified at ± 500 ns, though ± 200 ns is typical.[23]

5.3 Oscillators and clocks

Oscillators lie at the core of all clocks. Oscillators only provide a frequency, a counter needs to be added to measure time, but this counter mechanism needs to be set to a common reference to reflect some time, such as time of day. Since effectively all oscillators have frequency errors and frequency drift, after setting the clock the time of the clock will start to deviate from that of the reference. The relative frequency error will tell how much it deviates per second. Further, a frequency drift mechanism provides a parabolic deviation away in phase, which starts to dominate for longer times.

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[22] See Weiss, Marc, "Time Distribution: Current Technologies and Future Visions," presented at NIST/IEEE Timing Challenges for the Smart Grid workshop (October 26, 2016).

[23] http://rntfnd.org/2017/02/08/more-time-from-the-sky-orolia-and-satelles.

To make a local clock represent the reference time, a control loop is set up to keep the time of the local clock in close agreement with that of the reference. This requires cancellation of the clock's frequency error and phase error. A free-running clock is a clock which has never been (accurately) set to that of a time-scale such as UTC. An oscillator that does not have a control loop is free-running; its time is not related to any useful time, and its frequency can also be off (within limits).

A hold-over clock is a clock that maintains the phase (and time) over some period of time. A hold-over clock can be installed within a device or substation to provide frequency information when the device has lost its disciplining reference (as when the device temporarily loses access to GNSS signals).

Depending on the performance of the clock, maintaining the phase within some limits can be done for variable periods of time. A poor clock will quickly drift away while a good clock can maintain phase for days. When a clock has been operating for too long in hold-over, one can treat it as a poorly set free-running clock, that will give time but not be accurately coordinated with the time-scale. Timing performance and hold-over requirements depend on the needs of the system. For the PMU, the classical limit for 60 Hz is ± 26 μs, but other systems may need tighter limits.

Clock performance varies with price – the better the clock, the higher the price. To hold down costs, many substations will use a common clock to provide good hold-over performance for many timing uses within that substation. Only a few locations can afford the long-term high-stability clocks, but the proliferation of GPS/GNSS receivers have made it less necessary for users to install independent high-stability clocks.

A so-called "GPS clock" is actually a GPS-Disciplined Oscillator (GPSDO), which is not an independent clock but receives a time signal from GPS.[24] The main time service provided is UTC, but even when locked to the UTC of a GNSS receiver, the clock is neither calibrated nor traceable to UTC in a formal metrology sense. Rather, it is adjusted to a source which attempts to approximate UTC. This approximation of UTC is good enough for many operational purposes, if the system has been calibrated.

The simplest of oscillators is the crystal oscillator, which is used for a diverse range of purposes in equipment, including CPU clocks, real-time clocks (RTC), etc. For most of these uses, precision needs are relatively relaxed, allowing the use of relatively inexpensive timing components. More demanding timing purposes require better oscillators such as temperature-compensated crystal oscillators (TCXO) and oven-compensated crystal oscillators (OCXO). Typical GPSDO/GNSSDO use one or two OCXO options to fit different needs.

Rubidium oscillators are a more stable option. As packaged for telecom uses, these are small packages with good stability for its size, power consumption, and cost. Typical GPSDO/GNSSDO can use a rubidium clock as a high-end oscillator option.

High-end oscillators such as cesium beam and hydrogen maser have even higher cost, size, and power, but they provide excellent performance for longer time periods. These are primarily used

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[24] Now that additional GNSS signals are used, they can be referred to as GNSS Disciplined Oscillator (GNSSDO).

as master clocks in National Metrology Institutes (NMI), science set-ups such as radio-observatories doing Very Long Base Interferometry (VLBI), and as references for telecommunication networks. The proliferation of much cheaper GPSDOs have replaced cesium oscillators in telecommunications, and enabled both frequency coordination and phase coordination.

Table 4 compares the frequency instability and therefore the drift from reference time of several oscillators that are used to provide hold-over timing in power and telecommunications systems.

Table 4. Comparison of frequency instability and unit cost for several oscillators [Marc Weiss, NIST]

	Temperature-controlled crystal oscillator (TCXO)	**Oven-controlled crystal oscillator (OCXO)**	**Rubidium oscillator (5E- 12/mo. aging)**
Length of time holding a microsecond	10 minutes to 1 hour	1 to 8 hours	8 hours to 3 days
Cost range/oscillator	\$5-25	\$50-150	\$500-1,500

Cesium Cell (e.g., CSAC): Chip Scale Atomic Clocks were developed from research at NIST. The CSAC is a stand-alone clock that can be built into a wide range of devices, used to provide relatively stable frequency and phase with low power consumption. This is a small (16 cm^3) device capable of ±5.0E-11 accuracy at shipment. At 5.0E-11 offset from UTC, it would drift 4 μs in one day. It is notable for remaining stable within a wide operating temperature range, which makes it more suitable than full-scale atomic clocks for deployment in less protected field environments. These differ from laboratory cesium clocks, but are essentially the same as a very compact rubidium oscillator, but with much lower performance. They compete with crystal oscillators.

Cesium Beam Tube (e.g., full-scale atomic clock set-up): This device uses cesium to provide a precise time source. It weighs under 70 lb and is a rack-mounted device approximately 5″ tall by 19″ wide (see Figure 12). Full-scale atomic clocks are generally deployed at laboratories, metrology institutes, and telecom frequency production.

Figure 12 -- A full scale atomic clock setup based on Cesium beam tube standard.

CSAC and atomic clocks are inherently only frequency generators. Some of these can be assigned clock phase, but that clock phase will drift away from the actual phase as result of the clock's frequency error compared to the time-scale. For a clock to reflect the UTC time-scale, it effectively needs to be tied to that time-scale, which is what is achieved with GNSS. However, a full-scale Cs beam tube can hold a microsecond for several months once it is synchronized. Ovenized crystal oscillators and rubidium clocks are routinely used for hold-over, and are better than CSAC, but consume more power than a CSAC device. A 5071A cesium clock is very stable, but it will also deviate away from the UTC time-scale.

Network-distributed time: Network-distributed time is usually fed UTC time from a GNSS receiver such as GPS or GLONASS. It is distributed across a communications system using the NTP or PTP protocols. The ability to achieve and maintain stability and phase accuracy across the user network depends on many parameters. NTP is typically used across the public Internet, where accuracy is greatly reduced by the lack of control. PTP is a more accurate time transfer system if the network has employed devices to control performance at the physical layer. The evolving Nimbra TT and White Rabbit time transfer protocols may prove to be valuable time distribution alternatives. White Rabbit is being generalized in a developing update of PTP to be used as a high-accuracy option.

5.4 Precision clock operation

The transmission of time from one clock to another is sensitive to the time delay for the message, but the average frequency is usually conserved for fixed locations. The delay shift can be compensated if the distance between the locations is known, and the medium is relatively stable. Delay compensation of WWVB, MSF, and DCF-77 is operated in such a fashion. Another method is to have position capability in the system, for which the position of the receiver becomes known and hence the delay can be compensated. Loran-C, GPS, and other GNSS use this method. A further method is to transmit signals in both directions and perform a two-way time and frequency transfer, in which the delay is canceled under the assumption it is the same in both directions (symmetric). This assumption is never perfect, leading to a time transfer error equal to half the asymmetry. TWTFST, NTP, PTP, White Rabbit, and DTM TT are examples of such techniques.

When the transmitter and receiver move in relationship to each other, the frequency is also shifted due to Doppler shift, something which is inherent to satellite transmission (thereby affecting all GNSS signals). Further relativistic effects cause shifts that need to be handled by the receiver. The signals and specifications for each GNSS contain information and algorithms for canceling these effects.

5.5 Network time distribution methods

For networks including NTP, PTP, White Rabbit, and DTM TT, messages are transmitted in either packet form or using repeating framed structures. NTP was originally conceived for coordinating the clocks of computers, fully implemented in software and running over Internet. The achieved accuracy depends on many parameters, including how well the computer works, the quality of the software time-stamping, network performance etc. PTP, as standardized by IEEE 1588, initially distinguished itself by introducing hardware time-stamping (now also available with NTP), but the PTP v2 standard also introduced means to compensate for asymmetry as each packet is delayed through equipment. White Rabbit extends PTP by replacing the basic time-stamping mechanism using Synchronous Ethernet (Sync-E) and high-resolution time-stampers, providing a much higher resolution on measurements and thus reduced noise. The DTM TT builds originally on the 8 kHz SDH/PDH framing for two-way time transfer, being able to use the high-resolution properties of SDH framing, but have since been extended to include packet timing and utilize the high packet rate of the data to remove packet noise over links with no special support. All methods have inherent sensitivity to asymmetric delay (which may or may not be compensated).

Most grid time-using devices use GPS as the timing source, and distribute time within the substation primarily using copper cabling (IRIG-B), with growing use of Ethernet (IEEE 1588). IRIG-B systems do not have any delay-compensation mechanism, because they should be used only to deliver time signals across short distances (the time delay is proportional to the length of the IRIG-B cable). Delay compensation techniques must be used for IRIG-B transmittals across longer distances.

Each time transfer system has a system clock that it uses in its transmission. This clock typically is not encoded in a format of everyday civilian time. Interpretation problems of the internal clock format causes problems for users – for instance, GPS uses a 1024 week cycle, so it must restart the week count at the end of that span. Further, the system clock may not be directly in the form of UTC, so that an offset to UTC may be present. Problems with the UTC offset, and in particular the introduction of leap seconds, can cause problems. Many of these problems can be avoided by careful design and testing. In particular, the IRIG-B format can be set to a specific time zone, so that it is UTC-shifted by the time-zone offset.[25] The shift in and out of Daylight Saving Time (DST) can also cause problems, similar to the leap second, hence particular care in design and testing is needed to avoid issues.

NTP – Network Time Protocol: NTP uses a hierarchical system of levels of clocks, with the highest level ("Stratum 0") considered the reference (in practice, typically atomic clocks or GPS clocks). A node in the network usually synchronizes its local clock against one or more clocks in the same stratum or the stratum one level higher. If the remote clocks are accessed over the public Internet, the node can usually maintain its clock to within ten milliseconds of the reference clock; accuracies of one millisecond are possible if a time server is available on the local intranet.[26] Hierarchical approaches trade scalability for relaxed tolerance to variance: each leaf node is no longer necessarily synchronized to the stratum 0 reference, and there is no guarantee that the stratum 0 reference is exactly in synch with lower level strata (only to the NTP protocol itself).[27]

PTP – Precision Time Protocol: PTP (also known as IEEE 1588) is a standardized protocol designed to provide a precise clock for test and measurement systems. PTP is typically used in conjunction with hardware support and is applicable for embedded systems and military applications. Researchers at CERN have demonstrated site-wide time uncertainties under 1 ns via a carefully constructed PTP arrangement.

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[25] The IRIG-B format specification does not convey any time-zone information, so for its use with PMUs reserved bits in the IRIG-B format have been utilized to convey the time-zone information, as found in IEEE C37.118.1. IRIG-B also does not support leap-second information, which is needed to indicate upcoming leap-second and when it is introduced. The IEEE C37.118.1 similarly extends IRIG-B for this particular issue. Other IRIG formats can lack this capability, resulting in problems to meet the C37.118.1 and C37.118.2 standards for PMUs with regard to local time and leap-seconds.

[26] Becker, D., J. C. Linford, R. Rabenseifner & F. Wolf, "Replay-Based Synchronization of Timestamps in Massively Parallel Applications," *Scalable Computing: Practice and Experience*, Vol. 10, Num. 1, pp. 49-60 (2009).

[27] Mills provided a survey of the characteristics of roughly 10,000 machines on the internet [Mills:On:1989]. Offset error distributions were provided for several protocols with results ranging from multiple milliseconds to times exceeding 100 seconds.

IRIG: IRIG is a standard set of formats for transferring timing information created by the TeleCommunications Working Group of the U.S. military's Inter-Range Instrumentation Group (IRIG). Atomic frequency standards and GPS receivers designed for precision timing are often equipped with an IRIG output. The time-codes have designations A, B, D, E, G, and H (see Table 5). Perhaps the most commonly used is IRIG-B.

Table 5. IRIG time code. Note: C was in the original spec, but was replaced by H.

Code	Bit rate	Bit time	Bits per frame	Frame time	Frame rate
A	1000 Hz	1 ms	100	100 ms	10 Hz
B	100 Hz	10 ms	100	1000 ms	1 Hz
D	1/60 Hz	1 minute	60	1 hour	1/3600 Hz
E	10 Hz	100 ms	100	10 s	0.1 Hz
G	10 kHz	0.1 ms	100	10 ms	100 Hz
H	1 Hz	1 s	60	1 minute	1/60 Hz

Differential Operation: Frequently, more than one timing source can be combined to employ *differential* strategies. For instance, a differential WWVB approach can be constructed with three elements: the GNSS satellite, a reference station at a known location using a signal such a WWVB, and a roving GPS receiver. This scheme allows the roving receiver to make an improved calculation using the GNSS signal together with a second WWVB signal from the known location through a difference calculation of the two signals. Although WWVB has trouble reaching microsecond accuracies across the U.S., if combined with GPS in a differential set-up it can provide sub-microsecond time transfer, using a GPS and WWVB receiver at two fixed locations within a few tens of kilometers. GPS would then calibrate the difference in arrival time of the WWVB signal. This would remain nearly constant even if GPS were lost from one location. Then WWVB could be used to transfer UTC from the location that still had GPS.

6. Timing Problems, Anomaly Detection and Mitigation

It is a given that many power system applications depend upon communications networks and information technology, both of which are deeply dependent on reliable timing. Therefore, the NASPI TSTF is focusing only on timing uses internal to the power system. This analysis addresses only timing uses that are used specifically within the power system, since it is beyond the scope of the task force to address and remedy timing issues related to network communications and information technology. However, to the degree those external systems have timing and other vulnerabilities, those vulnerabilities could compromise the power system.

6.1 Common failure modes from the grid user's perspective

GNSS equipment and systems may fail to deliver accurate timing (often assisted by user errors) for many reasons.[28] A short list of causes for such failures includes:

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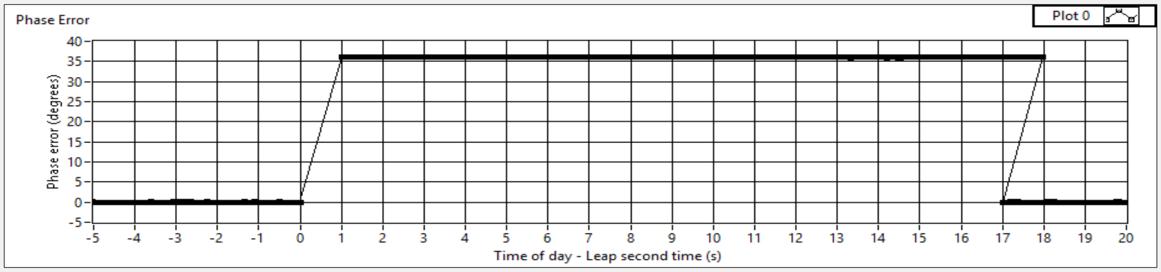
[28] See M. Danielson, "GPS incident on broadcast networks," (2016) and A. Silverstein & M. Danielson, "GPS Timing Challenges and Robustness Needs for Critical Infrastructures: Examples from Telecom, Broadcast and Power Delivery Industries," (2016).

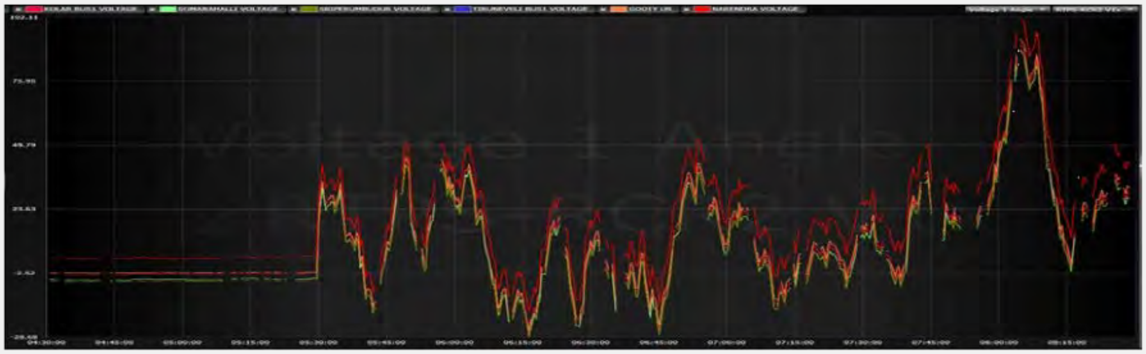
- From space
  - GPS signal-in-space anomalies
  - Ionospheric fluctuations, including solar storms, sunspots, and geomagnetic disturbances
  - Tropospheric issues – signal fading due to moisture
  - Events – satellite constellation changes
- On-site at the point of GNSS receiver installation and use
  - GPS receiver – poor quality, software bugs, no firmware updates, bad location, local jamming or spoofing or other radio interference, lost wire to the PMU, no correction for PNT broadcast problems, leap second and leap year processing
  - PMU – poor interoperability with GPS receiver, slow firmware patches, lost wire to GPS receiver, sloppy program for time-handling, no detection of timing problems, no back-up time source
  - In substation timing delivery (rare) – problems with cabling or Ethernet distribution of time signal to slave clocks
- PDCs and applications – inadequate detection of timing anomalies or gaps and computational errors resulting from those problems.

Example – Calculating Phase Angle with a Time Error



Source: "2015 NIST Investigation of PMU Response to Leap Second", Allen Goldstein, DJ Anand & Ya-Shian Li-Baboud, NIST (March 2016)

- Above – for 17 seconds, it appears that the phase has a 36° error (at 59.9Hz)
- Note that there are no reports for the second immediately following the leap second, and there are two sets of reports for the second between 17 and 18 seconds after.
- And different PMU models handled the leap second differently.
- Due to inconsistent time-determination methods (below), some PMUs in India reported wildly fluctuating phase angles.



Source: POSOCO, P.K. Agarwal, "Encounter with the Leap Second," NASPI Work Group (March 23, 2016)

Although most PMU owners were aware that another leap second would occur at midnight on December 31, 2016, several owners reported problems with delayed leap second processing and mismatches between time-stamps in different PMUs. As with the 2015 leap second, where such incidents occurred, they created false volatility in phase angle readings.

Synchrophasor measurements and applications that use PMU data are affected in various ways if GPS or the measurement time-stamp is inaccurate or lost. If there is an error or spoof of the time signal to a PMU, that error will cause false calculations of phase angle and misalignment of measured grid conditions relative to other PMUs. The 2015 leap second illustrated several outcomes:

- Where the GPS clocks skipped the second or were early/late, PMU measurements were too early or too late, causing PDCs to ignore the PMU measurements.
- Where there were duplicate time-stamps, there were "duplicate" PMU measurements.
- Phase angle error depends on accurate time information; bad time-stamps mean erroneous phase angle calculation.

In the case of the leap second, all of these errors were caused by flaws within the PMU or its time source, rather than by the GPS system per se, but the user does not always recognize that distinction.

6.2 GNSS security and problems

Problems caused by natural, accidental, or malicious radio interference cause significant concerns about the reliability and accuracy of satellite-based timing delivery systems (i.e., GNSS). Perhaps the most common cause of GPS problems is poor antenna installation, which can be prevented by using best practices for installation. Terrestrial or space-based interference can prevent the clean, accurate receipt of satellite signals at a GNSS receiver, and intentional spoofing can substitute false timing information to a receiver in lieu of the original, accurate signal. But the absence of a timing signal or the receipt of an inaccurate signal can cause systems such as synchrophasor networks to lose needed data or to act inappropriately on the false data received. In some extreme cases, this could cause operational problems for the electric grid.

DHS identifies three sets of threats to GNSS signals. As summarized in a 2012 presentation, those threats are:

- Unintentional
  - Interference – includes out-of-band emissions from other radio sources or in-band emissions from other systems, such as … other satellite navigation systems
- Intentional
  - Jamming – the deliberate drowning out of legitimate Positioning, Navigation and Timing and Frequency (PNTF) signals using higher power signals to cause loss of satellite lock and to prevent reacquisition
  - Spoofing – the deliberate emitting of legitimate-appearing false signals to shift the computed position or time of a victim's receiver
- Naturally occurring
  - Space Weather – variable conditions on the sun and the space environment that can influence the performance and reliability of space and ground-based systems.[29] [30]

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[29] Graham, Monty, "GPS Use in U. S. Critical Infrastructure and Emergency Communications," presented to the DOE, DoD and DHS, United States Technical Training Institute (2012).

[30] The members of the NASPI TSTF offer the following similar definitions:

- Interference is RF waveforms that unintentionally degrade or deny a receiver's ability to process signals, through raising the effective noise floor in the receiver processing, saturating the front end, or through various other mechanisms.
- Jamming is another term for interference. Many people use the term "jamming" to connote intentional, deliberate effort to degrade or deny a target receiver's operation.
- Spoofing signals are RF waveforms that mimic true signals in some ways, but deny, degrade, disrupt, or deceive the target receiver's operation when they are processed. There are two very different classes of spoofing. Measurement spoofing introduces RF waveforms that cause the target receiver to produce incorrect measurements of time of arrival or frequency of arrival or their rates of change. Data spoofing introduces incorrect digital data to the target receiver for its use in processing of signals and the calculation of position, velocity, and time (PVT).

Either type of spoofing can cause various effects, ranging from incorrect outputs of PVT to receiver malfunction. The onset of these effects can be instantaneous or delayed, and the effects can last as long as the spoofing is present, or longer. Since these two types of spoofing are so different in how they are produced, in their observable characteristics, and in their effects on receiver operation, they are explicitly given different names. It is possible, however, for a spoofing signal to produce both incorrect measurements and incorrect data in a receiver. Spoofing may be unintentional, such as when signals from a GPS repeater or simulator within a test enclosure leak out from the test enclosure and affect other receivers.

6.3 Cyber-security issues

Thus far this paper has assumed that an authentic timing signal (e.g., GPS) is being received by a functional device (PMU or PDC), and the device is acquiring data, time-stamping it, and reporting it faithfully. But it is a mistake to assume that GPS and other timing systems are trusted inputs, because time signals can be disrupted at the source (such as the GNSS satellite time origination or broadcast software or within network time delivery software), at the time signal receiver, or within the PMU.[31]

Consider a malicious actor who wishes to compromise the timing signal being received by the PMU, in order to corrupt the associated measurement data as it originates in the device. One way to compromise PMU data is by compromising the GPS signal, as through jamming and spoofing. Civilian GPS signals are susceptible to various cyber-attacks due to their weak signal strength and predictability. The signal strength of GPS measured at the surface of the Earth is typically about –160 dBw, which is roughly equivalent to viewing a 25 Watt light bulb from a distance of 10,000 miles.[32] Also, these signals are neither encrypted nor authenticated (unlike military GPS signals).

Jamming aims to intentionally block the reception of GPS signals. This kind of attack can be carried out by introducing a signal of similar frequency, but greater strength, or by shielding the GPS receiver's antenna. Since loss of signal is experienced during jamming, the receiver is aware of its occurrence.

Spoofing is aimed at intentionally faking malicious or duplicated GPS signals, so that the receiver estimates time and position erroneously based on the tracked false signal. This kind of attack can be carried out by broadcasting a fake GPS signal which matches the true signal's phase, code delay, and encoded data, but has signal strength higher than that of the true signal. Another form of spoofing, known as replay attack, consists of generating time-shifted copies of GPS signals through a delay, and transmitting them with higher energy in order to overwhelm the true GPS signal. Replay attack leads to overestimation of the time of signal transmission, thereby resulting in incorrect estimation results.

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[31] Early analyses of GPS attacks can be found in Shepard, Humphreys and Fansler, "Evaluation of the Vulnerability of Phasor Measurement Units to GPS Spoofing Attacks" (2012) and Nighswander, Ledvina et al., "GPS Software Attacks," *CCS '12 Proceedings of the 2012 ACM Conference on Computer and Communications Security*, pp. 450-461 (2012).

[32] Warner, J. S. and Johnston, R. G., "GPS spoofing countermeasures," *Homeland Security Journal* (2003).

A spoofing attack can introduce time error in a victim PMU, which in turn produces proportional phase angle error in the synchrophasor data originating from it. Such attacks can be easily accomplished by using Universal Software Radio Peripheral (USRP) devices, which are inexpensive and widely available. This type of attack is stealthy in nature, and most of the civilian GPS receivers available today lack any effective countermeasures.

As previously noted, if a PMU loses its external time signal, it will rely upon a local oscillator to determine time and compute synchrophasors. Left undisciplined by an external time signal, the frequency of a low-quality local oscillator will drift over time due to temperature variations and mechanical vibrations, yielding inaccurate time-stamps that degrade further over an extended time signal outage. If an oscillator synchronizes to a spoofed time signal, then it will maintain an incorrect stream of time-stamps. Incorrect time-stamps will cause errors in synchrophasor and phase angle calculations. The magnitude of these errors appears to increase over time.[33]

As an example of the consequences of a timing attack or loss of time signal, consider the synchrophasor-based control scheme in use at the Chicoasen-Angostura transmission link in Mexico, which connects large hydroelectric generators at Angostura to large loads at Chicoasen. PMUs are deployed at each end of this transmission line in order to monitor their phase angle difference, which can be an indicator of fault condition. These PMUs are configured to automatically trip the hydroelectric generators offline if the phase angle difference exceeds 10°.[34] A spoofing attack on any of these PMUs could lead to erroneous time estimation, which will ultimately lead to incorrect phase angle difference computation. If a phase angle difference greater than the mentioned threshold is obtained due to the attack-induced time error, it could cause an unnecessary generator trip.

Ways to modify or corrupt data at or within the PMU include:

- Modifications to the firmware resulting in false measurements (continually, or on demand), increased load on microprocessors and/or memory to disrupt timing functionality (i.e., decrease hold-over time, disrupt FFT, etc.), deliberate randomized events to force resources to be spent investigating errors;
- Modifications to the hardware arising from counterfeit components (supply chain security);
- Tampering with local keys and/or access policies.

PMU data is streamed using TCP/IP or UDP/IP transport protocols. These can be susceptible to interception attacks.[35] Along the data transmission path, legitimate PMU data can be modified or corrupted by:

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[33] Almas, M.S., L. Vanfretti et al., “Vulnerability of Synchrophasor-based WAMPAC Applications to Time Synchronization Spoofing” (2017).

[34] D. Shepard, T. Humphreys, A. Fansler, “Evaluation of the vulnerability of phasor measurement units to GPS spoofing attacks”, *International Journal of Critical Infrastructure Protection*, Volume 5, Issues 3–4, December 2012, Pages 146-153, ISSN 1874-5482.

[35] Almas et al. note that the range of synchrophasor data traffic interceptions includes: packet sniffing, side channel attacks, man-in-the-middle attacks, modification attacks such as malicious code injection, and fabrication attacks such as direct data spoofing. They also note that, “Denial of Service attacks at the physical layer [are] also possible by either disconnecting the power supply to the PMU, cutting the cable connecting a PMU with the

- Introduction of fake or spoofed data, potentially crafted to exploit vulnerability in PDCs and/or other systems (e.g., buffer overflows)
- Intercept/resend attacks which aim to slow message transit time across a communications link
- Denial of service attacks aimed at the PDC host, to disable the receipt of incoming PMU data.

Almas, Vanfretti et al. studied the effects of effective time synchronization spoofing attacks on a variety of synchrophasor-based wide-area monitoring, protection, and control applications, and report a variety of impacts from the time synchronization errors, including:

- Monitoring applications that use phase angle measurements will provide misleading information, which can produce false interpretations of grid conditions and inappropriate manual or automated control actions.
- Protection applications such as anti-islanding schemes that receive inaccurate phase angle information could be tricked into degraded performance, including false activation of a protection scheme with potential asset or system separation.
- Feedback control applications such as oscillation damping could be misled into activating the controller to produce negative damping that harms rather than helps the system.[36]

Almas et al. recommend that PMUs and PDC should have the ability identify the difference between authentic and spoofed time synchronization tools, have two time synchronization sources including one non-satellite signal, have the ability to detect and correct against jamming, spoofing and interference, and have internal hold-over oscillators as back-ups to loss of a trusted external time source.[37]

To protect access to the device, typical best practices cyber-security policies should be enforced, including:

- Changing default passwords
- Applying latest software patches and firmware upgrades where possible
- Timely key management and revocation policies
- Limiting physical access to hardware
- Disabling USB and other peripheral access where possible
- Enabling detailed logging & conduct log analysis
- Using encryption where possible given available computational and key storage resources

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communication network (switch/router) or jamming the GPS signals that provide time-synchronization input to the PMUs. Almas et al. cite several original sources on this topic, including a seminal work by D. Shepard, T. Humphreys & A. Fansler demonstrating the vulnerability of PMUs to GPS spoofing attacks.

[36] Ibid.

[37] Ibid.

- Implementing least-user privileges accounts where possible – minimizing administrator/root access
- Educating users on dangers of social engineering.

Maintaining the availability and integrity of the GPS signals is essential for ensuring correct estimation of time and phase angle measurements. Some of the recommended steps for allowing detection of suspicious activities are:

- **Amplitude discrimination** – Monitoring the observed absolute amplitude of the received signal for detecting any anomalies.
- **Time-of-arrival discrimination** – The time between the spoofed signals in case of most GPS satellite simulators is constant, unlike the time interval between true GPS signals.
- **Angle-of-arrival discrimination** – The angle-of-arrival (AOA) of GPS signals is monitored. Typical GPS receiver would receive signals from multiple GPS satellites with different AOAs, while in case of spoofing attack the AOAs will be the same.
- **Cryptographic authentication** – Information can be protected in transmission by using encryption and other message authentication schemes. Such schemes, however, need modification of the structure of the civilian GPS signals, which may take time.

These best practices and countermeasures will not stop all GPS-related cyber-attacks. However, these measures could thwart a large number of such attacks, and alert the user when suspicious activities are detected. From a cyber-security perspective, it is difficult to protect such a large attack surface (e.g., GPS or network-distributed time), but more sophisticated attack prevention and detection schemes are required to strengthen the security and resilience of synchrophasor-based monitoring systems. Response and recovery plans should also be developed in order to minimize the risks further, including assuring that every critical PMU and substation has access to a non-GNSS time source to assure redundancy fail-over and protect ongoing access to accurate time.

7. Improving Synchrophasor System Timing Delivery and Management

For synchrophasor applications to effectively advance power system reliability, they must receive and maintain accurate time signals to use for time-stamping and synchronizing data at the point of measurement and throughout the upstream data processing and analysis.

7.1 Good design and installation practices for PMUs

While in other industries, users may select and implement the timing schemes that best suit their needs, the power industry tends to default to consultants and vendors to select the timing source (such as GPS, IRIG-B) and build that into equipment. It is necessary to develop more demanding and specific timing requirements and demand high-quality equipment with good interoperability between timing components to assure that timing problems do not compromise synchrophasor and other grid timing-dependent systems.

7.2 Good planning and installation practices for GNSS systems

Antenna installation should be done using good practice, that can be provided from most GPS manufacturers. The delay through the equipment should be calibrated, usually by the manufacturer, and the antenna cable delay should be accounted for. Timing equipment and PMUs must execute specified timing requirements, including leap second handling. Time and leap seconds need to be conveyed from the time reference (GPS) properly into the time distribution format (IRIG-B, PTP, etc.) and into the PMU processing and data stream without disruption of measurement or time-stamping data. If a problem compromises the integrity of PMU data time-stamps, that data problem should be clearly conveyed so the applications using the affected data can handle it appropriately. Additionally, a synchrophasor system should be able to identify timing-related data problems and seek an alternate timing source to remedy the flaw and restore timing accuracy and stability.

Time source (GPS, GLONASS, GALILEO, etc.) variations should be tested for reasonable operation to be sure that they can handle allowed future signal challenges such as leap second introductions, unused satellite numbers and other similar variations. GNSS receivers should check the transmitted health of satellites, and not use satellites declared unhealthy. GNSS systems should have ways to identify time signal errors, and those systems should use robustness checks and alert users if there is an accuracy problem.

PMUs and GNSS receiver equipment should be tested to ensure proper operation with time signals, as well as conveying key timing and timing parameters. Users should also monitor equipment, including SNMP & SNMP traps to identify devices having issues, and pass the error condition to the system depending on its signal to either discriminate the data or to find an alternative timing source.

In order to maintain these properties, timing devices and PMUs should be maintained with remote upgrade capability, continuous revision of FW revisions to decide upon upgrades and regular upgrade windows to ensure that critical security and operational impacting bugs and features is tracked and eliminate the system risk of exposing such vulnerability. Timing equipment and PMUs should have support from vendors throughout their operational life-cycles. Equipment that does not receive support (either by vendor end-of-life or by dropping needed support contracts) should be retired from operation in critical infrastructure systems. Systems remaining in a mixed environment should be clearly marked so they are not used for critical operations. Isolation from operational environment may be required for security and safety reasons.

Equipment in use before it is shifted to critical operation should be reviewed and potentially upgraded or replaced to meet critical operation requirements. There have been multiple incidents when test-setups have not been upgraded even as their operational status shifts from test to critical operations.

Equipment used for test and educational use may receive and use the signals from critical operation equipment, as long as reasonable isolation can be maintained. This also includes co-location at station. Such equipment should be clearly marked to ensure that critical equipment is not confused with test and education set-ups.

DHS has published guidance on best practices for improving the robustness of time and frequency sources used in fixed locations[38] and for improving the operation and development of GPS equipment overall.[39] These documents include detailed information on topics such as antenna location and the use of blocking, redundant, and decoy antennas. DHS also recommends a number of measures for manufacturers, including better GPS hardware and software assurance, protected remote access, anti-jam capabilities, anti-measurement spoof processing and anti-data spoofing.

7.3 Some timing remedies and options

Numerous changes are needed to improve the robustness and resilience of timing problems within synchrophasor equipment and systems.

At the PMU level:

- Better detection of timing anomalies
- Status messages and error flags – When a PMU identifies a timing problem, it puts an error flag into the status message that is part of the individual PMU data frame. But PMUs and GPS clocks do not always process and identify timing problems consistently, nor do they issue timing-related error flags in consistent ways. Error flags related to timing accuracy and authenticity should be improved within C37.118.
- Back-up time sources independent of GNSS should be located within PMUs or within the host substation.

At the PNT level:

- Improved signal robustness checks
- Multi-frequency – L1 C/A, L2C, L5 (but multi-frequency receivers are expensive)
- Multi-system – GPS, GLONASS, GALILEO, eLoran, good internal oscillators
- Multiple receivers
- Jamming, spoofing, and interference detection and/or prevention
- More frequent software updates that properly address timing events such as leap seconds and week rollovers

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[38] United States Department of Homeland Security, ICS-CERT, “Best Practices for Improved Robustness of Time and Frequency Sources in Fixed Locations” (January 6, 2015).

[39] United States Department of Homeland Security, NCCIC & NCC, “Improving the Operation and Development of Global Positioning System (GPS) Equipment Used by Critical Infrastructure,” unclassified, (also called, “Best Practices for Improving the Operation and Development of GPS Equipment Used by Critical Infrastructure”) (January 19, 2017).

- Better antenna-receiver calibrations by the manufacturer

GPS-independent networks:

- Telecom network is capable of time transfer – avoids dependence on satellites and transmitter sites and requirement for large receiver network installation and maintenance
- Network-distributed time can receive accurate time from multiple sources (GPS, NTP, CDMA, PTP), some IRIG-B
- Distributed clock networks, some IEEE 1588
- Hold-over clocks in key devices for short-term back-up.

7.4 Standards conformance and interoperability requirements

The industry requirements are motivated by regulatory and technical standards. The regulatory requirements include the North American Electric Reliability Council for disturbance monitoring and recording. Technical standards and conformance requirements are essential to assure that equipment performs in clear, predictable ways that meet users' and applications' well-defined needs; conformance and interoperability testing are needed to assure that a wide variety equipment and applications work effectively together with end-to-end interoperability.

NERC regulatory standards include:

- PRC-018-1 Disturbance Monitoring Equipment Installation and Data Reporting, R1.1: Internal Clocks in DME devices shall be synchronized to within 2 milliseconds or less of Universal Coordinated Time scale (UTC)
- CIP Security Guideline for the Electricity Sector: Time Stamping of Operational Data Logs

Key technical standards in power systems device time synchronization, time-stamping, reporting rates, communication latencies and other temporal requirements are primarily driven by the IEEE Power Systems Relay Committee and IEC Technical Committee (TC) 57 "Power systems management and associated information exchange" and TC 95 "Measuring relays and computation equipment." The standards efforts include the PTP Power (IEEE C37.238) and Utility Profiles (IEC 61850-9-3) as well as complementary standards such as IEEE C37.118 "Standard for Synchrophasor Measurements for Power Systems, Design and Implementation of Time Synchronization Distribution Systems for Substation Automation," IEEE "Guide for Synchronization, Calibration, Testing and Installation of PMUs" and IEEE C37.237 "Draft standard for Requirements of Time Tags Created by Intelligent Electronic Devices (IEDs) – (COMTAG)." IEEE C37.118, IEEE 1646 "Standard Communication Delivery Time Performance Requirements for Electric Power Substation Automation" and IEC 61580 "Generic Object-Oriented Substation Events (GOOSE) and Sampled Values (SV)" define the requirements for sampling or reporting rates and communication latencies.

Conformance and interoperability among key timing standards will be critical to enabling optimal performance and assurance of accurate synchronization and timing in next-generation power systems networks. With one of the prevailing issues being inconsistencies in the handling of time and time discontinuities, NIST and the IEEE Conformity Assessment Program (ICAP) are supporting test and certification programs through IEEE Conformity Assessment Steering Committees (CASCs) based on relevant standards such as the IEEE C37.118 “Standard for Synchrophasor Measurements” and IEEE C37.238 “PTP Power Profile Standards.” There are also ongoing conformance and interoperability test suite development efforts through IEEE PSRC to support the industry in ensuring devices from different vendors can still work together and maintain the performance requirements. UCA International Users Group (UCAIug) is also planning interoperability (IOP) test event in October 2017.

Interoperability between power system devices that use different timing standards will require the ability to identify the standard each device uses, and for applications to correctly harmonize the data arriving from devices applying the different *time distribution* standards.

IRIG-B

IRIG-B code provides time once per second and is comprised of the following sequences of bits:

- Binary Coded Decimal (BCD)
- Straight Binary Seconds (SBS)
- Control Function (CF)

The time encoded in IRIG-B (or any other IRIG format) can be any local time, thus reflecting a particular time zone and its offset from UTC (including daylight savings time adjustments). The IRIG standard does not provide means to indicate the offset from UTC, and this is needed in PMU applications, so the IRIG-B code has been amended with a local time offset field that makes the UTC time available. The time encoded in IRIG-B does not provide leap second indicators, making it hard to warn about upcoming leap second and whether the current frame is a leap second. The UTC-TAI difference is not yet conveyed, so the leap second table needs to be sufficiently fresh for estimating the TAI from the UTC estimate.

IRIG-B DCLS (DC Level Shifted) provides an un-modulated signal with better synchronization accuracy on the order of 60 ns. Amplitude-modulated (AM) IRIG-B enables the signal to travel over longer distances with a tradeoff on accuracy, on the order of 1 to 5 μs.

The time quality (quality of time in hold-over) and continuous time quality (continuous tracking) indicate estimated clock errors, which shall be conveyed within the PMU data stream such that analysis can be aware of potential phasor errors/loss-of-accuracy.

The following standards include the legacy and future implementations of IRIG-B for power systems:

- IEEE 1344-1995 (Past): The first standard for synchrophasors to define year, time quality, daylight savings time, local time offset and leap second information. UTC is calculated by subtracting the offset from the timecode.
- IEEE C37.118-2005 (Past): The offset encoded in bits 14-19 changed from IEEE 1344-1995. UTC is now computed by adding the offset to the timecode.

- IEEE C37.118.1-2011 (Present): sets the basis for time synchronization accuracy by introducing the TVE computation and requirement. The tolerated TVE is 1% which translates to 26 µs for 60 Hz systems, if time is the only source of error.
- IEEE C37.237 (Future): Provides an alternative use for SBS as a time-domain multiplexed (TDM) extension comprised of additional information including source clock ID (both user settable (16-bit) and MAC address-based (64-bit)), offset between TAI and UTC time scales, and a 32-bit improved resolution time inaccuracy field up to nanoseconds.

Precision Time Protocol

PTP is a network-based time distribution protocol operating by default on the PTP time-scale which is based on TAI and is therefore not affected by leap seconds. PTP does provide information (leap flags and UTC offset) to end devices relying on time based on UTC to alert when a leap second is expected to occur.

IEEE 1588

IEEE C37.238 – 2011 (Current): Defines the IEEE 1588 Power Profile for Substation Automation. Includes the requirement for ± 1 µs accuracy to a standard traceable time reference over a network of 16 hops, where each transparent clock can introduce no more than 50 ns time error.

IEC 61850-9-3 (2016): Defines the IEEE 1588 Utility Profile. The profile includes new steady state performance requirements for Grandmaster, Transparent Clocks and Boundary Clocks. Defines steady state as 30 minutes after the device is powered on.

IEEE 1588 version 2.1 (Future): The revision is planned for completion in 2017 with potential provisions to include dynamic information on the synchronization performance as well as a high accuracy option, on the order sub-nanoseconds, and enhanced security option. The security options will be composed of *PTP Integrated Security Mechanisms, External Transport Security Mechanism, Architecture Guidance and Monitoring and Management guidance.*[40] The integrated approach includes a type length value (TLV) definition for authentication and integrity verification, including the key distribution protocol, Group Domain of Interpretation (GDOI), and symmetric key management, Timed Efficient Stream Loss-Tolerant Authentication (TESLA, a lightweight broadcast/multicast authentication mechanism adopted by IEC 61850). Integrity checks are based on the Integrity Check Value (ICV) in the proposed TLV. The external transport mechanisms include IPSec and MACSec, which provides integrity protection and authentication at the transport (Ethernet) layer. The guidance will be based on redundancy, including diverse sources and paths to PTP grandmasters, along with the inherent measurements related to architecture and performance measurements such as delay and offset. The guidance will include a definition of metrics in the PTP data sets to be monitored to detect security issues as well as the security guidance on optional management protocols, including the IEEE 1588 Management messages.

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[40] O'Donoghue, Karen, "Emerging Solutions in Time Synchronization Security," IEEE/NIST Challenges in the Smart Grid Workshop (October 2016).

IEEE/IEC 61850

IEEE/IEC 61850-9-3/C37.238 (Future): Merge into a single standard with two levels. Level 1 will be the Utility profile with steady state time inaccuracy information, while Level 2 will have two additional TLVs, Time Inaccuracy, to provide dynamic time inaccuracy information and to maintain compatibility with the new IEEE C37.237 definition of IRIG-B encoding. Level 2 will also include an optional Alternate Time Offset Indicator (ATOI) TLV for adjustment to local time.

Time tagging standards include:

- IEEE C37.118 Synchrophasor Measurement. The resolution is defined by FRACSEC / TIME_BASE fields, up to TIME_BASE equals 2^{24} or approximately 60 ns.
- IEEE C37.237 Requirements of Time Tags Created by IEDs.
- IEEE C37.239 Common Format and Event Data Exchange.
- IEC 61850 defines time-stamp format for both data objects and separate entry time format for event logs. The resolution of IEC 61850 time-stamps is about 60 ns.
- IEC 60870 for SCADA telemetry. The resolution of SCADA time-stamps is 1 ms.
- Distributed Network Protocol Version 3 (DNP3) is also used for SCADA telemetry. The resolution of DNP3 clocks and time-stamps is 1 ms.
- ISO 8601.

In addition to time synchronization and time tagging standards, power systems standards for synchrophasors, PDCs, as well as other substation IEDs have standards that specify timing requirements including reporting rates, sampling frequency, measurement latency, communication latency, time-stamp accuracy, etc. Substation station and process bus protocols such as GOOSE and SVs require communicate message rates on the order of 100 μs to 1 μs, respectively, as shown in Table 6.

Table 6. Communications protocols

Grid application	Timing requirements	Time-stamp resolution
SCADA (IEC 60870 / DNP3)	100 ms	1 ms
Substation local area network communication protocols (IEC 61850 GOOSE)	100 μs to 1 ms synchronization accuracy	~59.6 ns
Substation LANs (IEC 61850 SV)	1 μs up to 4800 frames/s for 60 Hz systems	~ 59.6 ns

7.5 Timing performance measurement

In a recent workshop on timing and the smart grid, NIST heard several participants identify the need for quantifiable time synchronization performance metrics. These metrics should apply to the correct behavior of clocks, time and time distribution, and will need to be tracked and tested with repeatable, reproducible methods. Some recommended metrics would include hold-over time, clock stability, and other measures of reliability, availability and serviceability.[41]

8. Recommendations

Time-synchronized data collection offers great promise for grid coordination and protection. But synchrophasor technology applications cannot be trusted for mission-critical uses until time signal delivery and the devices that use time signals (starting with PMUs, GPS receivers, clocks, and PDCs) becomes highly reliable and resilient.

As these uses continue and increase, grid users and application designers should consider several points:

- **Accuracy** – While accuracy requirements are achievable with today's technology, the mechanisms to provide it are too costly and too large physically if sources beyond GPS are employed. GPS-only solutions are vulnerable to interference, jamming, loss of signal, and spoofing, and so cannot be used as the sole source of timing for a mission-critical application. We also need better methods to identify when time signals have become corrupted due to events such as a leap second or spoofing.
- **Resiliency and reliability –** Tomorrow's timing sources must be able to function with high availability in the event of the loss of one time signal method (i.e., by failing over to a back-up timing system such as an on-board oscillator), and should work during power outages.
- **Security –** Since we cannot count on physical security to completely protect access to timing sources and the networks that transport their information, we must find new ways to ensure the integrity of our timing sources.
- **Flexibility –** There are many ways to use time-synchronized, PMU-like sensors for smart grid coordination and protection functions. This will require having small, highly accurate time-synchronized sensors that can be deployed cheaply and easily. The timing source should support "smart grid" capabilities (e.g., flow data with feedback from residences and businesses, and enable distributed, decentralized analysis and control) as well as improved support for advanced user/applications, better interoperability with other timing sources and grid components, and better inter-sector coordination.
- **Costs** – The industry is eager for manufacturers to develop small, inexpensive sensors that can collect high-speed, high-accuracy, time-synchronized grid data. But to deploy a time-synchronized sensor such as a PMU, the users need to buy the device, install it, and provide secure high-speed communications to collect and use the data. All of these elements need to become easy and low-cost to enable full utilization of time-synchronized sensors.

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[41] Anand et al., "Timing Challenges in the Smart Grid," NIST Special Publication 1500-08 (January 2017).

- **Standards and testing** – There is still work needed to fully incorporate clear, consistent timing performance requirements into standards and conformance testing, and to ensure interoperability between different timing methods and time-using devices.
- **Applications** – Given the many ways in which time signal delivery may fail, applications need to be more sensitive to whether incoming data is accurate and accurately time-stamped, and should be able to work around data gaps and losses where possible. Applications should warn users if data problems such as bad time-stamps are compromising the quality and trustworthiness of the application's analytical results.

As the use of time-synchronized data collection and applications grows across the grid, it is essential that electric system operators and application developers continue working with device manufacturers, standards developers and others to address and resolve the challenges identified here.

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