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# NASPI TECHNICAL REPORT

# LEAP SECOND EFFECTS ON SYNCHROPHASOR SYSTEMS -- RECENT LEAP SECOND EXPERIENCES

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## Disclaimer

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Other significant contributors included:

- Jeff Dagle, Pacific Northwest National Laboratory
- Magnus Danielson, Net Insight
- Allen Goldstein, National Institute for Standards & Technology
- Xiaochuan Luo, ISO-New England
- Sarah Mahmood, U.S. Department of Homeland Security
- Robert Orndorff, Dominion Virginia Power
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# 1) Introduction and summary

Recent timing events – principally the leap second shifts of 2012 and 2015 and the January 2016 GPS constellation error – have revealed many different impacts and means of failure for the timing devices that serve synchrophasor systems, and the interaction between the timing systems and the devices they connect to. This technical paper summarizes those impacts and failures without identifying either device vendors or models nor the affected companies.

The purpose of this paper is to document these problems to accelerate their resolution, and to warn synchrophasor system owners and other members of the electric industry that they cannot assume that timing delivery systems and synchrophasor equipment will operate smoothly through future leap second events. The next leap second is scheduled for December 31, 2016. Other leap second adjustments have not been announced yet, but a comparable timing event will occur on April 16, 2019 with the GPS epoch roll-over.[1]

Because synchrophasor technology is so dependent on precise, accurate timing to synchronize data on grid events, the North American Synchrophasor Initiative issued an alert to the synchrophasor community warning them before the June 30, 2015 leap second event, and asked members to share their observations of any problematic or anomalous synchrophasor system behavior associated with the event. In parallel with this effort, staff at the National Institute for Standards & Technology conducted a monitoring and analysis effort of PMU and clock behavior during the leap second. This paper summarizes the reports collected from these experiences and study (although it does not identify most of the utilities or equipment vendors involved).

Incorrect GPS clock handling of leap seconds, phasor measurement unit (PMU) handling of leap seconds, and poor interoperability between clocks and PMUs have caused:

- Poor time-stamping of grid measurements
- Duplicative and/or missing grid measurements
- Erroneous interpretation of PMU data
- PMU or clock failures from seconds to hours in length
- Dropped PMU measurements at the PDC due to perceived latency of incoming data frames due to the mis-match between PMU and PDC time-stamps.

It is worth noting that the problems described below are not problems caused by mis-performance of the GPS system per se; rather, they result from poor handling in and

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[1] The GPS time reference was designed to count the number of weeks since GPS went into use in 1980, and the number of seconds in the week. The bit count was designed to be 10 bits long, so it ranges from 0 to 1023, and repeats every 1024 weeks. The GPS week counter reached its first maximum on August 21, 1999 and reset to zero; it will reach its second reset to zero on April 6, 2019. See, for instance, http://www.npl.co.uk/reference/faqs/when-and-what-is-the-gps-week-rollover-problem-(faq-time) and http://www.usno.navy.mil/USNO/time/gps/gps-week-number-rollover . This roll-over event is expected to confuse some GPS-based equipment or software.

along the chain of software and hardware devices from the GPS receivers, the GPS clocks, PMUs, phasor data concentrators (PDCs), and network communications that process and handle the GPS time signal. The processing problems described below are sufficiently diverse that they reflect a variety of causes for failure, and therefore cannot be resolved through a few simple measures.[2] It is generally regarded as the responsibility of the vendors of the GPS timing equipment or software, rather than the GPS system, to account for and manage transitions such as leap seconds or epoch roll-overs.[3]

If PMU data were being used for mission-critical operations, such failures could cause problems as simple as lessened system visibility and situational awareness, or as significant as undesirable actions such as triggering system protection schemes or wide area control schemes that could complicate or compromise grid reliability.[4]

At the end of this paper, we offer some recommendations for users to address the leap second problem, and for institutional action to resolve some of the causes of the leap second problem and its adverse impacts upon users. It is also worthwhile for users to review the Department of Homeland Security's recommended best practices for handling the 2016 leap second.[5]

## 2) Leap seconds

Terrestrial time is based upon the earth's rotation, which changes in very small ways over time.[6] The leap second is a one-second adjustment to UTC time to assure that precise scientific time remains in sync with observed astrological time.[7] The number of leap

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[2] In principle, we could avoid GPS leap second processing failures by eliminating leap second adjustments (which has been proposed). However, such a solution lies beyond the scope and time horizon of this paper.

[3] See, for instance, http://www.usno.navy.mil/USNO/time/gps/gps-week-number-rollover.

[4] For examples of how failure to manage timing signals correctly affected the telecommunications and broadcast industries, which do use timing in mission-critical ways, see, "GPS Incident on Broadcast Networks, revision A6," by Magnus Danielson, Net Insight, April 20, 2016, prepared for the U.S. Civil GPS Service Interface Committee, at http://www.rubidium.se/~magnus/papers/GPSincidentA6.pdf .

[5] https://ics-cert.us-cert.gov/Best-Practices-Leap-Second-Event-Occurring-31-December-2016.

[6] Terrestrial time relative to the stars is measured as UT0. UT1 is corrected to time UT0 to account for the impacts of polar motion due to irregularities in the Earth's rotation. (See, for instance, http://tycho.usno.navy.mil/systime.html or http://www.stjarnhimlen.se/comp/time.html ).

UT1 is what we refer to as UTC (Coordinated Universal time) or Greenwich Mean Time. UTC lags behind the TAI (Temps Atomique Internationale), which counts Standard International seconds (http://www.npl.co.uk/reference/measurement-units/si-base-units/the-second ); TAI is ahead of GPS by 19 seconds. (http://www.leapsecond.com/java/gpsclock.htm )

[7] The purpose of the leap second adjustment is to keep the UTC to UT0 difference within +/- 0.9 seconds. (See ITU-R Rec. TF.460-6 Standard-frequency and time-signal emissions, https://www.itu.int/dms_pubrec/itu-r/rec/tf/R-REC-TF.460-6-200202-I!!PDF-E.pdf )

seconds inserted and the timing of that insertion is determined by the International Earth Rotation and Reference Service.[8]
The sequence of the dates and times for the December 31, 2016 leap second event will be:

2016 December 31, 23h 59m 59s UTC
2016 December 31, 23h 59m 60s UTC (this is the extra leap second)
2017 January 1, 0h 0m 0s UTC [9]

Leap second insertions require GPS navigation messages to be updated to include the date and time of the leap second insertion. Leap second events are announced about six months before the event occurs,[10] and shortly thereafter uploaded to the GPS system and other constellation systems, giving vendors and users enough time to prepare for the event.[11] Critically, the way a leap second is handled depends on how the handling method is implemented in the hardware and software of GPS receivers and GPS clocks, and users' applications and software, not by the GPS system.[12] [13]

Although GPS receivers should be built in accordance with GPS interface specifications IS-GPS-200H,[14] receivers and clocks may not all handle the leap second in the same way.[15] The United States Department of Homeland Security and others observe that

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[8] See IERS Bulletin C, July 6, 2016, at https://hpiers.obspm.fr/iers/bul/bulc/bulletinc.dat .

[9] National Cybersecurity & Communications Coordination Center, "Best Practices for Leap Second Event Occurring on 30 June 2015," May 26, 2015, at http://www.navcen.uscg.gov/pdf/cgsic/Leap_Second_Best_Practices_20150526_Intrl_Version.pdf .

[10] See IERS Bulletin C, July 6, 2016, op.cit.

[11] GPS clock and users' software vary by versions including device models and firmware updates; not all software is updated or patched to handle leap second events correctly, and not all users deploy all firmware updates and patches as necessary.

[12] Burnicki, Martin, "Technical Aspects of Leap Second Propagation and Evaluation," Pre-print AAS 13-504.

[13] At present, there are three options for how to process the leap second: (1) The system clock can be stepped back by one second at the end of the leap second, which introduces a discontinuity and may repeat a time-stamp; (2) The system clock can be held for one second during the leap second, which produces two identical time-stamps; or (3) The system clock can be slewed or increased to compensate for the leap second, which means that while there are no duplicate time-stamps there is a period during which some of the time-stamps are wrong. Meinberg notes that Linux- and Unix-based operating systems handle the leap second correctly but Windows system clocks have not (to date). See, "Leap Seconds and how they are handled by Meinberg Devices and NTP," at https://www.meinbergglobal.com/english/info/leap-second.htm#overview .

[14] GPS Interface Control Documents, http://www.gps.gov/technical/icwg/ . The GPS specifications detail the 59 seconds to 61 seconds of UTC as leap seconds occur, many implementations lack this capability and attempt to circumvent the use of the last second designation as 23:59:60. There are reports that the upcoming 2016 leap second is already causing problems – see, for instance, "Leap Second coming December 2016, already causing problems," by FSMLabs, at http://www.fsmlabs.com/news/2016/07/28/LeapSecond2016.html .

[15] DHS, "Best practices for leap second event occurring on 30 June 2015," op.cit.

some clocks “may use multiple 59s or 00s versus the 60s scheme above, or even just freeze the time for one second.”[16] Such handling may be sufficient for general, low-resolution timing and navigation uses where several seconds of time ambiguity don’t cause problems, but it can be highly problematic for synchrophasor systems and other timing uses that require time resolution at 30 samples per second or faster.

## 3) Actual synchrophasor system experiences and impacts from leap second events

Synchrophasor systems require a reliable, continuous time source for time-stamps to enable data synchronization for each time-instance. UTC is used directly or indirectly (with local time zone offsets, as will be seen below), for synchrophasor time-stamps. Many synchrophasor users access UTC via GPS receivers and GPS clocks.

PMU & GPS receiver/clock performance

Utilities using PMUs have experienced a variety of problems associated with leap second processing. These appear to be associated with GPS receiver/clock handling of the GPS time signal, problems in the IRIG-B time codes[17] that transport time information between the GPS receiver/clock and other devices (including PMUs), and in the way that NTP handles IRIG-B inputs.[18] There are also interoperability effects between various combinations of GPS receiver/clock and PMU, and inconsistencies in the ways that different models or firmware versions of receiver, clock, PMU and PDC handle the leap second that can compound the problem. A variety of these problems and impacts are described below.

**Utility A** has documented leap second problems associated with June 30, 2012, June 28, 2015 and June 30, 2015. These events have disturbed the reference time, causing erroneous time stamps, erratic system values and delivering misleading information to grid operators.[19] The company has seen:

- Random changes in the trend of angular difference in some PMUs after 23h 29m on June 28, 2015 (i.e., these PMUs added the leap second two days in advance)

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[16] Ibid, p.2.

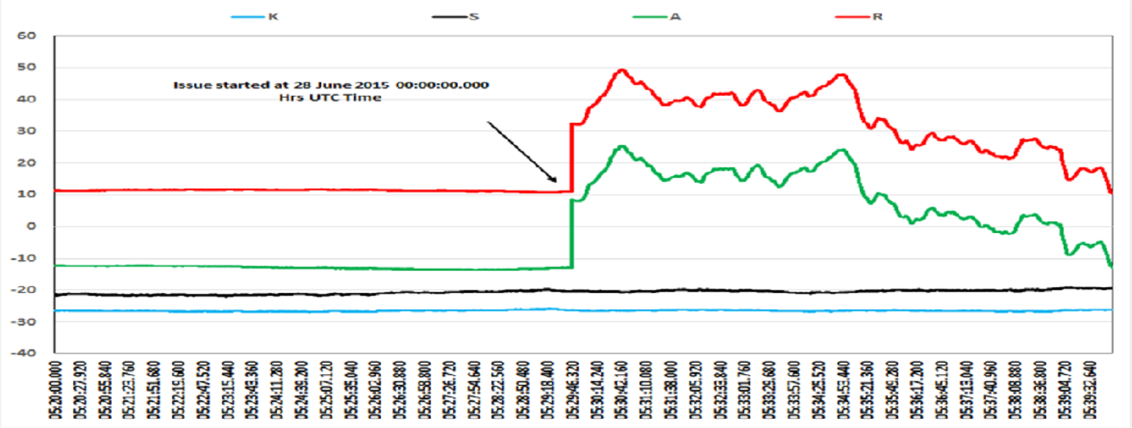
[17] IRIG-B time codes are specified in Standards IEEE 1344 and IEEE C37.118.

[18] “Leap Seconds and how they are handled by Meinberg Devices and NTP,” op. cit.

[19] P.K. Agarwal, Harish Kumar Rathour et al., Power System Operation Corporation Ltd., presentation at NASPI International Synchrophasor Symposium, March 23, 2016.

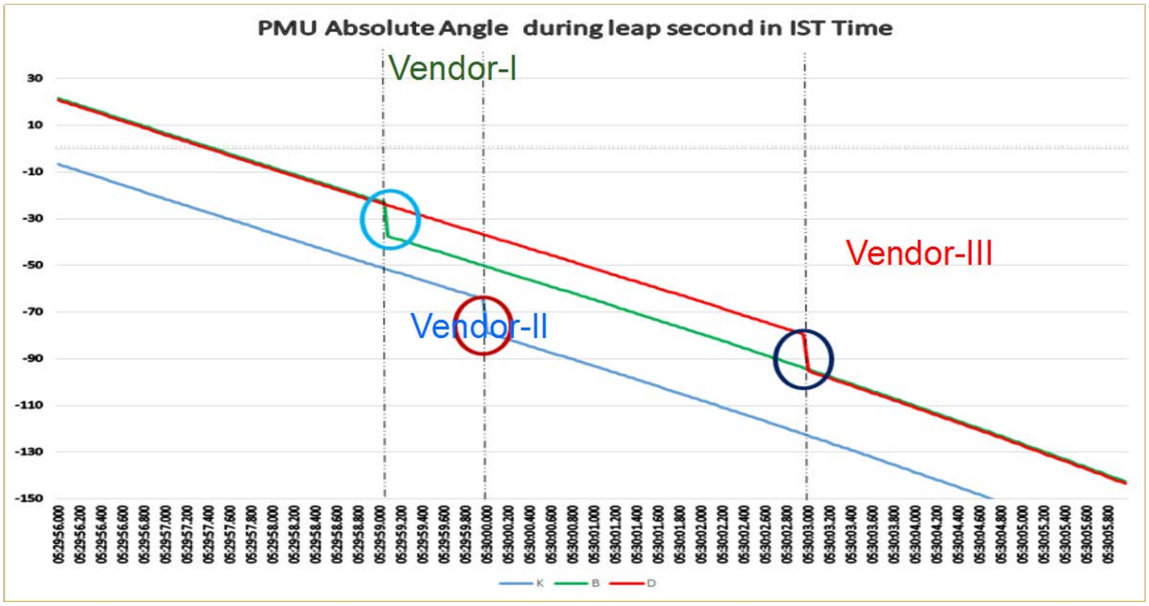
**Utility A -- Random Jumps in Phase Angles Measured After 23:29, June 28, 2015**

**Utility A – Different PMUs behaving badly**



- Around midnight on June 30, 2015, a drift of 1 second in some PMUs relative to others. Specifically, within their PMU fleet they saw four types of responses to the leap second insertion (including one set of PMUs that added the leap second slightly off the top of the second):
  - Added leap second at 05:29:59 (India Standard Time)
  - Added leap second at 05:30:00 (IST)
  - Added leap second at 05:30:03 (IST)
  - No leap second was added.

**Utility A – different GPS-PMU combinations handled the leap second differently**



**Utility B** had three different versions of firmware installed in its GPS clocks and PMUs, and each reacted differently to the 2015 leap second.[20] Overall, the utility and its clock vendor agreed that, "the slow exact ramp was coming from a slightly out-of-sync local clock versus the GPS time."

- For PMUs with version 1 firmware, the PMU data stopped at midnight UTC on June 30, 2015 and started again at July 1, 18:05 (hours:minutes). Voltage angles measured with these PMUs were suspect until July 3, 04:45.
- For PMUs with version 2 firmware, IRIG-B timing to the PMUs was lost for 2 seconds.
- For PMUs with version 3 firmware, the PMU data stopped at midnight UTC on June 30 and started again at 14:09 (hours:minutes) on July 1.[21]

**Utility C**'s PMUs stayed in sync with the leap second, but the Phasor Data Concentrator clock didn't account for the leap second. Therefore, all of the PMU data was one second ahead of the PDC time (PMU data is time-stamped at the PMU, not upon arrival at the PDC), creating data mis-alignment problems at the PDC.[22]

Several of **Utility D**'s PMUs reported timestamps one second in the future.[23]

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[20] Information provided by Utility B staffer in email to author, August 10, 2015.

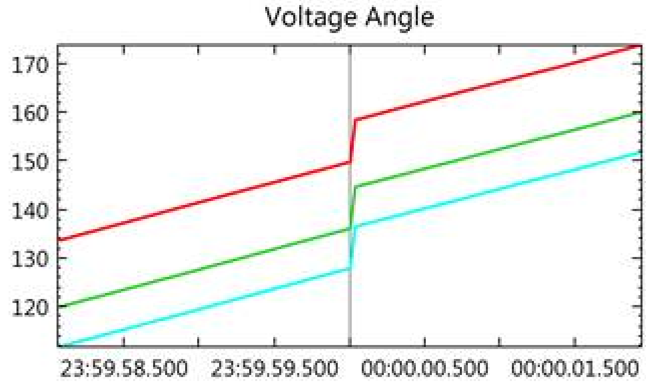
[21] Ibid.

[22] Information provided by Utility C staffer in email to author, August 4, 2015.

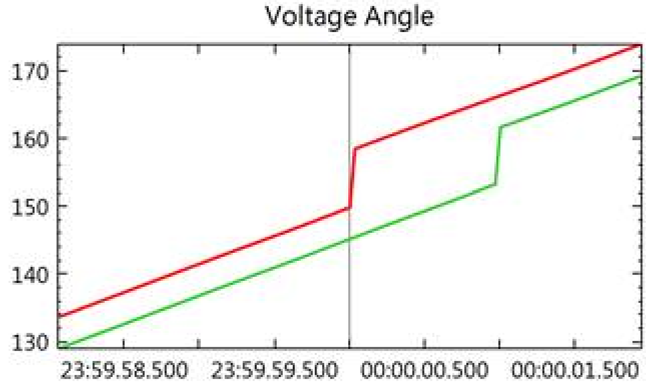
[23] Information provided by Utility D's reliability coordinator in email to author, July 10, 2015.

**Utility E** had a number of PMUs connected to clocks that didn't have the most up-to-date firmware. [24] These clocks issued the leap second occurrence on June 27 rather than June 30. The PMUs with updated clocks did issue the leap second correctly on June 30. However, two versions of PDC software did not seem "capable of storing the extra second. So the leap second really gets lost and what we saw when July 1, 2015 came around was a sudden 8.5 degree angle shift (Figure E-1)." Another vendor's clocks all leapt one second late (second screenshot), while a number of PMUs connected to GPS clocks with old firmware "kind of flopped back and forth at random for a second before stabilizing, taking a second leap (first one being on June 27), then correcting itself 6 seconds later."

**Utility E – (1) sudden 8.5 degree phase angle shift**



**Utility E – (2) some clocks leapt one second late**



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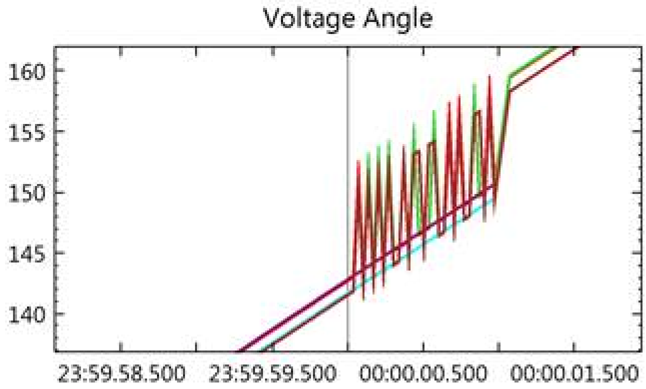
[24] Information provided by Utility E staffer in email to author, July 15, 2015.

**Utility E – (3) clock flopping for six seconds**



**Utility F** reported that, “We had one PMU on our system that looked like it was running roughly a second ahead of the rest of the system. Remote rebooting of the PMU appears to have addressed the immediate problem.”[25]

**Utility G** reported that, after taking account of the different PDCs and PMUs on its system from different manufacturers, and data streams received from multiple transmission operators, only two sets of data failed. Each failing set came from a different vendor’s PMUs. The transmission owners were able to get the PMUs reconnected after manual intervention.[26]

**Utility H** reported that its main PDC servers crashed due to a PMU buffer overflows causing maximum RAM usage. The root cause was that the utility’s substation GPS satellite clocks failed to implement the leap second at the correct time, causing all PMU data to be one second late, or one second off from the main PDC servers in the office. This one second difference exceeded the PDC’s wait time setting of one second, meaning the PDC flagged all incoming PMU data as bad, filling the PMU buffers in the PDC servers.

> Once our PMU data become one second late, the PDC dropped all incoming data as bad because the data arrived too late. Around 8:30pm, I changed the wait time to two seconds on the PDC server. This allowed the PMU data to get to our downstream applications and visualizations. However, this was only a temporary fix, as the PMU data was still behind by one second.[27]

**Utility I** lost two PMUs with the leap second; those PMUs wouldn’t restart because their time stamp was off, which affected the performance of their PDC. The PDC did not recognize the PMUs, getting the time stamp but not the phasor data. The utility had to manually switch off and restart the GPS clock and PMUs in the substations, wait, and

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[25] Email from Utility F staffer to the author, July 8, 2015.
[26] Email from Utility G staffer to the author, July 8, 2015.
[27] Email from Utility H staffer to the author, July 1, 2015.

then restart them; this process took four hours before the suite of clocks, PMUs and PDC were fully functional again. During this process, the utility stopped all synchrophasor-related applications and archiving and proactively opened two interconnection lines to protect system security.[28] Ultimately the utility determined that the problem cause lay with the time stamp given by the GPS satellite clocks.

A **reliability coordinator** reports that none of the streaming PMUs it was monitoring applied the leap second properly.[29] Different PMUs and time servers applied the leap second at a variety of different times. Most PMUs and PDCs took one sample to add the leap second, but others took an entire second, causing phase angles to bounce back and forth. Also, different PMU-to-clock pairs and different PDC-to-clock pairs responded differently to the leap second addition.

## 4) NIST testing of PMUs for the leap second

NIST tested 8 PMUs and one GPS receiver through the leap second to see if they operated correctly and in conformance with IEEE C37.118.1-2011 (current synchrophasor standard) and IEEE-1344 (first synchrophasor standard).[30] Four of the PMUs were fed by IRIG from a GPS receiver (offering potential interoperability problems) and four had internal receivers. All had issues processing the leap second effectively.

- The GPS receiver repeated the BCD second and SBS count at 23:59:59 and jumped directly to 00:00:00 rather than stepping through 23:59:60.
- Of the 8 PMUs, none handled the leap second correctly. The period of time when the SOC was not synchronized with UTC ranged from 0.150 to 47.0 seconds. The NIST team observes that of the four PMUs using IRIG, “only one of their behaviors could directly relate to the GPS receiver’s incorrect behavior, the other 3 had issues not directly attributable to the problem in the IRIG.”[31]

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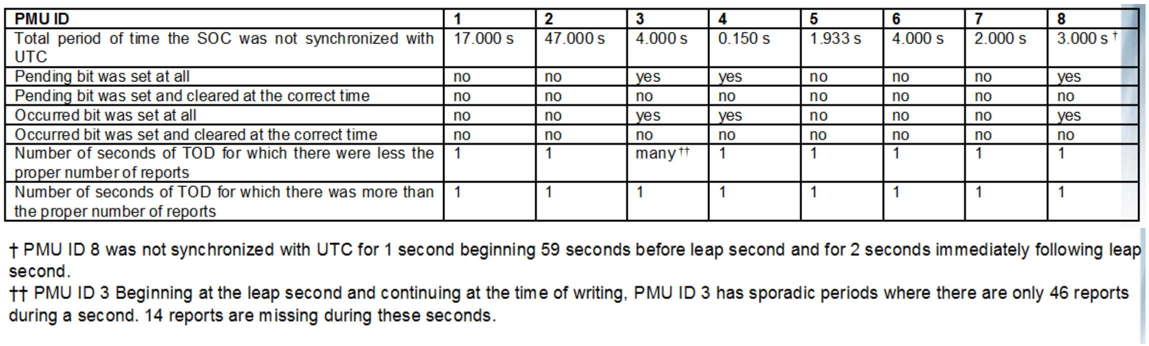
[28] Email from Utility I staffer to the author.

[29] Email from the RC to the author.

[30] Allen Goldstein, Dhananjay Anand & Ya-Shian Li-Baboud, “NISTIR 8077, Investigation of PMU Response to Leap Second: 2015,” August 2015.

[31] Goldstein, Anand & Li-Babound, NIST, ”2015 NIST Investigation of PMU Response to Leap Second,” presentation at the NASPI International Synchrophasor Symposium, slide 3, March 23, 2016.

### NIST PMU Response to the 2015 Leap Second[32]

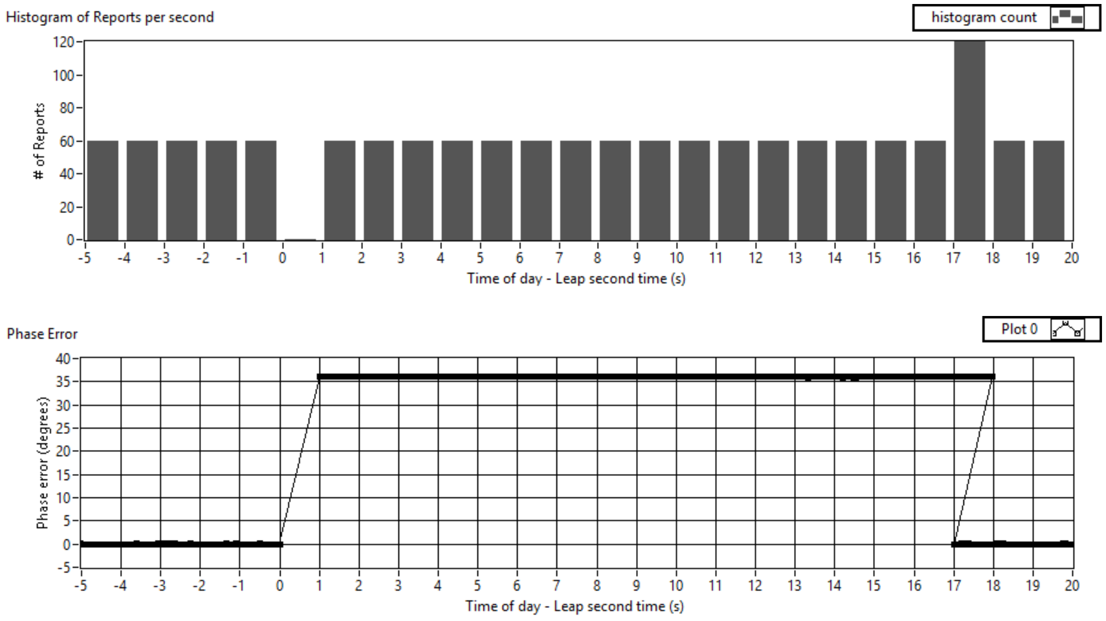


| PMU ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Total period of time the SOC was not synchronized with UTC | 17.000 s | 47.000 s | 4.000 s | 0.150 s | 1.933 s | 4.000 s | 2.000 s | 3.000 s † |
| Pending bit was set at all | no | no | yes | yes | no | no | no | yes |
| Pending bit was set and cleared at the correct time | no | no | no | no | no | no | no | no |
| Occurred bit was set at all | no | no | yes | yes | no | no | no | yes |
| Occurred bit was set and cleared at the correct time | no | no | no | no | no | no | no | no |
| Number of seconds of TOD for which there were less the proper number of reports | 1 | 1 | many †† | 1 | 1 | 1 | 1 | 1 |
| Number of seconds of TOD for which there was more than the proper number of reports | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

† PMU ID 8 was not synchronized with UTC for 1 second beginning 59 seconds before leap second and for 2 seconds immediately following leap second.
†† PMU ID 3 Beginning at the leap second and continuing at the time of writing, PMU ID 3 has sporadic periods where there are only 46 reports during a second. 14 reports are missing during these seconds.

These differing responses caused several problems – missing data frames (as though the time never happened) or duplicated reports (data was reported that should have had a different time stamps); either one would cause incorrect phase angles, as illustrated below for one of the several PMUs that behaved similarly.

### NIST PMU data frames and phase error associated with leap second[33]



A **PMU vendor** reported that its PMU detected the leap second, updated the “occurred bit”, “pending bit” and “direction bit”, but reported about 100 ms after the occurrence of the leap second event. This behavior occurred due to GPS receiver latency to calculate and parse leap second information.[34]

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[32] Ibid, slide 3.

[33] Goldstein, Anand & Li-Baboud, NISTIR 8077, op. cit., p. 8.

[34] Email from vendor representative to the author, August 24, 2015.

## 5) Clock performance

**Utility H** monitored its substation satellite clocks, which send IRIG-B with the IEEE 1344 extensions of the control bits. When the leap second occurred, they found that:

> [T]he leap second pending bit asserted one minute before the anticipated leap second and stayed asserted the entire minute (as expected). However, the clock went from 19:59:59 EDT (with the leap second pending bit asserted) to 20:00:00 EDT (with leap second pending bit off, and the leap second bit off). No leap second occurred. Then we found the clock repeated the exact frame at 20:00:05 EDT.[35]
>
> When our clock added the leap second at 20:00:05, the leap second bit was de-asserted (binary 0), which is correct per the standard. Therefore our clocks did the leap second pending correctly, but performed the leap second (with the correct leap second bit) five seconds late.[36]

One **individual** was monitoring GPS satellite clocks for both UTC plus local time IRIG-B outputs, and their 1588 power profile (IEEE C37.238) Ethernet outputs. He reported that one clock:

> … [S]howed the bizarre behavior of handling the leap second correctly on its 1588 output, but ignoring the event on its IRIG-B output (repeating a second two minutes after the event). Two attempted to provide the John-Edison interpretation of the 1588's "Alternate Time Offset TLV" using PTP (c.f. UTC for the reference), and stepped the offset by 1 at the event; but failed to see the JumpSecond fields per the 1588 spec (leaving them at the values for the DST event in the autumn).[37]

## 6) Conclusions and recommendations

Members of the synchrophasor community received myriad warnings from their peers, vendors and the trade press about the impending leap second event, and most of those members took affirmative action to update PMU or clock firmware and consult with their GPS clock and PMU vendors before the event. However, many systems' PMUs, clocks and PDCs failed to perform smoothly through the leap second, failing in a diverse set of ways documented above. Many of the entities reporting did not conduct or share detailed analyses of why their system elements failed – but most users view it as the vendors'

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[35] Email from Utility H staffer to the author, July 6, 2015. Like many other utilities, this entity uses the Time Zone Offset control bits in the IRIG-B 1344 extension, and its PMUs interpret the offset bits to get UTC from the clock.

[36] Email from staffer with Utility H to author, July 7, 2015.

[37] Email from individual to Allen Goldstein (NIST), July 13, 2015.

responsibility to assure smooth performance in a certain and predictable event, not the users' responsibility to suffer the failure and document and analyze its cause.

The Department of Homeland Security offers some generic best practices for GPS users anticipating the upcoming leap second.[38] Such guidance was available for the 2015 leap second event[39] and updated guidance has been developed for the December 30, 2016 leap second. However, much of this guidance and many GPS vendors' practices are aimed toward users whose timing needs can tolerate drops or shifts of one or more seconds in length. One-second or longer timing errors are highly problematic for synchrophasor technology users and others who require timing to be accurate at resolutions of 1 ms or smaller. To that end, NASPI offers the following recommendations as we prepare for the next leap second:

1. Before the leap second occurs, update all satellite clocks, GPS receivers, PMUs and PDCs to the latest firmware that addresses that corrects or fixes any timing related issues. Tell your vendors how early you need any leap second firmware updates to be available.
2. Consider placing more of your synchrophasor system on a consistent back-up timing source, so that even if the principal timing sources mis-perform, you can fall back to a consistent alternate source. Examples include highly accurate internal holdover oscillators and network-based timing synchronization (PTP).
3. Test your equipment in advance using a simulated leap second event to determine whether it will execute the leap second accurately, and document any failures or glitches. Several vendors and consultants have already developed GPS simulators and leap second tests for this purpose.[40] An ideal testing regimen would be to start testing GPS receiver and clock performance, and then run the sequence of leap second time signals through the connected system of PMUs and PDCs to determine whether any timing or data problems issues arise.
4. If you find problems in the leap second simulation, report them to NASPI and the sources indicated in the DHS alert, and ask your vendors to develop effective solutions to the documented problems. Be aware that some problems may be due not to mis-performance by an individual element of your system, but rather because your system components may not inter-operate effectively under unusual circumstances such as a leap second (even though all of the individual pieces may be configured to meet IEEE C37.118).
5. At least a week before the leap second event is scheduled to occur, consider setting up an independent substation GPS satellite clock that is not attached to a PMU. Record and monitor the raw IRIG-B output data from this clock and use it to determine whether the clock is processing the leap second event correctly by comparing the raw data to the expected data described in the IEEE C37.118 standard. This can be used as a check on whether any PMU data problems arise

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[38] https://ics-cert.us-cert.gov/Best-Practices-Leap-Second-Event-Occurring-31-December-2016.

[39] Op. cit.

[40] GPS testing and clock event simulation can be a complex process that many users don't have the time or expertise to research and conduct.

due to bad time sent from the clock, or from bad time handling within the PMU or PDC.

6. Anticipate that despite your best preparations, parts of your synchrophasor system may mis-perform or fail when the leap second occurs (or before or after it, as documented above). Monitor your system before, through and after the leap second to identify any problematic behavior. Have the appropriate staff and internal experts on hand, including those familiar with your GPS satellite clocks, PMUs, and PDCs, and even IT staff to support servers that run PDC software and PMU applications. Warn any operations and planning staff who rely on synchrophasor applications that there may be problems around the leap second event with respect to relative voltage angles, and be prepared to reduce reliance on or have work-arounds for synchrophasor system functions until you are sure that it is performing properly after the leap second event.
7. If you are buying new GPS receivers, clocks, or PMUs, consider buying those which can be updated, tested and restarted remotely (subject to appropriate security provisions), to avoid the possibility that a mis-performing unit can only be fixed or restarted with a truck roll to the field site. Also look for GPS receivers/clocks that perform internal logging of its raw data and any errors it encounters.

Over the longer term, it is clear that the timing industry and its technical standards need to be updated to meet the needs of current high-resolution timing users. Standards and practices that leave any ambiguity or room for interpretation in implementation are no longer appropriate or acceptable and must be resolved immediately. These include:

- The IEEE C37.118 standard is specific about how to handle time events, but PMU- and PDC-related standards and guidelines should be reviewed to be sure that there are no gaps or ambiguities in the relevant language and requirements.
- Technical standards for timing devices such as satellite clocks and timing protocols such as IRIG-B should be updated to be consistent with the other standards above, to assure smooth and consistent handling of anomalous timing events.
- IEEE and NIST should develop better laboratory testing procedures for both device handling of leap seconds and other timing events and interoperability between related time-using devices.
- IEEE C37.118 certification tests for PMUs, PDCs and satellite clocks should include timing event performance tests, including leap second events, daylight savings events, and year roll-over events.
- Users in the synchrophasor and other industries should hold their vendors to very high performance expectations with respect to performance during leap second and other anomalous timing events.
- Vendor upgrades and firmware updates should explain explicitly how they are handling a leap second event, and release notes for each upgrade should indicate what is being fixed and how.
- Reliability standards issued by the North American Electric Reliability Corporation pertaining to time-stamping and timing adjustments should be

reviewed to be sure that they allow formally sanctioned timing revisions such as those for the leap second and epoch roll-over.

- Some standards relating to timing allow the option to interpret leap second implementation in multiple alternative ways, allows second-long variations between different clocks that did execute the leap second event properly. It is time for relevant standards organizations to select and specify a single correct method for handling the leap second, that assures logical continuity of timing without ambiguity at resolutions down to the nano-second.