

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

IEEE Power and Energy Society

Sponsored by the
Power System Relaying Committee

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

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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; (d) Communications testing for connecting PMUs to other devices including Phasor Data Concentrators (PDCs).

Keywords: calibration, GPS, IEEE C37.242™, PMU, synchrophasor, testing

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Introduction

This introduction is not part of IEEE Std C37.242-2013, 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.

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1. Overview

1.1 Scope

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.

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.¹

IEC/TR 61850-90-5, Ed. 1.0, Communication networks and systems for power utility automation—Part 90-5: Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118.

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

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

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

IEEE Std C37.118.2™-2011, IEEE Standard for Synchrophasor Data Transfer for Power Systems.

IEEE Std C37.233™-2009, IEEE Guide for Power System Protection Testing.

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

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

IRIG Standard 200-04 (2004), IRIG Serial Time Code Formats, Telecommunications and Timing Group, Range Commanders Council, U.S. Army White Sands Missile Range, NM, USA.⁴

3. Definitions, special terms, acronyms, and abbreviations

These definitions, acronyms, and abbreviations are especially pertinent to GPS-synchronized devices, communications protocols, and communications media.

¹ IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch/>). IEC publications are also available in the United States from the American National Standards Institute (<http://www.ansi.org/>).

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⁴ This document available for download at <http://www.irigb.com/pdf/wp-irig-200-04.pdf>.

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.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.

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.

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 Global Positioning System (GPS)-synchronized over a geographically diverse area.

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).

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. 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.

3.3 Acronyms and abbreviations

CT	current transformer
CVT	capacitive voltage transformer
DFR	digital fault recorder
DUT	device under test

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

FPS	frames per second
GNSS	Global navigation satellite system
PMU	phasor measurement unit
PT	potential transformer
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 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 for time referencing, including both satellite (e.g., 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.

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 is required to describe and quantify performance of timing in PMU systems, to meet the accuracy requirements of IEEE Std C37.118.1-2011. 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 IEEE Std C37.118.1-2011, which establishes the relationship between the Coordinated

⁶ Information on references can be found in Clause 2.

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 timing signal generated by the synchronizing source must be referenced to UTC and provide enough information to determine that the time is in agreement with UTC. The synchronization signal must also be available without interruption at all measurement locations throughout the interconnected grid. The timing signal should be characterized by the availability, reliability, and accuracy suitable for power system requirements.

The timing signal 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 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 a flag in the PMU data output (STAT word Bit 13) should be asserted until the data acquisition is resynchronized to the required accuracy level.

In addition to the STAT word Bit 13, 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.

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.

4.3 Satellite-based synchronizing sources

This subclause summarizes the main technologies that could be adopted for PMU synchronization.

The following figures of merit have been considered in assessing the performances of the synchronization source technologies (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.

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

- *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

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. 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. 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. 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 3 ns/m—it may take slightly longer time for high-dielectric cables, and typically 5 ns/m for signals through optical fibers). The errors 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 antenna problems or even birds) can also reduce the timing accuracy, but since the PMU receiver has a known location, it may be possible to “lock” this position so that an accurate time may be provided even with only one satellite visible.

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.

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 low, and jamming equipment can be small. Further intentional interference could be induced by:
 - 1) Spoofing—Counterfeit signals
 - 2) Meaconing—Delay, interception, and/or rebroadcast of navigational signals
 - 3) System damage

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 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.

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 the air.
- 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).

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.

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 requires time distribution with $\pm 1 \mu\text{s}$ time accuracy over 16 network hops (Annex B). At the top of 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 Ethernet switches) is required to support IEEE C37.238-2011 to achieve $1 \mu\text{s}$ 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).

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

IEEE C37.238 distribution technology offers $1 \mu\text{s}$ 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:

- IRIG-B: The IRIG-B time code is fully described in IRIG Standard 200-04. It 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 μ s. The unmodulated IRIG-B code can deliver accuracy limited only by the slew rate of the digital signal, usually better than 1 μ s.

IEEE Std C37.118.1-2011 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 IEEE 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.
- IEEE 1588: IEEE Std 1588-2008 specifies a PTP and IEEE Std C37.238-2011 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.

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 IEEE Std C37.118.1-2011.

5. Synchrophasor measurement accuracy characterization

5.1 Introduction

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 Data accuracy characterization

The purpose of the instrumentation channel is to provide isolation from the high-voltage power system and to reduce the voltages and currents to standard instrumentation level. Figure 1 illustrates the devices forming voltage and current channels typically found in electric power substations. Ideally, it is expected that the instrumentation channel will produce at the output a waveform that will be an exact replica of the high voltage or current and scaled by a constant factor. In reality, the instrumentation channel introduces an error. Specifically, each device in this chain, namely, *instrument transformers*, *control cables*, *burdens*, *filters*, and *analog-to-digital (A/D) converters*, may contribute to some degree to signal degradation. Furthermore, the error introduced by one device may be affected by interactions with other devices of the channel. It may thus be important to characterize the overall channel error.

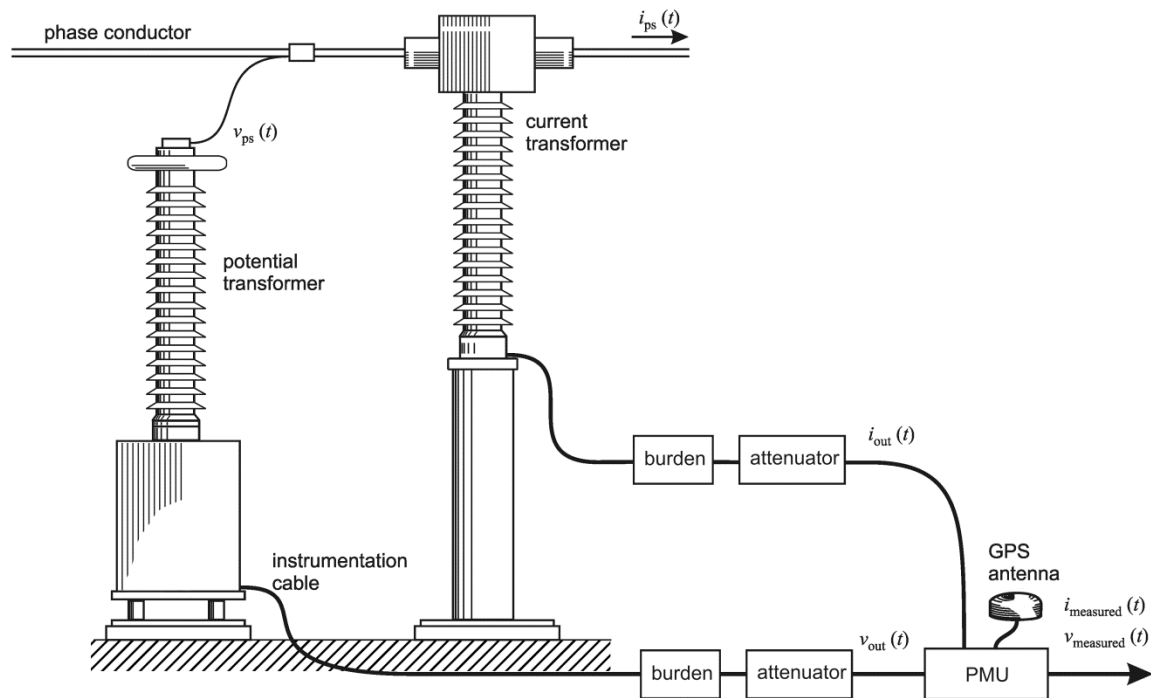


Figure 1—Typical voltage/potential and current instrumentation channels

The first link in the instrumentation channel equipment chain consists of voltage and current transformers (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 CTs based on magnetic core transformer technology. Another type of commonly used voltage transducer is the *coupling capacitor voltage transformers* (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* (OVT) and *optical current transformers* (OCT). There are also other sensor and transducer technologies available for voltage and current measurement (e.g., Rogowski coils and Hall-effect devices). 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, it is important to realize that each of these categories may have several options (e.g., a CT-based instrumentation channel may be implemented with different accuracy class CTs, see IEEE Std C57.13).

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.

Note that for most of the CT, VT, CCVT, etc., in substations, the associated secondary circuit wiring (significant component of the instrumentation channel) is not normally “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 because 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.

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 for a specific VT instrumentation channel with 500 ft of cable between the VT secondary and a PMU. Note that the VT introduces a very small error (0.01 degrees), while the 500 ft cable introduces an error of 0.54 degrees. The overall error is more than an order of magnitude higher than the error of a typical PMU.

Table 1—Representative instrumentation channel errors—example with 500 ft of cable between VT secondary and PMU

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 °

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, in case of optical CTs and VTs having analog outputs, the analog interface device, i.e., the electronic equipment associated with converting the optical CT/VT measurements to analog output signals, must be qualified for PMU related applications. Refer to IEEE Std C37.233-2009 for information related to optical sensor characterization and testing. The interface device introduces signal-processing and conversion latency, typically 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, 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. IEC 61850-9-2 allows for suitable digital outputs from the merging unit, 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 will be a simple mathematical conversion from “sampled values” to “synchrophasor data” through a purely digital algorithm (no analog-to-digital conversion errors), with very consistent accuracy and repeatability.

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 characteristics 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	Reliability (%)		Notes
	PMU	Signal	
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

6. PMU installation, commissioning, and maintenance

6.1 Preface

This clause discusses recommendations for PMU installation, and is based on general installation requirements for PMUs and typical substation configurations. The information found in this clause is only considered a starting point, and is expected to be expanded and modified as applications are expanded.

6.2 Overview

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 status inputs (Boolean 1 or 0) or other measured value (“analog”) inputs such as temperature, wind speed, or power factor. 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 will depend on the situation, but needs to be considered at the planning and specification stages. See IEEE Std C37.118.1-2011 for more detail on synchrophasors.

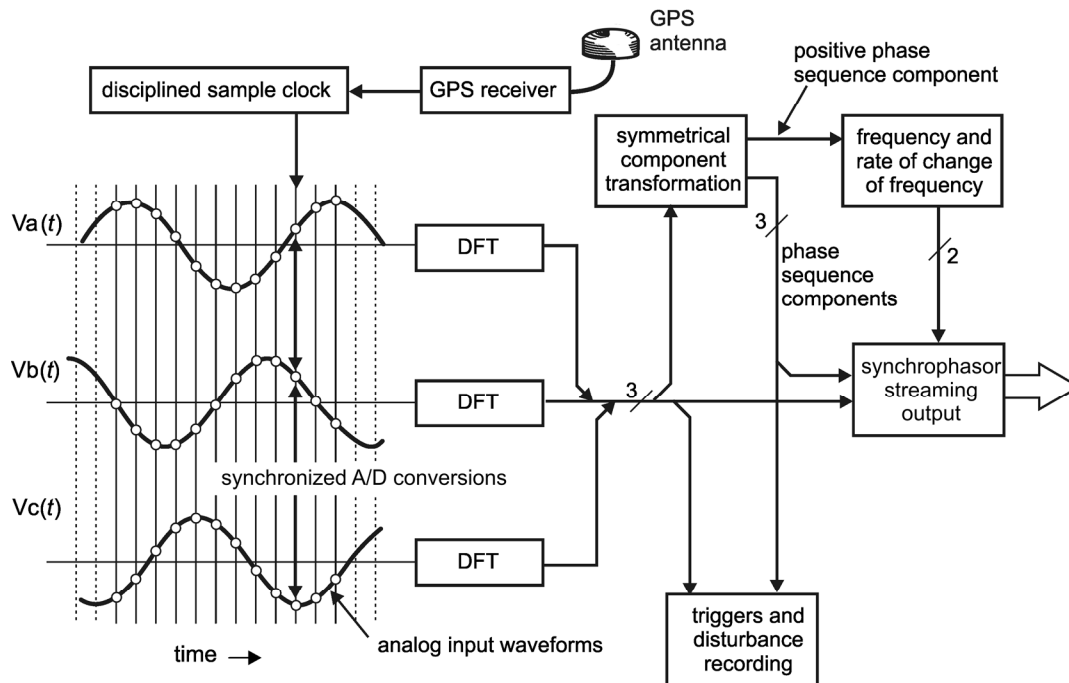


Figure 2—Representative (example) PMU system showing major elements

6.3 Pre-installation procedures

6.3.1 Installation design

In most cases, a PMU installation is considered a permanent installation and requires a complete design. Following are supplementary guidelines to help scope a project and proceed with the design. Typical design includes selection of power system sources, inputs, outputs, alarms, absolute time source, and communications interfaces. Some of the key components of a typical PMU are described in the following subclauses.

6.3.2 Timing input

Timing accuracy is critical. The choice of hardware, antenna location, cabling, and routing of the cable are therefore critical in the overall design of the PMU system. For a GPS system, an antenna open to GPS satellites should have a clear sky view (free from obstructions) above about a 10 degree elevation, so that some satellites are always in view. In cases where this is difficult to achieve, some compromise is possible because the PMU internal clock should be able to ride through complete or intermittent loss of GPS synchronization. When available, it is recommended that the GPS clock be configured with its position LOCKED (a setting in some GPS clocks). With the position LOCKED, the GPS clock can deliver accurate time with only one satellite visible / receivable.

Figure 3 shows recommended antenna mountings. In the northern hemisphere most of the signals will come from the south (see Figure 4). It is expected that there may be obstructions that obscure the sky within ten degrees of the horizon. Above that, good visibility of the sky should be achievable.

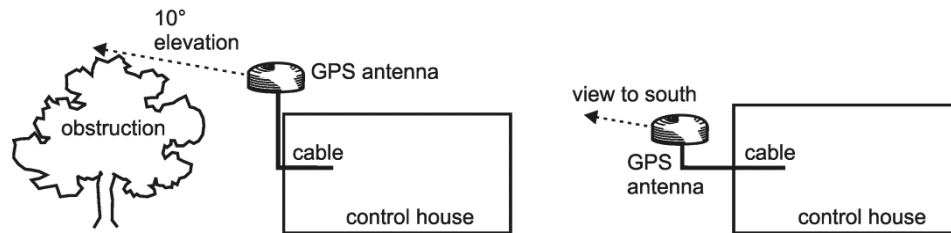


Figure 3—Recommended antenna mounting locations

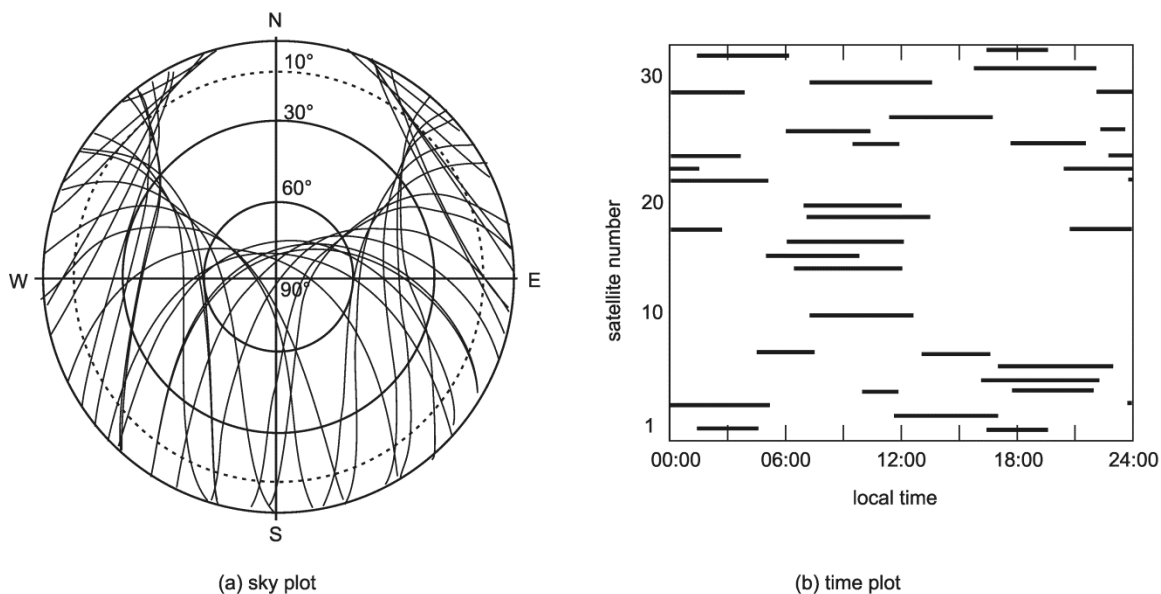


Figure 4—Example of GPS signal visibility pattern reflecting the orbit for various satellites

Figure 4(a) shows what is called a *sky plot* or a *polar plot* of the satellite orbits. It indicates the trajectories of the GPS satellites for a day, essentially the view from a fish-eye lens gazing upward. This particular plot is based on a latitude of 45 degrees north (about the latitude of Minneapolis), so the satellites trajectories across the sky are predominantly to the south. (The satellites would appear to rise in the east and set to the south, or rise in the south and set to the east. At this assumed latitude, some do go directly overhead. If the location were further north, the “hole” in the plot would move down the diagram, as no satellites would go directly overhead.) Figure 4(b) shows the time of day that the various satellites would be visible. At any latitude, at least six satellites should be in the sky at all times, and at this latitude, the number is often as many as nine.

In the northern hemisphere, the antenna should be mounted with a clear view to the south. Small obstructions more than half a meter away from the antenna will not cause a problem, but a large flat obstruction within a few hundred meters could act as a reflector and cause multi-path problems. Check around the mounting location for a structure, such as a flat metal roof, that is oriented so it can reflect a satellite signal to the antenna (keeping in mind satellites will traverse most points in the sky). Also check for obstructions that can block the signal, and high power signal sources that can saturate the GPS input. The most reliable antenna mounting option is an open air sky-view installation.

The satellite synchronization signal (center frequency) is transmitted in the 1 GHz to 2 GHz range, which attenuates rapidly in a cable. Most device suppliers recommend limiting cable runs to less than 50 m. There are alternatives for longer cable distances, such as high-gain antenna or in-line amplifiers and low-loss cable. It is common practice to compensate the time signal to address delays and latency associated with the length of the antenna cable. The cable length could be a straight run from the antenna to the clock receiver and/or the distance within the control room to distribute the clock signal. Cable delay compensation and/or clock offset are also available in some clocks.

When substations do not have adequate lightening protection that includes the antenna location, such as at distribution substations or pole line locations, it is advisable to incorporate a lightning arrestor into the antenna design.

It is common practice to use a signal source that will provide the required signals at the accuracy the PMU requires for meeting timing requirements. Some PMUs input time from a local source, such as a GPS receiver or clock server, using a local signal type such as IRIG-B, 1 PPS, or IEEE 1588. Some of these signals degrade rapidly. Delays are associated with the dielectric constants (i.e., capacitance of cable) and the length of the transmission medium. Therefore, excessive cable runs should be avoided. When using this type of PMU, consult the vendors as to what signals they require and whether the delays are compensated. For example, IRIG-B may be specified and can be used in any of its modulated forms, but the dc level-shift or the modified-Manchester coding forms will allow the highest accuracy. The example shown in Figure 5 uses Manchester time coding.

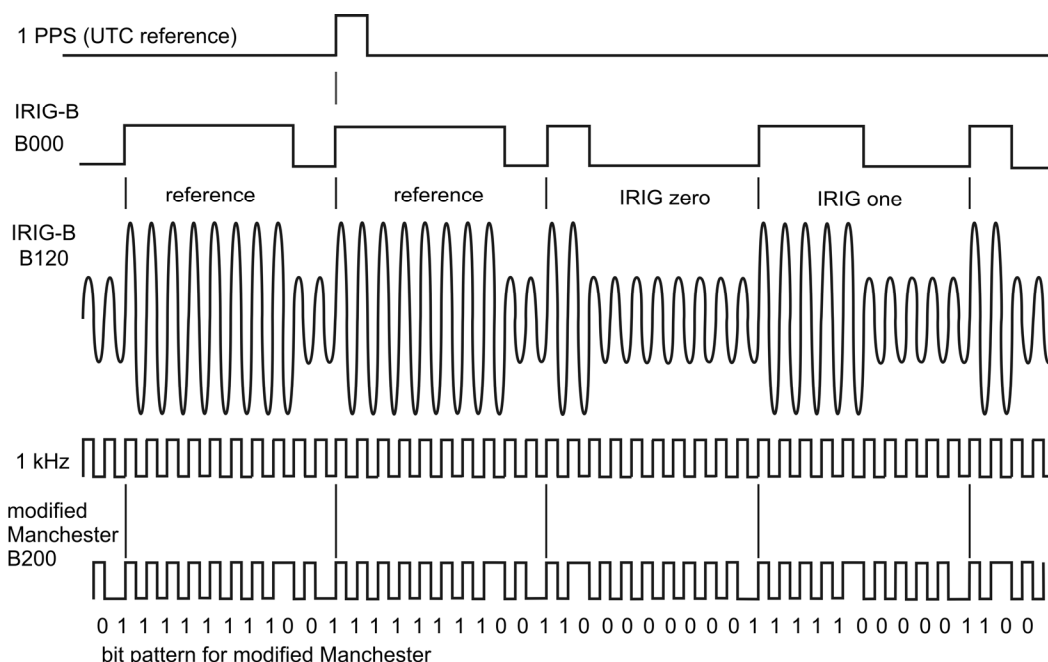


Figure 5—Example showing forms of IRIG-B comparing the unmodulated (level shift) B000, 1 kHz modulated B120, and modified Manchester B200

A GPS-fed clock can potentially serve a number of devices using one IRIG-B output port. The number of clients (users) that a clock can serve depends on both the drive capacity of its IRIG-B port as well as the amount of load (both capacitive and resistive) that the devices connected to the clock represent. The cabling, associated routing, and termination methods also affect the clock loading. To design a highly reliable timing circuit, product specifications should be studied and respective manufacturers may be consulted. Some of the key factors to consider are the following:

- Load and capacitance of the wire/cable—use ultra low capacitance cables. For example, twisted-pair usually has lower capacitance than coaxial cable;
- Cumulative sum of the loads represented by input impedances of all clock clients (PMU and non-PMU) and the associated cabling should not be larger than the clock's output port (IRIG-B port) output serving capacity with some safety margin (e.g., more than 30% margin).
- The impact or presence of redundant clock architecture should be considered. For example, if the application has primary and alternate clock provisions into the respective device input, both clocks need to have similar port output ratings.

The use of fiber-optic time distribution may overcome several of the issues previously referenced.

Signal propagation in cabling should be considered and corrected for longer cables (on the order of 1 ns/ft or 3 ns/m of delay for electrical cables and 5 ns/m for glass optical fibers). Also, dispersion in longer cable length (depending on the amount of effective impedance/capacitance) will be seen as slowing down the rise-time of the clock pulse edge received by the PMU. Accordingly, minimizing cable lengths will be beneficial. When daisy chaining of the clock signal is considered, the user should carefully examine the devices to make sure the receiving device does not process the clock and then pass to other devices that are part of the daisy chaining. Processing time by the first device will introduce delays for the other subsequent devices that are part of the daisy chain.

The type of connector, e.g., screw-terminal versus BNC, usually has negligible impact—all other factors being equal.

When driving several receiving devices from one time signal output, the signal level and termination should be checked to verify adequate signal amplitude and quality are available for the receiving device to lock into the timing signal.

When designing the timing circuit, the substation environment and routing of the cable should also be considered. In larger substations, it may be more practical and economical to use two or more clocks and GPS antennas to serve devices in different parts of the substation as opposed to running long cables to all devices from one clock. This approach also helps with distribution of the load on a given clock.

Some PMUs (and other devices) have options to accept clock signals (through IRIG-B, 1 PPS, etc.) and/or to use an internal GPS clock to provide internal timing information if connected to a GPS antenna. The choice of timing circuit depends on various factors. Generally, sharing GPS antenna signals can become complicated, especially when active antennas (antenna requiring power from the clock) are used. Accordingly, use of a PMU's internal GPS clock connected to the GPS antenna is more practical when the PMU is the only device (or one of very few devices) using the time information. In cases where absolute timing information is necessary for several devices, use of external clock connected via IRIG-B interface (or 1 PPS signal) is more practical. Use of an external clock may also facilitate on-site troubleshooting processes.

It should also be noted that the naming convention for identifying a clock when using 1 PPS signal is not standardized; it is product specific. Consequently, the use of IRIG-B protocol may be more appropriate as opposed to using the 1 PPS signal for sharing clock signals.

6.3.3 Voltage and current input

When possible, the PMU should be installed with test access to the PT and CT inputs so test signals can be injected for performance tests and calibration. When multiple PMU devices are installed, test procedures are required to account for the various sources of current and voltages signals.

Good measurements require consideration of the input signal sources. PT and CT characteristics and cable coupling and other loads may lead to distortion, both in amplitude and phase. PMUs require an accurate time source to generate accurately time-stamped measurements (in accordance with standards such as IEEE Std C37.118.1-2011). The most universally available time source for this purpose is the GPS satellite system. The fundamental GPS time pulse extraction may be augmented by *backup* or *flywheel* oscillators and may be distributed to PMUs internally, by direct connection, or by network.

The PMU measurement and reporting rates must be sufficient to capture the characteristics of interest. Performance standards describe necessary data rate and corresponding bandwidths, but desired parameters will dictate actual rates used. PMU full-scale ranges are a function, also, of the measurement being made and the system used. For example in steady-state configurations monitoring disturbances, full-scale settings will be different from a multifunction device performing protection or fault recording along with steady-state PMU data.

User-defined scaling factors will impact resolution and dynamic range for measurement/monitoring phasor quantities. Scaling factors are application driven. For example, under certain operating conditions, when voltages up to 200% of nominal voltage are of interest, the scaling factor of 50% would be desirable and would prevent the secondary voltage measurements from being clipped. This threshold set point gives some overhead for large swings, but good resolution for nominal input. On the other hand, current values will need a much larger dynamic range. It is very important to consider references to “nominal current” with respect to normal currents on the primary system. When connecting current measurement inputs of the PMU to the CTs, the rating and ratio of the CTs relative to normal primary current levels should be considered. For example, at a wind farm with certain energy generation capability, the nominal primary current may be 400 A while the short circuit duties near the station may be much higher (e.g., on the order of 60 kA). In order to have adequate resolution (and accuracy) at 10% of nominal current (40 A primary), using a protection CT output (operating near 1% of its 3000 A rated value) may not be appropriate.

Fault recording and relaying requires a scale that will accommodate very high currents; phasor measurements are concerned with normal operational and system swing currents that range from somewhat over nominal to light load (10% of nominal). Setting the maximum readable value at about two times nominal will give good measurements at light load and normally will cover swings. However, it may be considered more important to capture all swings and overloads at the expense of lighter loads. If synchronized measurements are desired during faults, values up to 40 per unit (pu) may be considered. Sometimes the PMU is a part of another device, such as a relay or digital fault recorder (DFR) and the calibration will be dictated by another requirement. This is a user consideration where the user needs to be aware of the tradeoffs.

The PMU will also derive frequency from the ac input signals. These are fully user selectable in some PMUs and fixed in others. Some PMUs will allow selecting a backup channel when the primary one has a low signal. To provide a good frequency measurement, it is best to select a voltage input channel that has good signal strength, since these do not vary as much as currents.

6.4 Analog and digital input

Some PMUs allow connecting other measurements such as megawatt (MW) transducers, or sensors for measuring temperature or wind speed. These values will be reported along with phasor values in the time synchronized data packet, which opens up the use of phasor data for many real-time and analysis applications. Generally these data signals are easier to transmit than high-current CT circuits, but they need to be considered. When a PMU provides “status” inputs such a breaker status, these parameters are represented as a Boolean logic (“0” or “1”) single bit in a digital word. Access to these signals is usually not difficult, but again needs consideration during installation.

6.5 Power input

Since PMUs need to operate continuously, and without interruption during disturbances, most applications are designed to connect the PMU to the station dc power. When using station dc, the impact of the dc ripple to the power supply should also be considered to make sure quality or accuracy of the measurements are not impacted. PMU Manufacturers should specify dc ripple immunity.

6.6 Communications

Communications interfaces are critical parts of phasor measurement systems. It is important to carefully plan the system and be sure all aspects are addressed. The first part will be cabling from the PMU to the communications interface device. Next will be the interface medium. The third component is the interface with the PMU. The overall system, including the application end (PDC or other devices), requires complete planning of both the physical and logical networks, both local to the substation and remote, where this Guide only discusses some of the physical design issues at the substation. IEEE Std 1615™ [B31] can be consulted for logical network design issues for substation networks. Station architecture must be considered in the design of the communications interfaces. For example, when an application includes an interface with station bus, the PMU communicates with the station bus processor. Likewise, in process bus applications, the PMU interfaces perhaps through a merging unit to the local data processor.

6.6.1 Cabling

Cabling is required between the PMU and the communications interface (e.g., modem, router). Cable installation recommendations can be found in IEEE Std 525™ [B28] and IEEE Std 1615 [B31], where care should be taken in routing communication cables in existing cable trays. The principal issues are interference and cable length. An additional consideration is the impact of the secondary voltage during a nearby fault. When possible, use fiber-optic (FO) cable for all signals that travel outside of a single rack (grounding unit). Care should be taken with communications cable to ensure that the length does not exceed maximum specified distances, as shown in Table 3. In addition, IEEE Std 1615 should be followed regarding the application of FO and copper cabling for serial and Ethernet cables. If the signal is to run between buildings (e.g., between a control building and a communications interface building), it is best to use FO cables. In some cases, this requires signal converters at each end, but many vendors have FO communication ports built into their equipment.

When metallic cables are used, considerations should be given to minimize the most likely sources of interference. Coaxial cable has good electrostatic shielding but is subject to electromagnetic interference, particularly where ground differences can occur (conduction through the ground). Shielded twisted pair (CAT5) has good rejection for both electrostatic and electromagnetic interference, but all shielding has limitations. High magnetic fields can penetrate most kinds of shielding and are best treated with appropriate grounding and bonding practices. It is best to route cables with some thought as to what is in close proximity. Also note that many substation cables are large and heavy, so they may pinch a poorly routed communications cable, which may result in loss of shielding and transmission properties. Table 3 summarizes the signal types, the recommended and practical length, and some comments.

In addition to the physical installation considerations, the communication types need to match in type and rates. Some, but not all, PMUs can report at higher rates than required by IEEE Std C37.118.1-2011, if required by the application.