



IEEE Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMUs) for Power System Protection and Control

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Developed by the
Power System Relaying and Control Committee

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Abstract: Guidance for synchronization, calibration, testing, and installation of phasor measurement units (PMUs) applied in power systems is provided. The following are addressed in this guide: (a) considerations for the installation of PMU devices based on application requirements and typical substation electrical bus configurations; (b) techniques focusing on the overall accuracy and availability of the time synchronization system; (c) test and calibration procedures for PMUs for laboratory and field applications; and (d) communications testing for connecting PMUs to other devices including phasor data concentrators.

Keywords: calibration, GNSS, IEEE C37.242™, phasor measurement unit, PMU, synchrophasor, testing

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Introduction

This introduction is not part of IEEE Std C37.242-2021, IEEE Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMUs) for Power System Protection and Control.

Use of synchrophasor technology in the electric power industry is rapidly growing, moving from research and pilot projects into system-wide production-level deployment. Accordingly, a practical guide for installing and testing phasor measurement units (PMUs) is expected to be very beneficial to field practitioners, sharing and leveraging the early experience that the pioneers in this area have accumulated. This document was developed by IEEE PES Power System Relaying Committee to guide and educate various professionals interested in deploying PMUs and using the associated synchrophasor data.

In the years that passed since the publication of the first edition of this guide, many thousands of PMUs have been installed worldwide and many have been connected to PDCs and to synchrophasor applications. These PMUs and phasor measurement systems have provided a wealth of information about power systems and are increasingly being used in operations. This usage is supporting an increase in the knowledge of the technology. In 2018, a revised synchrophasor performance standard was published jointly by IEC and IEEE (IEC/IEEE 60255-118-1). The second edition of this guide is an update and expansion reflecting the 2018 standard and makes recommendations based on experience both in the field and in research. This guide supersedes the 2013 revision and is applicable to IEC/IEEE 60255-118-1.¹

Acknowledgments

The Working Group especially acknowledges the contributions of its member, Richard Jay Murphy, who passed away shortly before the approval of this standard. This standard is dedicated to his memory.

¹ Information on references can be found in [Clause 2](#).

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1. Overview

1.1 Scope

This guide ~~The document~~ provides guidance for synchronization, calibration, testing, and installation of phasor measurement units (PMUs) applied in power system protection and control.

The following are addressed in this guide:

- a) Considerations for the installation of PMU devices based on application requirements and typical bus configurations.
- b) Techniques focusing on the overall accuracy and availability of the time synchronization system.
- c) Test and calibration procedures for PMUs for laboratory and field applications.
- d) Communications testing for connecting PMUs to other devices including Phasor Data Concentrators (PDCs).

1.2 Purpose

This guide is intended to be used by power system protection professionals for PMU installation and covers the requirements for synchronization of field devices and connection to other devices including PDCs.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{2, 3}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 61850-3, Communication Networks and Systems in Substations—Part 3: General Requirements.

⁴⁺

² The use of *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

³ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

⁴⁺ IEC publications are available from the International Electrotechnical Commission (<https://www.iec.ch/>) ~~and IEC publications are also available in the United States from~~ the American National Standards Institute (<https://www.ansi.org/>).

[IEC/ IEEE 60255-118-1, Standard for Synchrophasor Measurements for Power Systems.](#)

IEC/~~IEEE TR~~ 6185-09-3-90-5, ~~Ed. 1.0~~, Communication networks and systems for power utility automation—Part [9-3: Precision time protocol profile for power utility automation](#). ~~90-5: Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118.~~

IEEE Std 1588TM, ~~2008~~ IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems. ^{5,6 2,3}

IEEE Std C37.118.2TM, IEEE Standard for Synchrophasor Data Transfer for Power Systems.

[IEEE Std C37.237TM, IEEE Standard for Requirements for Time Tags Created by Intelligent Electronic Devices—COMTAG.](#)

~~IEEE Std C37.118TM 2005, IEEE Standard for Synchrophasors for Power Systems.~~

~~IEEE Std C37.118.1TM 2011, IEEE Standard for Synchrophasor Measurements for Power Systems.~~
~~IEEE Std C37.118.2TM 2011,~~

IEEE Std C37.238TM, ~~2011~~, IEEE Standard Profile for Use of IEEE 1588TM Precision Time Protocol in Power System Applications.

[IEEE Synchrophasor Measurement Test Suite Specification, https://ieeexplore.ieee.org/document/8765656.](#)

~~IEEE Std C57.13TM, IEEE Standard Requirements for Instrument Transformers.~~

IRIG Standard 200-[16](#) ~~04 (2004)~~, IRIG Serial Time Code Formats, Telecommunications and Timing Group, Range Commanders Council, U.S. Army White Sands Missile Range, NM, USA. ^{2 4}

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3. Definitions, ~~special terms~~, acronyms, and abbreviations

These definitions, acronyms, and abbreviations are especially pertinent to [GNSS](#) ~~GPS~~-synchronized devices, communications protocols, and communications media.

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause. ^{8 5}

~~**Global Positioning System (GPS):** A satellite-based system for providing position and time. The accuracy of GPS-based clocks can be better than 1 μ s.~~

intelligent electronic device (IED): A general term indicating a multipurpose electronic device typically associated with substation control and protection.

phasor data concentrator (PDC): A function that collects phasor data and discrete event data from PMUs and possibly from other PDCs, and transmits data to other applications. PDCs may buffer data for a short time period but do not store the data.

phasor measurement unit (PMU): A device or a function in a multifunction device that produces synchronized phasor, frequency, and rate of change of frequency (ROCOF) estimates from voltage and/or current signals and a time synchronizing signal.

uncertainty: A parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

~~**virtual private network (VPN):** VPN is an end-to-end communications method that employs encryption and key exchange as the security mechanism. VPNs can be established over either public or private networks.~~

⁸ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

⁵ *IEEE Standards Dictionary Online* subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

wide area measurement system (WAMS): One or more networks of measuring devices that may include phasor measurement unit (PMUs), local recorders, legacy equipment, or advanced technologies that are synchronized with Coordinated Universal Time (UTC) over a geographically diverse area.

~~Uncertainty of measurement is conventionally divided into two components. Type A uncertainty may be evaluated from the statistical distribution of the results of a series of measurements. Statistical processing can be used to reduce the value of this kind of uncertainty. Type B uncertainty can be evaluated from assumed probability distributions based on knowledge from other than that from the measurements, such as the manufacturer's specifications, reference data from handbooks or calibration certificates.~~

3.2 Special terms

~~error: In this guide, error is the difference between the result of a measurement and the value of what is generally called the *true value* (of the measurand).~~

3.2 Acronyms and abbreviations

CT	current transformer
CVT	capacitive voltage transformer
DFR	digital fault recorder
DUT	device under test
FPS	frames per second
GNSS	global navigation satellite system
IRIG	Inter-Range Instrumentation Group
NASPI	North American Synchrophasor Initiative
NTP	network time protocol
PMU	phasor measurement unit
PT	potential transformer

PTP	precision time protocol
RFI	radio-frequency interference
ROCOF	rate of change of frequency
TVE	total vector error
VT	voltage transformer

~~Refer to IEEE Std C37.118.1-2011 and IEEE Std C37.118.2-2011 for additional acronyms and abbreviations.⁶~~

4. Synchronization techniques, accuracy, and availability

4.1 Introduction

~~This~~ Clause [4](#) reviews the main technologies available to synchronize geographically distributed PMUs, and the basic principles of clock synchronization and its impact on the phasor measurement accuracy. This clause also examines common synchronization sources [and time distribution methods](#) for time referencing, including both satellite (e.g., [GNSS](#) ~~GPS~~) and terrestrial [e.g., Precision Time Protocol (PTP)] based technologies. The main advantages (e.g., timing accuracy) and potential vulnerabilities (e.g., susceptibility to intentional and unintentional interference) of these techniques are also reported. [Specific considerations for installation and connection to synchronizing systems can be found in 6.4.](#)

~~This clause also presents testing procedures (e.g., periodic timing signals measurement, measurement of two consecutive timing signals) aimed at assessing the main performance characteristics of synchronization sources (e.g., short-term stability, “bad” data management, hand-off algorithm).~~

~~Lastly, the synchronization distribution infrastructure is also discussed within this clause.~~

4.2 Role of time synchronization in PMUs

The clocks used for time synchronization in PMUs are required to be very accurate. However, their accuracy may vary over time due to manufacturing defects, changes in temperature, electric and magnetic interference, oscillator age, and altitude. Additionally, even small errors in timekeeping can add up significantly over a long period.

Careful work and analysis ~~are is~~ required to describe and quantify performance of timing in PMU systems, to meet the accuracy requirements of [IEC/IEEE 60255- Std C37. 118-1⁹-2011](#). Some clock variations are random, caused by environmental or electronic variations; others are systematic, caused by a miscalibrated or misconfigured clock.

Correct operation of a PMU requires a common and accurate timing reference. The timing reference is described in [the synchrophasor standard IEEE Std C37.118.1-2011](#), which establishes the relationship between the Coordinated Universal Time (UTC) time scale and the phase of the reference cosine wave. ~~The required performance could be realized by either synchronizing the samples directly to the timing reference or by software-based post processing of the acquired samples.~~ To achieve a common timing reference for the PMU acquisition process, it is essential to have a source of accurate timing signals (i.e., synchronizing source) ~~that may be internal or external to the PMU. In the first case the synchronization source is integrated (built-in) into the PMU (external GPS antenna still required). In the latter case, the timing signal is provided to the PMU by means of an external source, which may be local or global, and a distribution infrastructure (based on broadcast or direct connections).~~ [The source may be a GNSS receiver built into the PMU, Precision Time Protocol \(PTP\) via IEEE Std 1588, IRIG distribution of time throughout the substation, or future means timing distribution over a wide area.](#)

The timing signal generated by the synchronizing source ~~is must be~~ referenced to UTC and [provides](#) ~~provide~~ enough information to determine that the time [agrees is in agreement](#) with UTC. ~~(e.g., a “locked” status indicator).~~ [For proper operation,](#) the synchronization signal ~~is must also be~~ available without interruption at all measurement locations throughout the interconnected grid. The timing signal [can should](#) be characterized by the availability, reliability, and accuracy suitable for power system requirements. [If PMUs are to be used in mission critical situations, the availability of redundant, differently routed sources of synchronizing time is beneficial to avoid loss of synchronization due to inattentional or unintentional interference.](#)

²⁶ Information on references can be found in Clause 2.

The timing signal is expected to ~~should~~ be accurate enough to allow the PMUs to maintain synchronism with an accuracy sufficient to keep the *total vector error* (TVE) within the limits defined in the synchrophasor standard IEEE Std C37.118.1-2011 ~~(see 4.3 of that standard for discussion)~~ .

The PMU is required to detect a loss of time synchronization that would cause the TVE to exceed the allowable limit, or within 1 min of an actual loss of synchronization, whichever is less ~~(IEEE Std C37.118.2-2011, 4.5)~~. In this case an indication ~~a flag~~ in the PMU data output (e.g., STAT word Bit 13 of the IEEE C37.118.2 data frame) would ~~should~~ be asserted until the data acquisition is resynchronized to the required accuracy level.

To continue the example from IEEE Std C37.118.2, in addition to the STAT word Bit 13, this standard ~~IEEE Std C37.118.1-2011~~ specifies further signals intended to describe the time quality of the synchronization source. Each of the PMU output messages defined (Configurations 1, 2, and 3, Header, and Data) have a time quality field of 4 bits. This field allows the PMU to state the quality of the time source from clock locked, 1 ns to 10 s uncertainty (estimated worst-case error), or clock failure. Also, the Data message STAT has two bits to indicate the length of time the clock has been unlocked. This varies from locked to unlocked for more than 10 s, 100 s, or more than 1000 s. Other data transport protocols will also have time quality information.

~~Even though a clock may be unlocked for over 1000 s, a quality oscillator is able to maintain better than 1 μ s accuracy over this period. Consult the clock manufacturer's documentation for its drift specification.~~

IEEE Std C37.118.2-~~2011~~ adds a 3-bit PMU time quality field to the status word in place of a previously unused security bit field. When used, this field indicates the uncertainty in the measurement time at the time of measurement and ~~indicates time quality at all times~~, both when locked and unlocked, and unknown when the clock is starting up.

Even though a clock may be unlocked for an extended period, some clocks may be able to maintain sufficient accuracy for longer periods than other clocks. Consult the clock manufacturer's documentation for its drift specification.

4.3 Satellite-based synchronizing sources

This subclause summarizes the satellite-based ~~main~~ technologies that could be adopted for PMU synchronization. Because they are satellite-based, they ~~The following figures of merit~~ have vulnerabilities and countermeasures as described ~~been considered~~ in IEEE Std 2030.101 [B12].

When assessing the performances of ~~the~~ synchronization source technologies, consideration of the following figures of merit is beneficial ~~(Lilley, Church, Harrison) [B37])~~⁷:

- *Accuracy*: The degree of conformance between the measured synchronization signal and its true value.
- *Availability*: The capability of the synchronization system to provide usable timing services within the specified coverage area.
- *Continuity*: The probability that the synchronization system will be available for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation. The factors that affect availability also affect continuity.
- *Reliability*: The probability that a synchronization system will perform its function within defined performance limits for a specified period of time under given operating conditions. It is a function of the frequency with which failures occur within the synchronization system.
- *Integrity*: The ability of the synchronization system to detect the timing signals' degradation and provide timely warnings to users.
- *Coverage*: The geographical area in which the application-specific synchronization system requirements for accuracy, availability, continuity, reliability, integrity, and coverage parameters are satisfied at the same time. System geometry, signal power levels, receiver sensitivity, atmospheric noise conditions, and other factors that affect signal availability influence coverage.
- *Ride-through capability*: The clock accuracy that is maintained and for how long upon loss of satellite synchronization.

⁷~~The numbers in brackets correspond to those of the bibliography in Annex A.~~

4.3.1 Satellite navigation systems

The carrier signals transmitted by Global Navigation Satellite Systems (GNSS) disseminate precise time, time intervals, and frequency over wide geographic areas. GNSS is a generic term [and is described in IEEE Std 2030.101 \[B12\]](#). It may be noted that not all systems are equivalent in satellite orbits or time accuracy.

Satellite-based timing signals are particularly suitable for PMU applications, since they make possible accurate synchronization without requiring the PMU user to deploy the user's own primary time and time dissemination systems. At the same time, GNSS systems provide intrinsic advantages such as wide area coverage, easy access to remote sites, and adaptability to changing network patterns.

Global Positioning System (GPS) is a U.S. Department of Defense satellite-based radio navigation system. It consists of 24 satellites arrayed to provide a minimum worldwide visibility of four satellites at all times [and is described in detail in IEEE Std 2030.100 \[B11\]](#). ~~At the time of publication of this guide, GPS is the most commonly used. GPS derives its timing from a ground-based clock ensemble that itself is referenced to UTC. Each satellite provides a correction to UTC time that the receiver automatically applies to the outputs. The GPS satellites broadcast on two carrier frequencies: the L1 at 1575.42 MHz, and the L2 at 1227.60 MHz. Each satellite broadcasts a spread-spectrum waveform called a pseudorandom noise (PRN) code on L1 and L2, and each satellite is identified by the PRN code it transmits (Lombardi et al. [B38]). At this time, GPS is the most common~~ source of time synchronization for synchrophasor systems.

Timing accuracy is limited by short-term signal reception whose basic accuracy is 0.2 μ s. This accuracy can be improved by advanced decoding and processing techniques, giving actual performance orders of magnitude better than required for PMU application. The inherent availability, redundancy, reliability, and accuracy make it a system well suited for synchronized phasor measurement systems ~~(Holbert, Heydt, Ni [B25] and IEEE Std C37.118.1-2011)~~.

[The Russian Global Navigation Satellite System \(GLONASS\) provides similar capabilities to GPS as described in IEEE Std 2030.101 \[B12\]](#).

[The BeiDou Navigation Satellite System \(BDS\) is a Chinese satellite system as described in IEEE Std 2030.101 \[B12\].](#)

[The Galileo satellite navigation system was created by the European Union as described in IEEE Std 2030.101 \[B12\].](#)

~~The Russian Global Navigation Satellite System (GLONASS) provides similar capabilities to GPS. Sporadic funding, and the resulting inconsistent satellite coverage, have hampered widespread acceptance of the GLONASS system, although it is in some ways superior to GPS with respect to accuracy (Dickerson [B13]).~~

~~These systems, and others to come on line in the future, provide timing accuracy that easily exceeds the needs of the power industry. Future development in receiver technology is expected to provide the ability to receive signals from two or more GNSS systems, though existing receivers generally are limited to a single system. Specifically, international cooperation efforts have led to new GPS and GLONASS signals for new satellite deployments.~~

4.3.2 Timing errors

Timing errors in systems that use satellite-based synchronization may be caused by various sources, including uncompensated antenna cable delays and distribution delays (delay of clock output signals going to PMUs). Uncorrected delays cause errors in the received timing signals at the PMU. The magnitude of the errors can be estimated by dividing the electrical length of the cable with the propagation velocity of the signal along the cable (approximately [4.3 ns/m](#) ~~to it may take slightly longer time for high-dielectric cables, and typically 5 ns/m for signals through optical fibers~~). The errors [can](#) ~~must~~ be compensated ~~in power system applications~~ if they introduce uncertainties not consistent for the desired level of performance.

Loss of signal from one or more satellites (perhaps due to [limited sky view](#) ~~antenna problems or even birds~~) can also reduce the timing accuracy. ~~For, but since the PMU receiver has~~ a known location, [some GNSS receivers](#) ~~it~~ may be [able](#) ~~possible~~ to “lock” this position so that an accurate time may be provided even with only one satellite visible. [Some receivers have a user setting to inform the receiver that the position is fixed. This is suitable for PMUs as their positions are fixed.](#)

4.3.3 Systems vulnerabilities

Satellite-based synchronization systems rely on information transfer over the airwaves. The wireless nature of satellite communications links and the weak power levels of received GNSS signals make them vulnerable to radio-frequency interference (RFI). Any electromagnetic radiation source can act as an interference source, if it can potentially emit radio signals in the GNSS frequency bands. [As PMUs may be reliant on the signals from GNSS, a brief overview of the classification of vulnerabilities follows.](#)

The disruption mechanisms that could limit the GNSS performance can be classified as the following:

- a) *Ionospheric effects*: Sunspot activity causes an increase in the solar flux—charged particles and electromagnetic rays emitted from the sun. This solar flux affects the ionosphere and influences the transit time of satellite signals through the ionosphere. Consequently, the receiver equipment may experience degraded performance in tracking of the satellites due to scintillations, rapidly varying amplitude and phase of the satellite signal. The equatorial and high latitude regions are most severely affected by this increased ionospheric activity (~~Orpen, Zwaan [B57], Volpe [B60]~~).
- b) *Unintentional interference*: If the line of sight to satellites is restricted (e.g., in urban areas, near or under foliage), the synchronization signal quality could deteriorate for short or long periods of time. It is important to have realistic expectations of GNSS availability under conditions where there is not a clear view of the sky.
- c) *Radio-frequency interference*: RFI is caused by electronic equipment radiating in the GNSS frequency band (e.g., television/radio broadcast transmitters, mobile phones). Although transmission is designed to not interfere with GNSS signals, it can radiate at the same frequency as the GNSS signals if it is faulty or badly operated. This interference, if powerful enough, can lead to degradation of the GNSS signal received.

d) *Intentional interference*: Received GNSS signals are extremely weak and can therefore be deliberately jammed by radio interference. The levels of interference needed to jam a typical consumer GNSS receiver are quite low⁷ and jamming equipment can be small. Further intentional interference could be induced by [the following](#):

- 1) Spoofing—Counterfeit signals
- 2) Meaconing—Delay, interception, and/or rebroadcast of navigational signals
- 3) [Physical](#) ~~System~~ damage

[GNSS vulnerabilities are covered in detail in IEEE Std 2030.100 \[B11\].](#)

4.3.4 Countermeasures

The main strategies that could be adopted to protect GNSS receivers from RFI attacks are based on the principle of raising the power levels required by the jammers to disrupt the receivers. This makes attacks too expensive, unsustainable in terms of the power required to run, or easily detectable and therefore readily intercepted.

Mitigation strategies, such as physically shielding the GNSS receiver's antenna from interference sources, rely on prior knowledge of the location of the interference but may be useful under some circumstances.

Intentional spoofing is much harder to mitigate. There are methods [\(Lombardi et al. \[B20\]\)](#) to test and mitigate spoofing, which are telecommunications technology related and are not addressed in this guide. ~~(Wesson, Shepard, Humphreys [B61]).~~

The use of modular and flexible synchronization systems, including multiple external timing signals and local oscillators, can provide a high degree of redundancy to increase reliability and accuracy of the overall synchronization system.

[Countermeasures to GNSS vulnerabilities are covered in detail in IEEE Std 2030.100 \[B11\].](#)

4.4 Alternatives to GNSS: Wide-area time distribution

At the time of this publication, there are no alternatives to GNSS when it comes to wide-area distribution of synchronizing time. However, it is widely known that redundant and differently routed sources of synchronizing time may be required before PMUs can be used in mission critical applications. Several technologies are being researched and developed in this area and this subclause considers those technologies (Goldstein [B5]).

a) Network Time Protocol: ~~(NTP)~~ is a robust and mature technology for synchronizing a set of network clocks; however, its performance is inadequate for typical PMU timing by several orders of magnitude.

b) Precision Time Protocol (PTP): Specified by IEEE Std 1588 is available for local distribution of time (e.g., within a substation) and a number of PMU models can be synchronized to PTP using the IEEE C37.238 power profile and the IEC/IEEE 61850-9-3 Utility Profile for PTP. Wide Area distribution of PTP is being researched and developed at this time.

c) eLoran: LORAN is short for “Long Range Navigation” and was a radio navigation system used worldwide for many decades of the 20th century. By 1991, the system had been phased out and completely replaced by more modern systems such as Loran-C. However, by 2009, most of those systems were being phased out in favor of GNSS. Some private companies began researching eLoran and in 2010, 2014, 2015, and 2016 some U.S. congressional bills supported eLoran as a backup to GNSS. In 2014 Britain began operating some eLoran stations, but in 2016 the European Union pulled its support for eLoran. Theoretically, eLoran has the potential to deliver wide-area time distribution with accuracy similar to GNSS. Research is continuing.

d) Radio station callsign WWV (B and H): In the United States, the National Institute for Standards and Technology (NIST) operates a distributed system of transmitting time via terrestrial radio waves. Typically, the uncertainty of the time is of the order of 100 μ s, which is not sufficient for PMUs. Some experiments have shown that the uncertainty can be brought below 10 μ s without the use of additional repeaters, but with additional repeaters, the uncertainty can be brought low enough to be useful for PMU synchronization. NIST and the National Laboratories are conducting studies to determine what further research and development in WWV time distribution would be beneficial.

As these technologies develop, it remains to be seen whether signals in the frequency bands of eLoran and WWV (60 kHz to 100 kHz) will be useable in the high electrical noise environment of an electrical substation.

As other means of time distribution become available, the prudent approach would be to bring GNSS, as well as one or more of these redundant and differently routed sources into electrical substations and have devices which can compare the timing and seamlessly fail-over and fail-back between the multiple sources. In this case, it would be best then to use a local time distribution within the substation as discussed in 4.5. This means that PMUs with internal GNSS receivers without alternative means of receiving time would not be the most favored solution moving forward.

4.5 Local synchronization distribution methods

Today, many PMUs have internal GNSS receivers and a GNSS antenna input. Some of these also support other means of local time distribution and some PMUs do not contain GNSS receivers but rely on one or more of the local time distribution methods. The following technologies all require a wide area distributed source of synchronizing time. The most common option available in 2018 is GNSS, though some pilot studies using wide-area PTP are being made. Once the wide area time source is available, time can be distributed locally using one of the following technologies:

- IRIG: The IRIG time code is fully described in IRIG Standard 200-16. IRIG can be transmitted in seven different formats, (A through H) IRIG-B is typically used for PMU applications. IRIG-B can be transmitted using three types of modulation:

- [Type 0: Pulse width code, provides sufficient time accuracy but is good only for short distances](#)
 - [Type 1: Sine wave, amplitude modulated, can be used for longer distances but is not accurate enough to be used for PMUs without a pulse-per-second \(1 PPS\) qualifying signal distributed via a second medium](#)
 - [Type 2: Manchester modulated, can provide time accuracy comparable to type 0 without a 1 PPS qualifying signal](#)
- IRIG-B~~1xx~~: ~~The IRIG time code is fully described in IRIG Standard 200~~ repeats each second and has a total of 100 bits per second. Some of these are framing (sync)-bits, some are assigned for time, and some are available for control functions. ~~IRIG-B code may be used in either logic level (unmodulated) format or as an amplitude modulated signal with a 1 kHz carrier (Dickerson [B13]). The modulated IRIG signal is generally capable of accuracy exceeding 1 ms (one period of 1 kHz), but not usually better than 10 μs. The unmodulated IRIG-B code can deliver accuracy limited only by the slew rate of the digital signal, usually better than 1 μs.~~
- IEEE Std C37.237 ~~118.1-2011~~ defines use of the control bits in the IRIG message to provide extensions for real-time applications: leap second and daylight savings or summer time status; year of century; and time quality. These extensions are generally required to meet the requirements of [IEC/IEEE.60255-Std C37.118-1-2011](#).
- 1 PPS: A one pulse per second positive pulse with the rising edge on time with the second change provides precise time synchronization (~~IEEE Std C37.118-2005~~). However, since each pulse is identical there is no way of knowing which second a pulse is associated with. Resolving this ambiguity requires a simultaneous data channel [such as IRIG-B](#).

- [Precision Time Protocol](#): ~~IEEE 1588~~ IEEE Std 1588-2008 specifies a PTP. [IEC/IEEE 61850-9-3](#) and IEEE Std C37.238 [work together to specify a Utility/Power](#) ~~-2011 specifies an IEEE 1588~~ profile for power system applications, ~~such as PMU~~. PTP distributes precise time over Ethernet-based networks over multiple network hops and requires special hardware support at each Ethernet port to achieve high time accuracy. Messages containing precise actual time are transmitted once per second. By adding dedicated timing hardware to each port in a data network, the time of transmission and reception of certain messages can be determined with accuracy sufficient to transfer time with performance comparable to that of an IRIG-B or 1 PPS signal. The protocol supports corrections for variable cable and processing delays in intermediate devices (e.g., Ethernet switches). The protocol needs to be supported by all devices in time distribution chain to achieve 1 μ s time accuracy.

[The PTP utility and power profiles distribute synchronizing](#) ~~IEEE Std C37.238-2011 requires~~ time ~~distribution~~ with ± 1 μ s ~~time~~ accuracy over 16 network hops (~~Annex B~~). At the top of [the](#) time distribution chain, there is a grandmaster clock that synchronizes the clocks in the entire system to UTC. Each device in the time distribution chain (including [any](#) Ethernet [switch](#) ~~switches~~) is required to support [the profile](#) ~~IEEE C37.238-2011~~ to achieve 1 μ s time accuracy. ~~Ethernet switches supporting IEEE C37.238-2011 should perform measurements and corrections for cable delay and residence time (e.g., variable time in which a synchronization message spends inside an Ethernet switch due to queuing and other processing delays).~~

[The profiles specify](#) ~~IEEE Std C37.238-2011 specifies~~ extensions for real-time applications: leap second and daylight savings, local time (if needed), and time quality. In addition, a flag that indicates if provided time is traceable to UTC is supported. These extensions are generally required to meet the requirements of [the PMU standard](#) ~~IEEE Std C37.118.1-2011~~.

[In 2018, PTP does not operate with sufficient accuracy over wireless networks.](#)

4.3.5 Performance testing

~~The performance of commercially available GNSS receivers may vary depending on the receiver hardware and software architecture. For example:~~

— *Satellite selection:* Receivers could adopt different algorithms to automatically select the satellites used in the timing solution (e.g., the satellites providing the best geometric dilution; see Mills [B51]). Moreover, each algorithm could be characterized by a different set of thresholds defining the condition for keeping, dropping or acquiring a satellite. Therefore, different receivers can obtain different results even when connected to the same antenna in the same location.

— *Short term stability:* This is influenced by the hardware architecture of the receiver. In particular, receivers integrating a satellite disciplined oscillator (e.g., an oven-controlled quartz oscillator or a rubidium oscillator) exhibit improved short term stability. To avoid perfect lineup between sampling frequency and satellite spreading code, an alternative technique currently adopted in commercial receivers is based on the employment of a temperature-controlled crystal oscillator for down-sampling of the satellite signals. This type of receiver accumulates time errors until the total error reaches a maximum value (i.e., a multiple of the half period of the oscillator), and then generates a phase step that reduces the time error to a minimum. Some receivers step phase in increments of 100 ns (or less) or 1 μ s (or larger) (Lombardi et al. [B38], Mills [B51]). Consequently, the short term stability of these receivers could vary significantly (although their long term performance may be equivalent to models integrating a disciplined oscillator).

— *Hand off algorithm:* Since the satellite position within the range of the GNSS receiver changes with time as the satellite movements changes the position, various hand off strategies may be implemented in the receivers. The application will determine the level of knowledge and testing needed by the user.

— *“Bad” data management:* Receivers manage satellite broadcast errors in different ways. Although some receivers are equipped by specific software routines able to remove bad data, they might fail under certain critical conditions (Lombardi et al. [B38], Mills [B51]).

Therefore in order to assess the performances of GNSS receivers applied in PMU time synchronization, detailed experimental testing is necessary.

4.3.6 Experimental tests

The minimum set of measures may include tests of the Time to First Fix (TTFF), drift tests (time drift rate after loss of satellite signals), and position accuracy/repeatability. Other tests that may be performed are more suited in a laboratory environment.

TTFF accuracy measurements are most important in the design validation stage of a GPS receiver. The most common TTFF conditions are as follows:

- *Cold start:* The receiver must download almanac ephemeris information to achieve a position fix.
- *Warm start:* The receiver has some almanac information that is less than one week old, but does not have any ephemeris information.
- *Hot start:* The receiver has up-to-date almanac and ephemeris information. In this scenario, the receiver only needs to obtain timing information from each satellite to return its position fix location.

In most cases, TTFF and position accuracy are specified at a specific power level. It is worth noting that it is valuable to verify the accuracy of both of these specifications under a variety of circumstances.

To perform both TTFF and position accuracy measurements, three different sources of data could be adopted:

- a) Live data where the receiver is set up in its deployment environment with an antenna.
- b) Recorded data where a receiver is tested with an RF signal that was recorded off of their.
- c) Simulated data where an RF generator is used to simulate the exact time of week when live data was recorded. When testing a receiver with three different sources of data, it is necessary to verify that the measurements from each source are both repeatable and correlated with other data sources.

4.4 Terrestrial systems

Synchronizing signals may also be disseminated using terrestrial systems (e.g., radio broadcasts, microwave, and fiber optic systems).

~~A time distribution protocol called *Precision Time Protocol* (PTP) is also available now. PTP Version 2 is specified in IEEE Std 1588-2008, and its profile for power system applications is specified in IEEE Std C37.238-2011.~~

~~IEEE Std C37.238-2011 and IEEE Std 1588 do not operate over wireless networks at this time.~~

~~IEEE C37.238 distribution technology offers 1 μ s time accuracy for PMU applications, the use of the same communications infrastructure (Ethernet) for PMU/PDC data and time distribution, and reduced use of GPS connectivity whenever possible. Due to these benefits a rapid adoption of this technology is expected.~~

~~4.5 Synchronization distribution methods~~

~~IEEE Std C37.118.1-2011 requires a PMU to be synchronized to UTC time. UTC time synchronization may be delivered to the PMU by using, for example:~~

5. Synchrophasor measurement accuracy characterization

5.1 Introduction

The measurement accuracy of PMUs (i.e., magnitude and phase, frequency, and ROCOF accuracy) depends very much on the algorithm used for synchrophasor, frequency, and rate of change of frequency estimation as well as the sampling and synchronization hardware. There are many different algorithms, including fixed and adaptive filtering, frequency tracking using fixed and adaptive sample rates, and various internal filter topologies, windowing, and coefficients. PMU accuracy also depends on the configuration of the PMU. The choice of class and reporting rate has a great effect on accuracy, and many PMUs have other configurations affecting the filtering, frequency tracking, transformer compensation, etc. It is recommended that the susceptibility to error of the applications using the PMU data be understood and that the PMU accuracy with the specific configuration and settings with which it will be installed be assessed using the tests outlined in the IEEE Synchrophasor Performance Test Suite Specification (TSS) [B17].

The IEEE Conformity Assessment Program (ICAP) is the worldwide certification authority for PMU conformity assessment. PMUs that have been assessed as conformant with the performance standard are listed on the <https://standards.ieee.org/products-services/icap/certification-registry/index.html>

Most of the PMUs available in 2018 have not been certified compliant with the performance standard and many of them are not compliant. Having non-conformant PMUs in the system may or may not be a cause for concern. Many applications are operating with non-conformant PMUs in 2019. However, when considering system expansion or the addition of new applications, it is a good idea to understand the performance of the installed PMU. This can be accomplished by configuring an example model of those installed PMU as they are configured in the installation and having it tested in accordance with the IEEE Synchrophasor Performance TSS. The test report shows plots of the performance under all conditions mandated by the standard.

Once the error performance of the PMU in a test environment is understood, the error performance in the installed environment can be estimated from the ratings of the CTs and PTs to which the PMU is connected and an estimate of the “accuracy class” of the PMU. Generally, transformers are rated with an accuracy class over a rated dynamic range. System designers want to know what the accuracy class of the entire measurement chain is. By studying the test results from the PMU performance assessment, one could determine an accuracy class. For example, if the TVE for the PMU, under the given dynamic and frequency range of for the system remains below 1%, then it can be considered that the PMU has a 1% accuracy class. If it remains below 0.1% TVE under the given dynamic and frequency range, then it can be considered that the PMU has a 0.1% accuracy class.

The combined accuracy of the PMU and the transformer can be estimated by taking the square root of the sum of the squares of the transformer accuracy and estimated PMU accuracy classes and choosing a reasonably conservative standard accuracy class. For example, the standard accuracy classes are 0.1%, 0.5%, 1%, and 5%. If a PMU remains below 1% and is attached to a 1% class transformer, the root sum of the squares is 1.4%. If a 0.1% PMU is attached to a 0.5% class transformer, then the root summed square (RSS) value is 0.51% or 0.5% accuracy class.

Accuracy class is used by system designers to specify the requirements of a system. For others, knowing the “accuracy class” of the signal chain does not necessarily provide knowledge of the accuracy of some measurement results. For example, if the signal is distorted (as may happen during faults or switching operations), errors greater than the combined accuracy class may be produced in the result.

~~The overall objective of this clause is to provide a method by which users can assess the overall accuracy of the instrumentation channel including their selected instrument transformers and GPS-synchronized phasor measurement equipment. To do this, users should define accuracy characterization tests to be performed on GPS-synchronized equipment, which will provide the necessary information to make informed decisions as to the quality of data obtained with these units. Users should also determine the level of inaccuracy injected into the measurements from instrumentation channels and provide methodologies to quantify this inaccuracy.~~

~~Sources of error include instrumentation channel characteristics, GPS equipment characteristics, and system asymmetries.~~

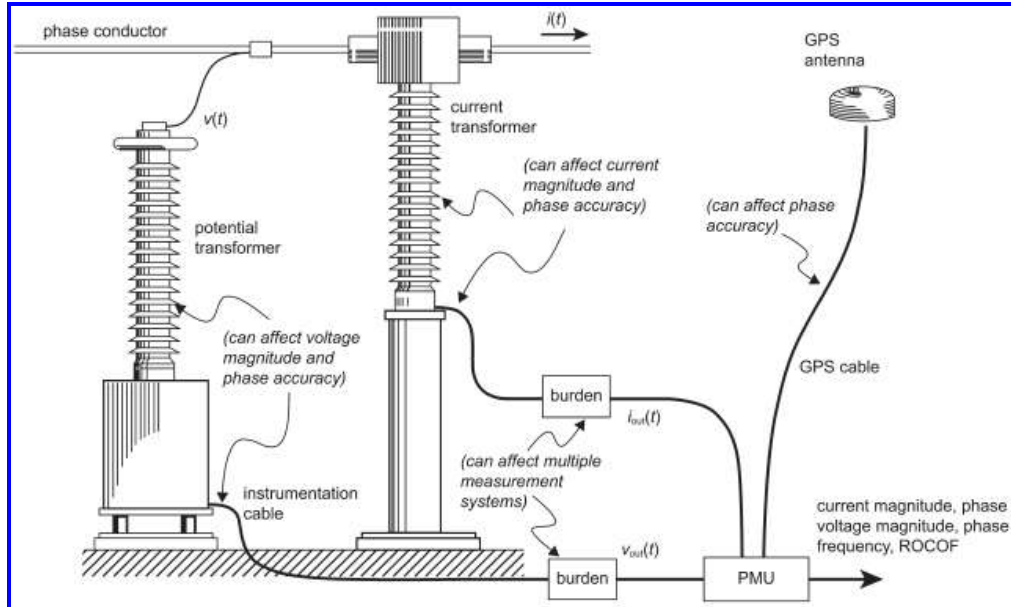
~~The characterization process is separated into two parts, as follows:~~

- ~~- Accuracy for power frequency data (fundamental frequency phasors)~~
- ~~- Accuracy during dynamic changes~~

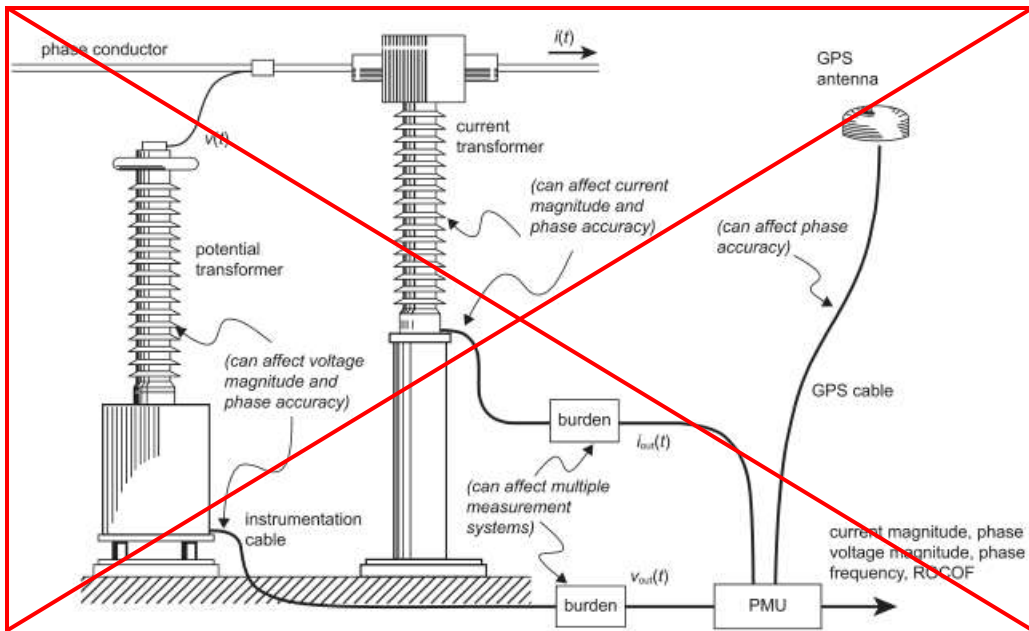
5.2 Steady-state ~~Data~~ accuracy characterization

In a high-voltage application, a system of transformers and cables brings a replica of the signal to be measured to the measuring equipment. One might designate that as a signal path for the instrumentation system; it provides ~~The purpose of the instrumentation channel is to provide~~ isolation from the high-voltage power system and reduces ~~to reduce~~ the voltages and currents to standard instrumentation levels ~~level~~.

Figure 1 illustrates the devices forming voltage and current signal paths ~~channels~~ typically found in electric power substations, along with the parameters they can affect.



(New)



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Figure 1—Typical voltage/potential and current [signal path](#)
instrumentation channels

Ideally, it is expected that the [signal path instrumentation channel](#) will produce ~~at the output~~ a waveform [at the PMU input](#) that will be an exact replica of the high voltage or current, ~~and~~ scaled by a constant factor. In reality, the [signal path instrumentation channel](#) introduces an error. ~~Specifically,~~ Each device in [the path this chain, namely, instrument transformers, control cables, burdens, filters, and analog-to-digital \(A/D\) converters, may contribute to ~~some degree to~~ signal \[modification degradation\]\(#\). Furthermore, the error introduced by one device may be affected by interactions with other devices ~~of the channel~~. It ~~is~~ ~~may~~ thus ~~be~~ important to characterize the overall \[path channel\]\(#\) error.](#)

[5.2.1 Instrument transformers](#)

The first link in the [signal path instrumentation channel equipment chain](#) consists of voltage and current transformers ([VTs and CTs](#)), collectively called *instrument transformers*. These devices transform power system voltages and currents to levels appropriate for driving relays, fault recorders, ~~and~~ other monitoring equipment, isolated from the original quantities.

Several instrument transformer technologies are presently in use. The most common devices are *potential or voltage transformers* (PTs or VTs) and [current transformers \(CTs\)](#) based on magnetic core transformer technology. Another type of commonly used voltage transducer is the *coupling capacitor voltage transformers* ([CCVTs](#) ~~CCVT~~), based on a combination of a capacitive voltage divider and a magnetic core transformer. Voltage and current instrument transformers have also been constructed based on ~~the~~ electro-optical and magneto-optical phenomena. These devices are known as *optical voltage transformers* ([OVTs](#) ~~OVT~~) and *optical current transformers* ([OCTs](#) ~~OCT~~). There are also other sensor and transducer technologies available for voltage and current measurement (e.g., Rogowski coils and Hall-effect devices).

[Instrument transformers are specified under IEEE Std C57.13 \[B16\] and the IEC 61869 series of specifications \[B7\], which has replaced the IEC 60044 series. All of the classical transformers listed in this subclause are specified and some new electronic instrument transformers and a device called a “Stand Alone Merging Unit” \(SAMU\) are standardized in IEC 61869 part 13. Electronic instrument transformers and SAMU output sampled values that may be used in the future as the input to a PMU algorithm.](#)

~~While reference is made to some of these newer types of instrument transformers, this guide mainly focuses on VT, CT, and CCVT devices.~~

~~These varieties of primary sensors allow us to classify instrumentation channels into five common categories, depending on the instrument transformer used, as follows:~~

- ~~a) CT-based instrumentation channel~~
- ~~b) Wound-type VT-based instrumentation channel~~
- ~~c) CCVT-based instrumentation channel~~
- ~~d) OVT-based instrumentation channel~~
- ~~e) OCT-based instrumentation channel~~

~~Although this guide provides information of possible sources of error for each one of the five generic categories listed above, focusing on the top three as~~ The most commonly used instrument transformers are the VT, CT, and CCVT. ~~it is important to realize that~~ Each of these categories ~~may~~ have several options. For example, ~~(e.g.,~~ a CT-based instrumentation channel may be implemented with different accuracy class CTs. See IEEE Std C57.13) [B16] for further information.

Characterization and correction of these errors may be possible. Ghiocel et al. [B4] show the use of state estimation for this purpose . In addition to actual field calibration, in many cases these errors may be accounted for and corrected via software. The following two software approaches are available:

- a) Modeling the instrumentation channel and providing model-based correction algorithms
- b) Using state estimation methods to model the power system and correct the error

A combination of these two approaches has advantages.

Annex D provides examples of instrumentation channel characterization and the effects on the overall accuracy of the GNSS-synchronized measurements. Further work is continuing to develop methods for characterizing the instrumentation channel errors, and algorithms to correct for these errors.

In some jurisdictions, utility regulators have mandated the use of dedicated instrument transformers for revenue or tie-line metering for transformer-connected equipment. Access to transformer secondaries may be controlled. There is a risk that the presence of PMUs may be overlooked when changes are made to the secondary circuits of “shared use” instrument transformers. Due consideration of the steps to be taken to reduce impact on the accuracy of individual PMU installations might be beneficial.

5.2.2 Burdens and cables

Note that for most of the CTs, VTs, CCVTs, ~~CT, VT, CCVT~~ etc., ~~in substations~~, the associated secondary circuit wiring (~~significant component of the instrumentation channel~~) is not normally shielded, twisted-pair “instrumentation class” wiring. ~~In many cases, this wiring is control type cabling (non-twisted pairs) and is often unshielded.~~ Often changes are made to these secondary circuits that affect the overall secondary circuit burden (~~e.g., adding or replacing relays or other devices when electromechanical or static equipment is used, which has a high burden~~), without a detailed engineering analysis of the impact on high-accuracy applications such as the PMU installation. ~~This problem does not exist~~ When the modern microprocessor relays are used, the issue is not as severe because those ~~they~~ have a very low burden. The use of isolating switches, the application of grounds on ~~these~~ secondary circuits, and the presence of nonlinear burdens are a few of the items that can have a significant impact on the accuracy of the instrumentation channel.

5.3 Data accuracy

~~GPS-synchronized equipment has the capability to provide a data acquisition system with the following accuracy:~~

- ~~a) Time tagging with accuracy better than 1 μ s (or equivalently 0.02 degrees of phase at 60 Hz).~~
- ~~b) Magnitude accuracy of 0.1% or better.~~

~~This accuracy may not be available in all GPS-synchronized equipment. Even for the equipment that conforms to IEEE Std C37.118-1 2011, this accuracy cannot be achieved for the overall system in any practical application (e.g., in the substation environment). In addition, depending on the implementation approach and equipment used, the accuracy of the collected data and the reliability of the data availability may differ. Typical GPS-synchronized equipment (PMU) are very accurate devices. However, the inputs to this equipment are scaled down voltages and current via instrument transformers, control cables, attenuators, etc., collectively referred to as the *instrumentation channel*. The instrumentation channel components are typically less accurate. Specifically, potential and current instrument transformers may introduce magnitude and phase errors that can be orders of magnitude higher than the typical PMU accuracy. Although high-accuracy laboratory-grade instrument transformers are available, their application in the substation environment is practically and economically infeasible.~~

~~In some jurisdictions, utility regulators have mandated the use of dedicated instrument transformers for revenue or tie line metering (including those located in high-voltage substations) as well as the application of specific design and testing criteria for the associated secondary circuit wiring. In at least one jurisdiction,~~

~~this secondary wiring is “secured” to help ensure that other devices (burdens) are not inadvertently connected, either permanently or temporarily. In other words, the instrument transformer secondary circuit is carefully designed and tested (measuring actual burdens), and, then, access is controlled to help ensure the ongoing accuracy of the overall revenue metering installation.~~

~~With many users in the long term, there is a risk that the presence of PMUs may be overlooked when changes are made to the secondary circuits of “shared use” instrument transformers. Care should be taken to avoid such inadvertent impact on the accuracy of individual PMU installations.~~

~~The previously described issues are some of the commonly practiced considerations for the purpose of assessing the quality of data from PMUs.~~

5.4 Characterization of instrumentation channels

High-voltage instrumentation channels introduce errors to phasor measurements. The level of error is dependent upon the type of instrument transformers, control cable type and length, and protection circuitry at the input of the PMUs. Table 1 illustrates an example of the errors calculated for a hypothetical ~~specific~~ VT instrumentation channel with 150 m ~~500-ft~~ of cable between the VT secondary and a PMU. Note that the VT itself introduces a very small phase error (0.01 degrees), while the 150 m ~~500-ft~~ cable introduces an error of almost half a degree (which may be corrected using an internal setting in some PMUs) ~~0.54-degrees~~. The overall error is more than an order of magnitude higher than the error of a typical PMU.

**Table 1—Representative signal path ~~instrumentation channel~~ errors—
Example with 150 m (500 ft) of cable between VT secondary and PMU**

Primary voltage		VT secondary voltage	Transformer error	PMU input voltage	Cabling error
$V_{ph-ground}$	62.5 kV 27.52°	62.2 V 27.51°	0.5% 0.01°	61.6 V 27.1°	1.4% 0.40°

(New)

Primary voltage		VT secondary voltage	Error	PMU input voltage	Error
V_{an}	62.53 kV 27.52°	62.19 V 27.51°	0.68% 0.01°	61.63 V 27.11°	1.44% 0.41°
V_{bn}	62.96 kV -92.68°	62.61 V -92.70°	0.55% 0.02°	63.09V -92.85°	0.2% 0.17°
V_{cn}	62.33 kV 147.46°	61.99 V 147.45°	0.54% 0.01°	61.72 V 148.00°	0.98% 0.54°

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In [the](#) case of optical CTs and VTs having analog outputs, the analog interface device [is qualified for PMU related applications. Electronic](#), ~~i.e., the electronic~~ equipment associated with converting the optical CT/VT measurements [of to](#) analog output signals [is considered as part of the overall system](#), ~~must be qualified for PMU related applications~~. Refer to IEEE Std C37.233 [\[B14\]-2009](#) for information related to optical sensor characterization and testing. [For example](#), the interface device introduces signal-processing and conversion latency, typically [on in](#) the order of few tens of microseconds (equivalent to TVE of 1% to 4% if not compensated ~~for~~). There are methods to compensate for delays associated with this signal conversion, ~~either in the optical CT/VT analog interface device (preferred), or within the PMU~~, for example, [delay or phase shift compensation settings in the PMU configuration](#), ~~adjusted time tagging within the PMU (i.e., subtracting sensor latency before generating the PMU time stamp) can yield very accurate synchrophasor data.~~

~~Ultimately, optical sensors providing digital output may be more suited for PMU applications than analog outputs.~~

~~Depending on the instrumentation channel, characterization of these errors may be possible. Meliopoulos, Cokkinides [B45] provides some additional information. In addition to actual field calibration, in many cases these errors may be accounted for and corrected via software. The following two software approaches are considered:~~

- ~~a) Modeling the instrumentation channel and providing model based correction algorithms~~
- ~~b) Using state estimation methods to correct the error~~

~~A combination of these two approaches has advantages. Addressing this issue is important for overall accuracy.~~

~~Annex C and Annex D provide examples of instrumentation channel characterization and the effects on the overall accuracy of the GPS-synchronized measurements. Further work is recommended to develop methods for characterizing the instrumentation channel errors, and algorithms to correct for these errors.~~

~~GPS-synchronized equipment may also be connected to existing instrumentation in substations that may serve other purposes (e.g., metering). For example, the instrument transformers may be connected in an arrangement that generates a phase shift (e.g., delta connection). The resulting phase shift must be accounted for.~~

~~Optical CTs and VTs present an opportunity for more accurate measurement because of their inherently linear response. Nevertheless,~~

5.2.3 Sampled values

IEC 61869-9 [B7] specifies IEC 61850-9-2 as the data transmission protocol from electronic instrument transformers (EIT) and ~~the allows for suitable digital outputs~~ merging units (MU), which provide digital time-tagged measurements of voltage and current signal waveforms with the signal processing delays already accounted for (within the accuracy specification of the digital instrument transformer). In these cases, the PMU function ~~is will be~~ a ~~simple~~ mathematical conversion from “sampled values” to “synchrophasor data” through a purely digital algorithm For additional considerations concerning the use of sampled values for synchrophasor measurement, see Annex E of IEC/ IEEE 60255-118-1:2018 ~~(no analog-to-digital conversion errors), with very consistent accuracy and repeatability.~~

5.2.4 Time system accuracy

UTC time system errors, such as offset in the PMU’s time from UTC time, affects the accuracy of the synchrophasor phase angle. A 1 μ s time offset will result in a phase error of 0.018° at 50 Hz and 0.0216° at 60 Hz. Offsets in PMU to UTC time due to, for example, cabling delays can often be compensated using an internal setting to the PMU.

A check on the performance of the timekeeping system is a necessary part of installation. While a small time error may make little difference to the measurement of amplitude, it translates directly to a phase measurement error and may impact frequency and ROCOF measurements under dynamic conditions.

There are three methods by which the time accuracy can be evaluated:

- Software testing
- PPS comparison
- Clock output comparison

Concentrate on the PPS signal—software-based testing involves parts of the system to which the user does not usually have access, and clock output comparison is valuable if the comparison has to be done at a faster rate than once a second. That is not a requirement for PMU work, which employs clocks that are disciplined with much filtering, and do not change frequency rapidly.

The check on timing is therefore one of comparing the PPS signal from a reference device (almost certainly GNSS-based) with the PPS signal from the PMU, if available, which may be using GNSS or PTP. An oscilloscope enables the user to observe differences in the timing of the PPS signal. There are several cautions to be observed.

First, the connections to the sources of the PPS pulses may involve equipment that is not part of the ordinary operation of the PMU. Thus, what appears as the output of the PPS from the clock may actually be slightly delayed.

Second, the connections to the oscilloscope (or other measuring equipment) involve a cable-length-dependent delay. While not large (less than 5 ns/m), it may have to be taken into account. Third, since the stability characteristics of clocks are not all the same, observation over a period of seconds is advisable, and the result of the observation expressed statistically as a difference and an uncertainty with a given confidence level.

5.3 Accuracy characterization during dynamics

The PMU is designed to measure (estimate) RMS magnitude, phase, frequency, and ROCOF of a power system signal. The results of each measurement are reported for a given moment of time. However, these values cannot be obtained from a single sample of the power system signal at that moment of time but is estimated from a group (window) of samples including the sample at the time of the report. If the signal were constant and without electrical noise, disturbances, or interfering signals (called “influence quantities”), then the estimate could be highly accurate. However, such stability is not a characteristic of a real power system. Electrical noise, disturbances, and other influence quantities exist and minute changes are taking place all the time.

5.3.1 Problem statement

It is known that a signal parameter such as frequency cannot be measured from signal samples at a single point of time (Rutman [B26]). It can be shown that in the absence of noise on the signal, the parameters measured by a PMU can be accurately measured in with a very short observation window. However, with noise on the signal, the measurement takes longer to achieve accuracy.

If the PMU report is needed in a short amount of time (low latency), then the PMUs may take as few as two cycles to make a measurement (P class). However, P class estimates, with short estimation windows, are more susceptible to noise and other influence quantities than the M class estimates, which include many power system cycles of samples. If the measurement results from two different class devices were compared, that fact alone could account for different readings of a real-world signal. Even if the two devices were of the same class, a different result may be obtained because the PMUs are configured for different reporting rates and/or the designers used different filter characteristics for the same configuration of PMU. The effect of the filtering characteristics means that the results of the measurement are not *independent*. Any given result contains some information from earlier measurements, so that the total is dependent on how much the signal parameters are changing. The effect is that when subject to the typical small variations taking place constantly in the power system, PMUs that are compliant with the standard may give results that differ.

5.3.2 Acceptable differences

Given real-world signals, readings from one PMU can be compared to another, but even if one is known to be calibrated, comparing measurements is not to be regarded as a calibration. The uncontrolled nature of the real-world signal being observed makes such a designation inappropriate.

Some observations regarding the results of two PMUs measuring the same power system signal include the following:

- a) If the two measurement systems being compared are connected to the same device, the measurement of voltage or current magnitude is not greatly affected by instrument transformer errors. If there is a burden problem, both may be affected in the same way. The difference between P and M class, using different reporting rates, different PMU algorithms such as frequency tracking versus non-tracking, and other differences may show variations in magnitude under dynamic power system conditions.
- b) The measurement of frequency will not be affected by instrumentation or cabling errors. However, even allowing for the filtering, harmonics on the signal being observed could affect the PMUs differently. That would be especially true if the harmonics were above the level specified in PMU compliance testing, typically 0.2% THD.
- c) Phase error can be caused by uncorrected errors in the UTC timing signal, by uncorrected phase errors in the instrumentation transformers and by cabling and burden related issues.
- d) If the PMU is known to be compliant with IEC/IEEE 60255-118-1, the uncertainty under normal system conditions will be bounded by the requirements of the standard. Compliance may not mean that results are acceptable for all applications that rely on the PMU reports. Some understanding of the application accuracy requirements as well as the performance of the PMU, as configured, is needed for assurance that the application yields the desired results (North American Synchrophasor Initiative, Part F [B22]).

5.5 ~~Characterization of GPS-synchronized measurement devices (PMUs)~~

~~Equipment for synchronized measurements from various vendors may have different designs and, therefore, different ways of data acquisition and processing and different accuracy characteristics. It is expected that devices conforming to IEEE Std C37.118.1-2011 will have matching and perform similarly within the allowed error limits. It is additionally possible for a user to identify specific application requirements and coordinate expected performance with manufacturers.~~

~~Full characterization of a GPS-synchronized device should include error analysis of both timing accuracy and magnitude accuracy over a generally accepted range of operating conditions defined in terms of frequency, frequency rate of change, voltage magnitudes, current magnitudes, harmonics, and imbalances. IEEE Std C37.118.1-2011 defines the standard and testing ranges and limits.~~

5.6 GPS-synchronized equipment reliability

Reliability data for GPS-synchronized equipment are scarce. The few in-service reliability data available from first-generation equipment may not be representative of the present technology. Nevertheless, we have included Table 2 to illustrate reliability data for some PMUs on the western system (North America) over a two-month period in 2002. The synchrophasor system performance analysis typically includes recording of data loss, signal loss, and PMU time synchronization failures. In Table 2, *signal reliability* is the percent of time the system continuously received data from the PMU. *Sync reliability* is the percent of time the PMU is synchronized with a GPS. Note that the few available data indicate that most of the unreliability is due to the GPS signal availability.

It should be emphasized that device quality might have improved significantly since 2002, and many new devices and systems provide much better reliability. This example is only a reference. System reliability additionally depends on system architecture, which, in turn, is influenced by system requirements and purpose.

Table 2—Synchrophasor system performance for a random two-month period in 2002

Station PMU	Reliability (%)		Notes
	Signal	Sync	
GCoul	97.52	99.974	PMU failed after 2 days
JDay	99.929	99.996	Normal, modem
Malin	99.997	93.74	PMU clock failure
Colstrip	99.82	100	Communications system problems
BigEddy	99.99	99.988	Normal, fiber, digital
MValley	99.983	99.74	PMU clock problems
Keeler	99.996	99.95	Normal, modem

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6. PMU installation, commissioning, and maintenance

This clause discusses recommendations for PMU installation, and is based on general installation requirements for PMUs and typical substation [electrical bus](#) configurations. The information found in this clause is only considered a starting point, and is expected to be expanded and modified as [more](#) applications [become available](#) are expanded.

6.1 Overview ~~Preface~~

A PMU installation requires access to the power system signals to be measured and a time signal to time-stamp the measurements (~~see Figure 2). It also requires a communications system to transmit the measurements to a remote location in real time, at the PMU reporting rate and matching the format and the interface.~~ In some cases, the PMU will have binary status inputs (Boolean 1 or 0) to indicate equipment status such as breaker open or closed. ~~or~~ Other measured or computed values (“analog”) ~~inputs~~ such as power (watts/ vars), temperature, wind speed, or power factor, or other synchronous values may also be included as inputs. ~~The choice.~~ ~~PMU communication provides support for analog and digital data as well as phasor, frequency, and rate of change of frequency (ROCOF) data.~~ ~~Access to these~~ signals to be included depends ~~will depend~~ on the system requirements and equipment capability. However, access to these bus signals ~~situation, but~~ needs to be considered at the planning and specification stages. ~~See IEEE Std C37.118.1-2011 for more detail on synchrophasors.~~

A PMU also requires a means to output data to a real-time storage or communications system. To prevent data loss, sufficient bandwidth is required for the planned data set, sent at the PMU reporting rate, as well as all other communications (such as other PMUs).

Other installation considerations include PMU power, local and remote access, and security, both physical and cyber.

6.2 Classification of PMUs

IEC/IEEE 60255-118-1 has defined two classes of performance: P class and M class. In general, P class is intended for applications requiring fast response such as protection and some control applications but is less immune to out-of-band interference such as electronic noise or harmonics. M class is intended for applications that could be adversely affected by aliased signals caused by out-of-band interference yet do not require low measurement reporting latency or short step response time. Some control applications require M class immunity to interference.