North American SynchroPhasor Initiative (NASPI)

Performance & Standards Task Team (PSTT)

Guidelines for Synchronization Techniques

Accuracy and Availability

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i. Disclaimer

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Table of Contents

1.0 Introduction

The document presents a critical review of the main technologies available for Phase Measurement Units synchronisation. In particular, after discussing the basic principles of clock synchronization and timing reference for geographically distributed PMU and their impact on the phase measurement accuracy, the document analyses the main synchronization sources adopted for timing reference. In this connection both satellite (i.e. GPS, GLONASS, GALILEO, etc.) and terrestrial (i.e. LORAN, Network Timing Protocol) based technologies are considered. The main performances (i.e. timing errors) and the potential vulnerabilities (i.e. robustness toward intentional and unintentional interferences) of these techniques are also reported.

The documents presents also testing procedures and laboratory testing (i.e. periodic Timing Signals Measurement, measurement of Two Consecutive Timing Signals) aimed at assessing the main performances of synchronization sources (i.e. short term stability, "bad" data management , handoff algorithm) .

Finally some issues about the "synchronization distribution infrastructure" are presented and discussed.

2.0 The role of synchronization techniques in PMU

Electronic clocks in Phase Measurement Units (PMU) devices keep inaccurate time. They are likely to vary due to manufacturing defects, changes in temperature, electric and magnetic interference, the age of the oscillator, or even computer load. Additionally, even the smallest errors in keeping time can significantly add up over a long period. The types of inaccuracies that exist in PMU clocks are difficult to classify. Some clock variations are random, caused by environmental or electronic variations; others are systematic, caused by a miscalibrated clock.

Consequently correct operation of PMU requires a common and accurate timing reference. The reference is determined by the instant at which the samples of the nodes voltages and currents are acquired. This acquisition could be realised by synchronising directly the samples to the timing reference (i.e. 1 PPS signal through the hardware) or by a software based post processing of the acquired samples. In order to achieve a common timing reference for the PMUs acquisition process, it is essential to achieve an accurate synchronization of the sampling pulses. This requires the deployment of a source of timing signals (i.e.: synchronizing source) that may be internal or external to the PMUs. In the first case the synchronization source is integrated (built-in) into the PMUs while, in the latter case, the timing signals are provided to the PMUs by means of an external source, that may be local or global, and a distribution infrastructure (based on broadcast or direct connections).

The timing signal generated by the synchronizing source should be referenced to Coordinated Universal Time (UTC). It should provide enough time information to determine second-of-century in agreement with UTC. It must be available without interruption at all measurement locations throughout the interconnected grid. The timing signal should be characterised by a degree of availability, reliability, and accuracy suitable with the power system requirements.

The timing signal shall be accurate enough to allow the PMUs to maintain synchronism with an accuracy sufficient to keep the Total Vector Error-TVE (i.e. the magnitude of the vector difference between the theoretical phasor and its estimate computed by the PMU, expressed as a fraction of the magnitude of the theoretical phasor) within the limits defined in [1] for the user-required compliance level (i.e. level 1 is intended as the "standard" compliance level; level 0 is provided for applications with requirements that cannot be served with level 1).

In this connection it is important to note that an uncertainty of 1 microseconds on the synchronization signal leads to a phase error of 0.022/0.018 degrees for a 60/50 Hz system. Thus a maximum synchronization uncertainty of 26/31 microseconds for a 60/50 Hz system (corresponding to a phase error of 0.57 degree) cause a 1% TVE (assuming that the magnitude of the signal is 100% accurate).

The PMU should detect a loss of time synchronization which cause the TVE to exceed the allowable limit or within 1 min of actual loss of synchronization, whichever is less [1]. In this case a particular 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, the standard [1] specifies further signals aimed at assessing the time quality of the synchronization source. In details each of the four PMU output messages defined in [1] (Configurations 1 and 2, Header, and Data) have a time quality field of 4 bits. This field estimates the uncertainty of the source from clock locked, or uncertainties from 1 ns to 10 s, 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 10s, 100s, or more then 1000s.

3.0 Synchronizing sources

This section reports a critical review of the main technologies that could be adopted for PMU synchronisation.

The following figure of merits have been considered in assessing the performances of the synchronisation source technologies [14]:

- **Accuracy** - It is the degree of conformance between the measured synchronization signal and its true value.
- **Availability** - It is the capability of the synchronization system to provide usable timing services within the specified coverage area.
- **Continuity** - It is the probability that the synchronisation 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**- It is a function of the frequency with which failures occur within the synchronization system. It is the probability that a synchronization system will perform its function within defined performance limits for a specified period of time under given operating conditions.
- **Integrity** - It is the ability of the synchronization system to detect the timing signals degradation and to provide timely warnings to users.
- **Coverage** - It is the geographic area where the application-specific synchronisation 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.

3.1 Satellite Navigation Systems

The carrier signals broadcasted by Satellite Navigation Systems disseminate precise time, time intervals, and frequency on wide geographic areas.

The employment of satellite based timing signals could be particularly suitable since it could make possible the realization of an accurate PMUs synchronization without requiring the deployment of primary time and time dissemination systems and assuring, at the same time, a set of intrinsic advantages such as wide area coverage, easy access to remote sites and adaptable to changing network patterns. The only user cost is for the receiver equipment, although fees may be levied in future satellite systems.

The 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 is steered by a ground-based cesium 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 1227.6 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 [7].

With this continuous adjustment, timing accuracy is limited only by short-term signal reception whose basic accuracy is 0.2 microseconds. This baseline accuracy can be improved by advanced decoding and processing techniques. The inherent availability, redundancy, reliability, and accuracy make it a system well suited for synchronized phasor measurement systems [1,5].

The new INMARSAT system satellites will carry a GPS-like transponder. The signal will be similar to existing GPS transmissions, so it can be used with slightly modified GPS receivers. INMARSAT satellites are geostationary, which may make reception difficult at some locations.

The Russian GLONASS (Global Navigation Satellite System) provides similar capabilities to GPS. Sporadic funding of GLONASS 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 [2].

The European Space Agency (ESA) GALILEO system is the third global satellite time and navigation system to come on line. It comprises a constellation of 30 satellites divided among three circular orbits at an altitude of 23222 km to cover the Earth's entire surface. Galileo will have an integrity signal to ensure the quality of the signals received and to inform the user immediately of any error. The GALILEO time precision in terms of time errors (95% confidence) for different signals range from 0.7-8.1 ns [3].

China is also considering developing its own GNS system, called Beidou.

These systems 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 even more GNS systems, though existing receivers generally are limited to a single system.

3.1.1 Timing errors

Timing errors in satellite based synchronization systems could be due to antenna cable delays and distribution delays (delay of clock output signals going to PMUs). Uncorrected, these delays cause errors in the output of the Satellite clock. The magnitude of the errors can be estimated by dividing the electrical length of the cable with the propagation velocity of the signal along it, typically they are closer to 5 ns per meter. These errors should be compensated in power-system applications if they introduce uncertainties not suitable with the desired level of performance.

3.1.2 Systems vulnerabilities

Satellite based synchronization systems greatly relies on information transfer over the air interface. This wireless nature of satellite communications links and the weak power levels of GNS signals make them vulnerable to radiofrequency interference. Any electromagnetic radiation source can act as an interference source, if it can emit potential radio signals in the satellite signals frequency bands.

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

1. Ionospheric effects: The 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 [12,13].
2. Unintentional Interference: since satellite signals travel through the upper reaches of earth's atmosphere, they can be affected by solar disturbances. Moreover, when there will be restricted lines of sight to satellites (i.e. in urban areas, near or under foliage) the synchronization signal quality could deteriorate for short or long term. It is important to have realistic expectations of GNS availability under conditions where there is not a clear view of the sky.
3. Radio Frequency Interference (RFI): It is caused by electronic equipment radiating in the GNS frequency band (i.e. television/radio broadcast transmitters, mobile phones). Although transmitter equipments are designed to not interfere with GNS signals, they can radiate at the same frequency as the GNS signals if they are faulty or badly operated. These interferences, if powerful enough, lead the GNS receiver to badly receive the satellite signals.
4. Intentional Interference: GNS signals are extremely weak. Therefore they can be deliberately jammed by radio interference. The levels of interference needed to jam a typical consumer GPS receiver are quite low and jamming equipment can be small. Further intentional interferences could be induced by:
   - Spoofing – Counterfeit Signals
   - Meaconing – Delay & Rebroadcast
   - System Damage

3.1.3 Countermeasures

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

The main mitigation techniques that could be adopted are [4]:

1. The employment of a “Controlled Reception Pattern Antenna” (CRPA) that has the capability of determining the direction of the jamming source and modifying its antenna reception pattern to ignore signals from that direction;
2. The implementation of a narrowband interference processing that attempt to measure the frequency of the jamming signal and then ignore it. This technique only works well when the frequency band of the jamming signal is much narrower than that of the GNS satellite signal.
3. The adoption of a jamming signal to thermal noise (J/N) ‘powermeter’ that measure the total amount of power received by the antenna, and knowing the amount of power expected from thermal noise, it estimate the amount of received jamming power. In this way, the receiver can monitor the likelihood of becoming jammed and inform the user of its reliability.

Other mitigation strategies, such as physically shielding the GNS receiver’s antenna from interference sources, rely on a-priori knowledge of the location of the interference but may be useful under some circumstances.

Intentional spoofing is much harder to mitigate since a very high level of technical expertise is required to successfully deploy a spoofing attack and the equipment to successfully conduct an attack is relatively expensive, the risk associated with encountering such a threat is very low.

Further countermeasures that can be applied to effectively address both the intentional and unintentional interferences are based on the redundancy of the synchronization source.

In this connection the employment of local oscillators (i.e. quartz or rubidium oscillators) and/or multiple (complementary) timing signals have been proposed as possible solution strategies [15,16]. These “back-up systems” come into effect in the case of a GNS failure providing a more reliable timing source. Plus, if one signal is degraded or unavailable, the receiver should still operate within overall system requirements.

In this field an established solution is ensemble time base generation, in which various weighting factors based upon the predicted or measured accuracy and stability of various different time sources (i.e. Loran and GPS [16] or Galileo and GPS [17]) are taken into account to provide a disciplined time scale generator (i.e. steer the frequency and phase into alignment with an external reference source).

The employment of modular and flexible synchronisation systems that include multiple external timing signals and local oscillators can provide a high degree of redundancy to ensure reliability and accuracy of the overall synchronisation system.

3.1.4 Performances testing

The performances of the commercially available GNS receivers could sensibly vary in function of the receiver hardware and software architecture and, in particular:

- **Satellites selection**: the receivers could adopt different algorithm to automatically select the satellites used in the timing solution (i.e. the satellites providing the best geometric dilution [8]). Moreover, each algorithm could be characterised 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**: It is influenced by the hardware architecture of the receiver. In particular the receivers integrating a satellite disciplined oscillator (i.e. an oven controlled quartz oscillator or a rubidium oscillator) exhibit good performances in term of 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-conversion and sampling of the satellite signals. This type of receivers accumulate 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 micros (or larger) [7,8]. Consequently, the short term stability of these receivers could be very poor (although their long term performance may be equivalent to models integrating a disciplined oscillator).
- **Handoff algorithm**: since each satellite is visible at a given location for a limited time, the receiver should adjourn the satellites group used to obtain the time information. To support this complex activity various handoff strategies could be implemented in the receiver firmware.
- **“Bad” data management**: receivers could 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 [7,8].

Therefore in order to assess the performances of GNS receivers applied in PMUs timing synchronization, detailed experimental testing is necessary.

3.1.5 Laboratory measurements

Experimental testing aimed at assessing the GNS receiver performances should comprise the following laboratory analysis:

1. Periodic Timing Signals Measurement
2. Measurement of Two Consecutive Timing Signals:
3. Short-term stability test
4. Long-term stability test

The minimum set of measures that should be adopted to test a GPS receiver comprises sensitivity, time to first fix (TTFF) and position accuracy/repeatability.

Sensitivity is one of the most important measurements of a GPS receiver's capability. It defines the lowest satellite power level at which a receiver is still able to track and achieve a position fix on satellites overhead. To amplify the received signal to the appropriate power level, GPS receivers integrate several cascaded Low Noise Amplifiers (LNAs). This improves the received signal power but it also degrades SNR. Consequently, as the RF power levels of a GPS signal decrease, SNR decreases and eventually the receiver will no longer be able to track the satellite.

Sensitivity can be assessed by measuring the receiver's carrier-to-noise (C/N) ratio at a known satellite power level.

The typical test system adopted for single-satellite sensitivity measurement employs a simulated L1 single-satellite carrier feeding the RF port of the DUT through a direct connection. To report the C/N ratio, the DTU should be configured to communicate via the NMEA-183 protocol. According to the GPS specification documents, the power of a single L1 satellite should be no less than -130 dBm at the Earth's surface.

The first step in developing this measurement is to perform a basic system calibration process aimed to assess the RF power level accuracy of the adopted laboratory equipment. This process is oriented to determine the exact power of the test stimulus. System calibration can be carried out by connecting the simulated L1 single-satellite carrier to an RF vector signal analyzer by using the exact same cable adopted to test the DUT. In particular, since receivers report C/N to with 0 digits of precision (i.e. 34 dB-Hz), sensitivity measurements in production test are made within ± 0.5 dB of power accuracy. Thus, it is important to ensure that the adopted instrumentation will be characterised by equal or better performance.

After the measurement system has been calibrated, it is possible to measure the sensitivity by programming the RF generator to the power level at which the receiver is expected to return the minimum C/N. The C/N ratio that can be achieved at a given power level is determined by the noise figure of the entire receiver.

To measure sensitivity several strategies can be adopted. Since RF power is directly correlated with sensitivity, it is possible to measure the receiver's C/N ratio at the given sensitivity power level, or derive sensitivity based on RF power at a different power level. Once the C/N ratio has been measured, it is possible to calculate the noise figure of the receiver or chipset which is directly proportional to the RF power level and the C/N ratio.

To measure the other figure of merits characterising the receiver's accuracy (i.e. time to first fix, position accuracy, and dilution of precision), it is necessary to employ a test stimulus which simulates multiple satellites. This happens because these measurements require the receiver to obtain a position fix and, consequently, it should acquire at least four satellites.

Time to first fix (TTFF) and position accuracy measurements are most important in the design validation stage of a GPS receiver.

The most common TTFF conditions are:

- 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: A hot start occurs when a 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: 1) live data where the receiver is set-up in its deployment environment with an antenna, 2) recorded data where a receiver is tested with an RF signal that was recorded off of the air, and 3) simulated data where an RF generator is used to simulate the exact time-of-week when live data was recorded. By 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.

3.2 Terrestrial systems

Synchronizing signals may also be generated from terrestrial systems as far as radio broadcasts, microwave, and fiber-optic transmission systems are concerned.

LORAN (LOng RAnge Navigation) is a terrestrial radio navigation system based on low frequency radio transmitters. Loran uses ground based transmitters that only cover certain regions. Coverage is quite good in North America, Europe, and the Pacific Rim. The current version of LORAN in common use is LORAN-C, which operates in the low frequency portion of the EM spectrum from 90 to 110 kHz. LORAN suffers from electronic effects of weather and the ionospheric effects of sunrise and sunset. Magnetic storms have serious effects as with any radio based system [9,10].

The Network Time Protocol (NTP) is a robust and mature technology for synchronizing a set of network clocks using a set of distributed clients and servers over packet-switched, variable-latency data networks [8]. It is built on the User Datagram Protocol, which provides a connectionless transport mechanism. It is evolved from the Time Protocol and the ICMP Timestamp message and is a suitable replacement for both.

At the top of any NTP hierarchy are one or more reference clocks synchronized to a common time reference and each other using some methods outside the scope of NTP (i.e. GPS signals, radio signals, or extremely accurate frequency control). Reference clocks are assumed to be accurate. The accuracy of other clocks is judged according to how “close” a clock is to a reference clock, the network latency to the clock, and the claimed accuracy of the clock. It not only corrects the current time, it can keep track of consistent time variations and automatically adjust for time drift on the client. Flexibility of the client/server relationship and security methods allow NTP to work well in many environments and on a wide variety of platforms [11].

The version 4 of the NTP can usually maintain time to within 10 milliseconds (1/100 s) over the public Internet, and can achieve accuracies of 200 microseconds (1/5000 s) or better in local area networks under ideal conditions.

In environments that need more accurate time than an Internet link will allow (due to latency or other concerns), or environments that cannot rely on Internet time sources due to security implications, a radio time clock or GPS system (or cesium clock), can be used to keep the primary NTP servers aligned with UTC.

4.0 Synchronization distribution infrastructure

PMUs acquisition shall be synchronized to UTC time derived from the previously described synchronizing sources. UTC time and synchronization may be provided to the PMU by using

- IRIG-B: IRIG-B time code is fully described in IRIG STANDARD 200-04 [6]. 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 [2]. The modulated IRIG signal is generally capable of an accuracy exceeding one millisecond (one period of 1 kHz), but not usually better than ten microseconds. The unmodulated IRIG-B code can deliver accuracy limited only by the slew rate of the digital signal, much better than one microsecond.
- 1 PPS: A one pulse per second positive pulse with the rising edge on time with the second change provide precise time synchronization [1]. However, since each pulse is identical, and there is no way of knowing which second a pulse is associated with, the 1 PPS signal has a one-second ambiguity. Resolving this ambiguity requires a simultaneous data channel.
- high-precision format time code: The high precision format described in the IEEE Standard 1588 provides hardware-level time accuracy using a standard network connection. In particular 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 comparable to that of an IRIG-B or 1 PPS signal.

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