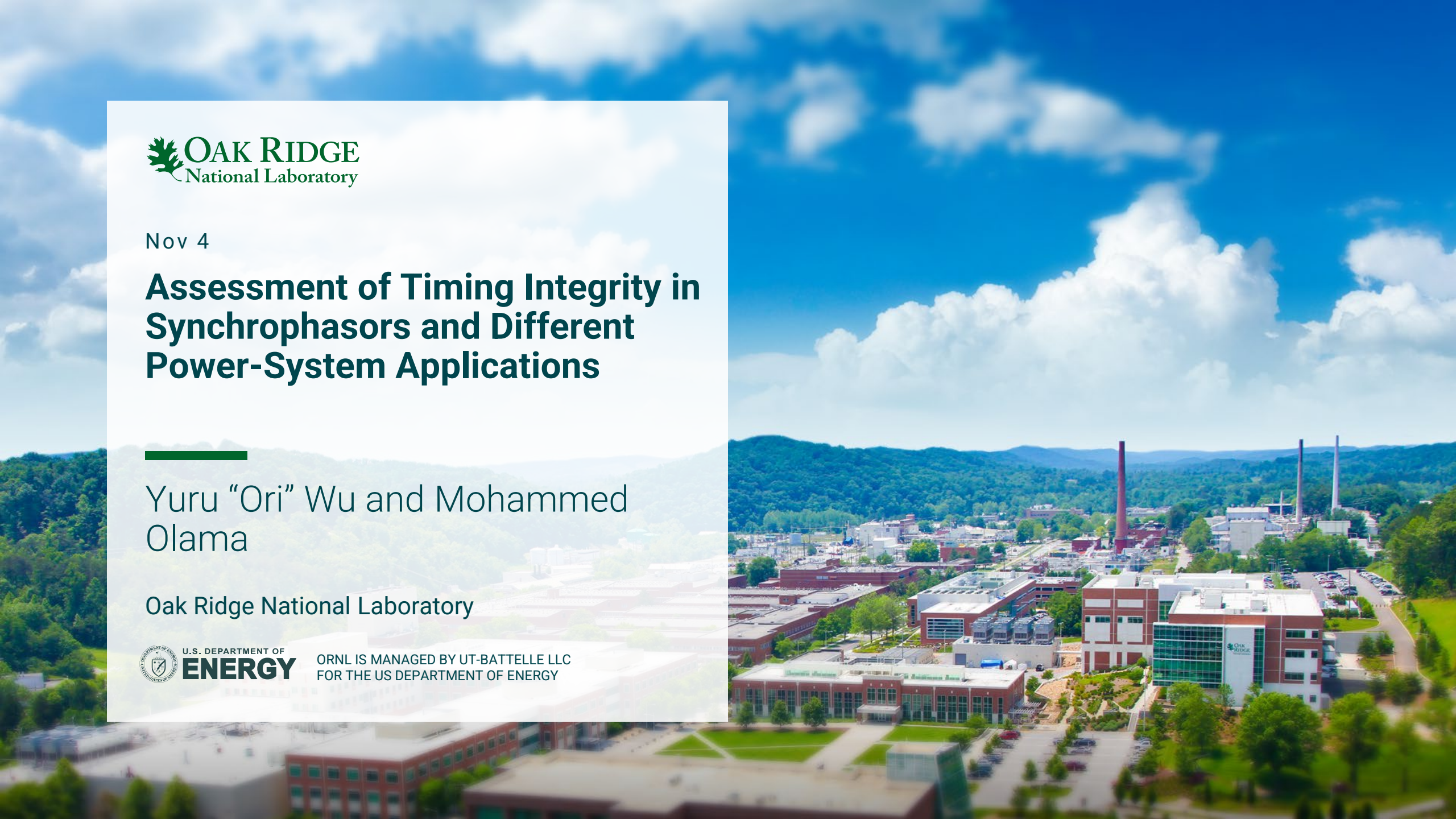

OAK RIDGE National Laboratory

Nov 4

Assessment of Timing Integrity in Synchrophasors and Different Power-System Applications

Yuru “Ori” Wu and Mohammed Olama

Oak Ridge National Laboratory

U.S. DEPARTMENT OF ENERGY

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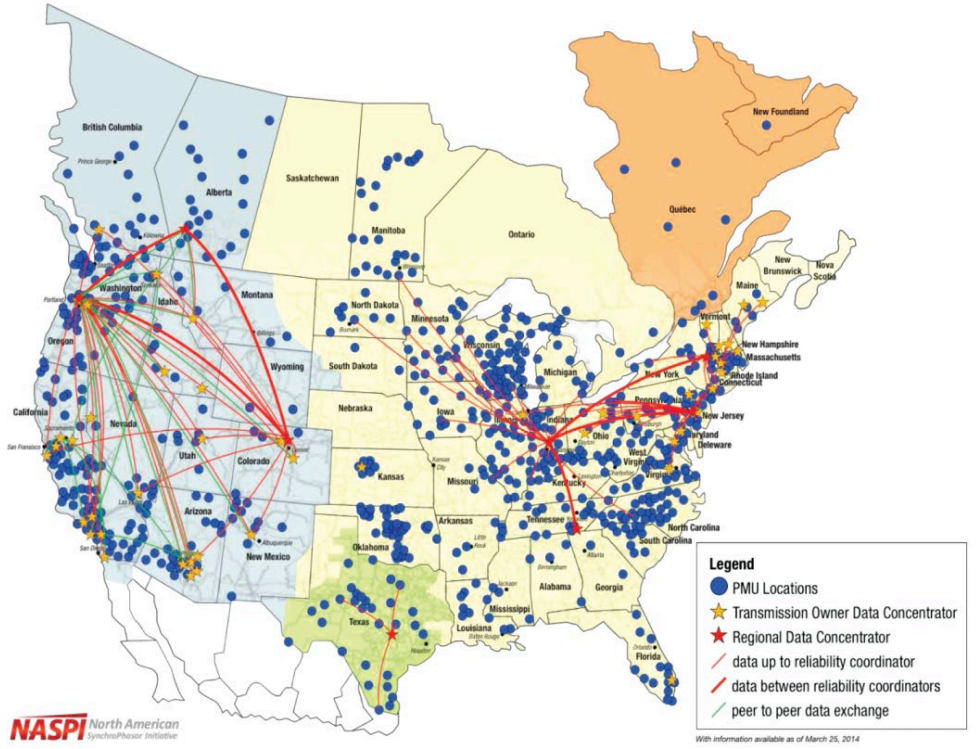
Synchronization is Essential for Power Grid Operation

- Timing and synchronization are critical to grid operations in many traditional ways
  - OT device operations, IT services orchestration, data logging, etc.
- Timing is also critical to highly specialized grid use cases
  - Power system protection
  - Wide-area monitoring, protection, and control (WAMPAC)
  - Frequency stability and load balancing
  - Electrical event reconstruction
- 55,000+ substations with 1+ GPS antenna in the US

Figure 3.13 Data Flows from Transmission Owners to Regional Hubs, Between Reliability Coordinators, and Between Transmission Operators



Thousands of networked PMUs deployed throughout the US (2015)

Image source: DOE Quadrennial Technology Review (2015) https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter3.pdf

Timing & Synchronization Now More Important than Ever

- Distributed generation is bringing thousands of new devices online
- Shift in grid structure and operations
  - Consumers = producers (bi-directional flows)
  - Data centers, Distributed control
- Wide-area monitoring through precision sensors and advanced analytics is critical to this transition



- Time synchronization across the sensors (and operational zones), to support analytics and inferencing, is necessary

Image source: https://commons.wikimedia.org/wiki/Category:Data_centers#/media/File:CERN_Server_03.jpg
Image source: https://commons.wikimedia.org/wiki/File:Car2Go_Charging_Station_Stuttgart_2013_01.jpg

Timing and Dissemination Today

- Timing for deployed grid assets and systems today is largely delivered by GPS (GNSS)

- Timing for IT systems operating the grid is largely delivered by Network Time Protocol (NTP)



GPS antenna installation at WAPA site



Representation of GPS satellite

Name	IP Address	Location	Status
time-a-g.nist.gov	129.6.15.28	NIST, Gaithersburg, Maryland	All Services available
time-b-g.nist.gov	129.6.15.29	NIST, Gaithersburg, Maryland	All services available
time-c-g.nist.gov	129.6.15.30	NIST, Gaithersburg, Maryland	
time-d-g.nist.gov	129.6.15.27	NIST, Gaithersburg, Maryland	All services available
time-d-g.nist.gov	2610:20:6f15:15::27	NIST, Gaithersburg, Maryland	All services available
time-e-g.nist.gov	129.6.15.26	NIST, Gaithersburg, Maryland	All services available
time-e-g.nist.gov	2610:20:6f15:15::26	NIST, Gaithersburg, Maryland	All services available
time-a-wwv.nist.gov	132.163.97.1	WWV, Fort Collins, Colorado	All services available
time-b-wwv.nist.gov	132.163.97.2	WWV, Fort Collins, Colorado	All services available
time-c-wwv.nist.gov	132.163.97.3	WWV, Fort Collins, Colorado	All services available
time-d-wwv.nist.gov	132.163.97.4	WWV, Fort Collins, Colorado	All services available
time-d-wwv.nist.gov	2610:20:6f97:97::4	WWV, Fort Collins, Colorado	All services via IPv6
time-e-wwv.nist.gov	132.163.97.6	WWV, Fort Collins, Colorado	All services available
time-e-wwv.nist.gov	2610:20:6f97:97::6	WWV, Fort Collins, Colorado	new server, services via IPV6
time-a-b.nist.gov	132.163.96.1	NIST, Boulder, Colorado	All services available
time-b-b.nist.gov	132.163.96.2	NIST, Boulder, Colorado	All services available
time-c-b.nist.gov	132.163.96.3	NIST, Boulder, Colorado	All services available
time-d-b.nist.gov	132.163.96.4	NIST, Boulder, Colorado	All services available
time-d-b.nist.gov	2610:20:6f96:96::4	NIST, Boulder, Colorado	All services available
time-e-b.nist.gov	132.163.96.6	NIST, Boulder Colorado	All services available
time-e-b.nist.gov	2610:20:6f96:96::6	NIST, Boulder, Colorado	All services available

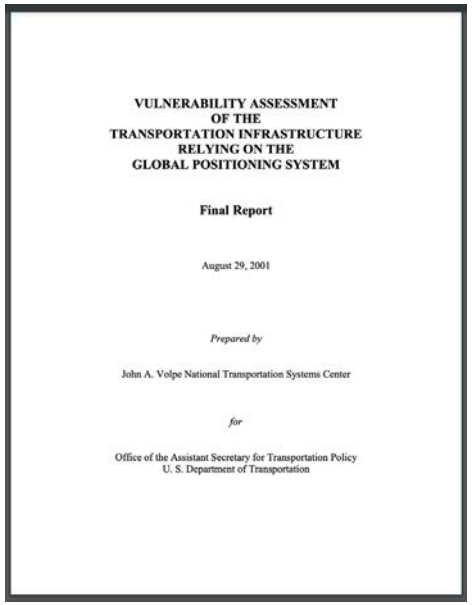
NIST NTP service dashboard

NIST image source: https://tf.nist.gov/tf-cgi/servers.cgi

GPS image source: https://www.gps.gov/multimedia/images/GPS-III-A.jpg

GPS Risks and Vulnerabilities are Driving New Investments

- GPS vulnerabilities and the need for resilience have been well-documented
  - Signal is known and unencrypted
  - Jamming, spoofing accomplished with off-the-shelf gear
- NTP delivered via unencrypted service, vulnerable to being a cyber intrusion vector (e.g., man-in-the-middle attack)
- A **more secure** time delivery system is needed to ensure grid resiliency in the face of cyber threats.


VULNERABILITY ASSESSMENT
OF THE
TRANSPORTATION INFRASTRUCTURE
RELYING ON THE
GLOBAL POSITIONING SYSTEM

Final Report

August 29, 2001

Prepared by

John A. Volpe National Transportation Systems Center

for

Office of the Assistant Secretary for Transportation Policy
U. S. Department of Transportation


9359

Presidential Documents

Executive Order 13905 of February 12, 2020

Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services

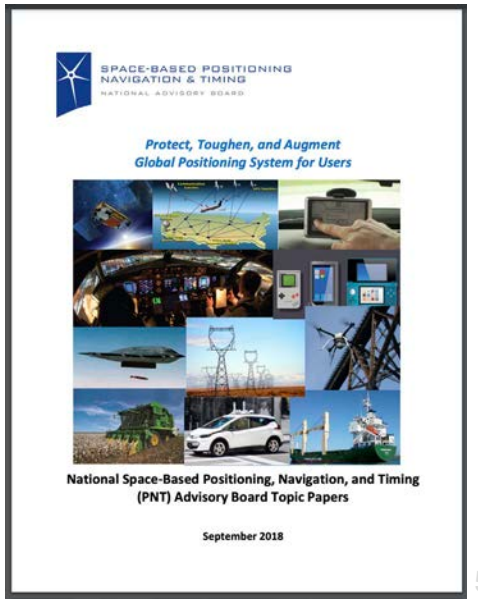

THE PRESIDENT'S NATIONAL SECURITY TELECOMMUNICATIONS ADVISORY COMMITTEE

NSTAC REPORT TO THE PRESIDENT

on

Communications Resiliency

May 6, 2021


SPACE-BASED POSITIONING NAVIGATION & TIMING
NATIONAL ADVISORY BOARD

Protect, Toughen, and Augment Global Positioning System for Users

National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board Topic Papers

September 2018

ORNL Timing & Synchronization Test Bed: Center for Alternative Synchronization and Timing (CAST)

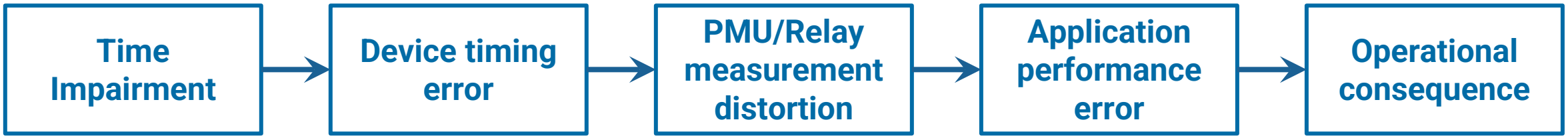
- Test, evaluate, and document the capabilities and limitations of today's technology for **augmenting GPS** timing in the grid
- Perform **R&D** and provide **technical assistance** to federal and commercial partners to implement alternative timing & synchronization solutions
- Design and test **complementary timing/synchronization architectures** that:
  - Drive **reliable** and economical scaling to large geographic areas
  - Easily integrate into existing technical environments to bolster **resilience**
  - Use **affordable** COTS capabilities
  - Ensure **security** and resistance to adversarial and natural disruptions



Motivation:
Linking Timing Impairments to System Impact

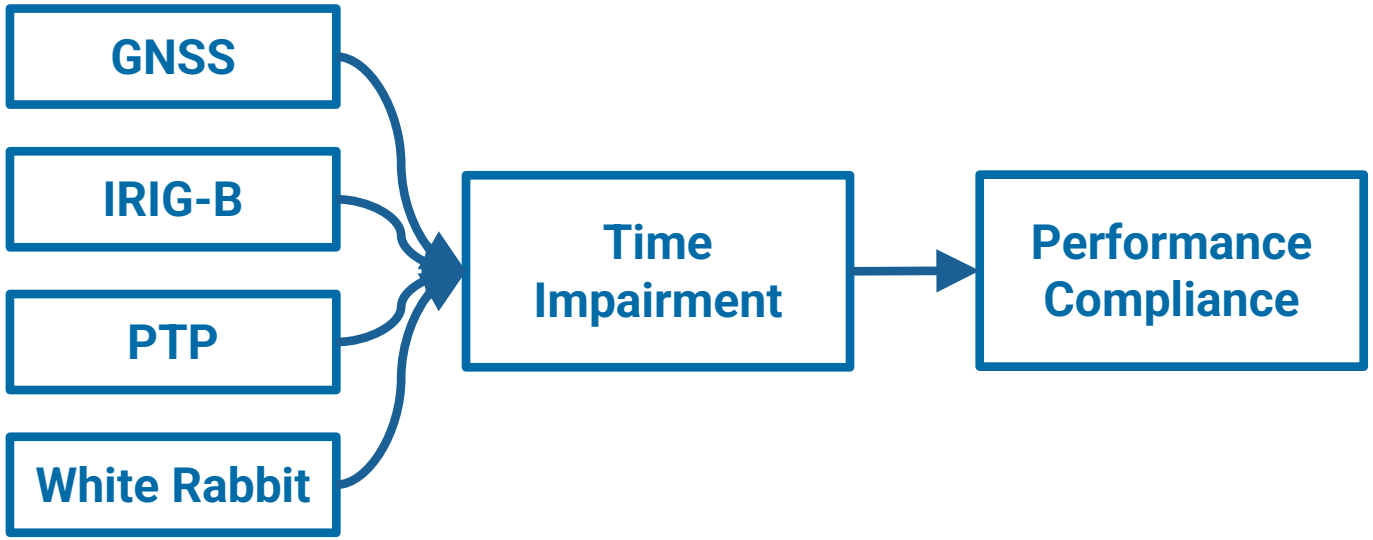
How to quantify the Error Chain?

- **Realistic device response:** Timing impairments can originate from network delay variation, timing-source disruption, or malicious manipulation. Their effect depends on synchronization, device implementation, and measurement processing; these effects are not fully represented by idealized timing assumptions.
- **Controlled timing characterization:** A controlled test platform enables repeatable injection of specified timing conditions and measurement of the resulting device timing error and PMU response.
- **Application specific consequence:** Simulation models use quantified measurement errors to evaluate their impact on timing-sensitive applications.



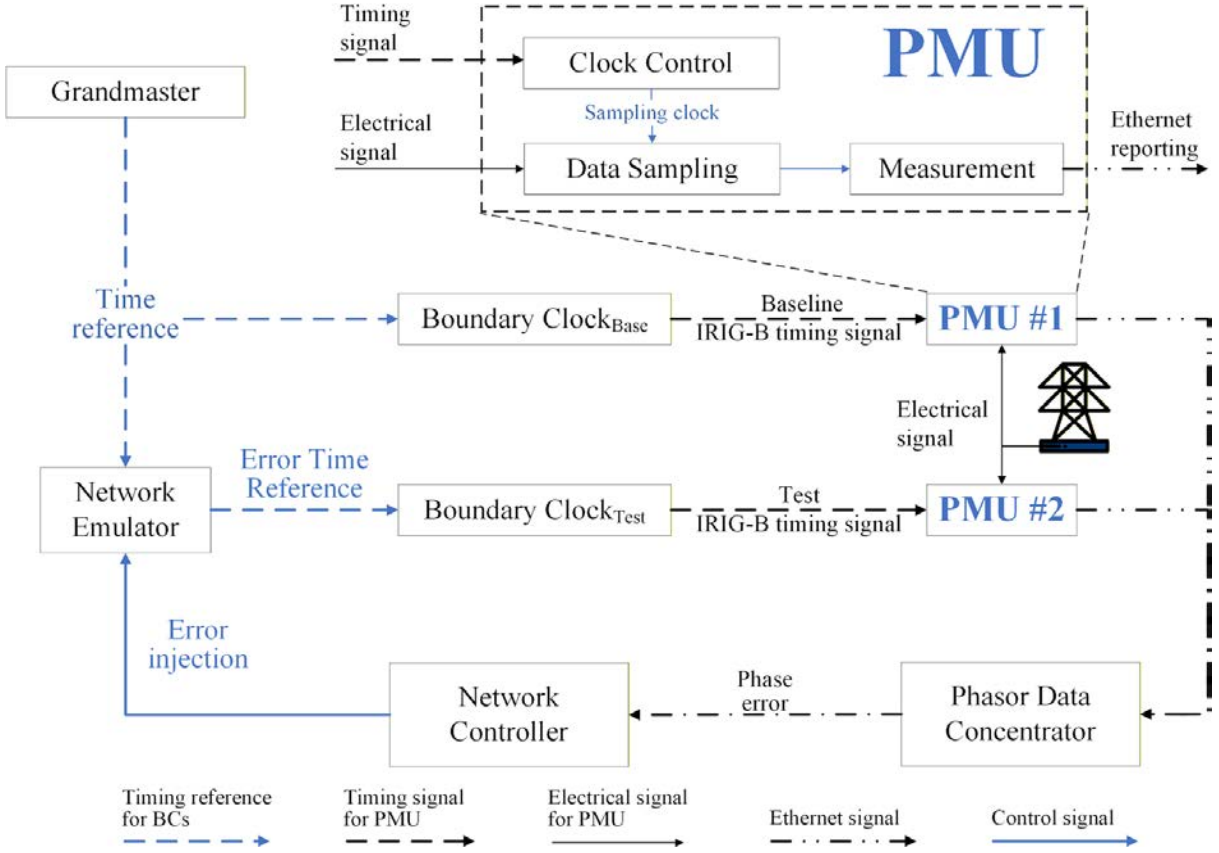
Evaluating Resilient Timing for Grid Services

- **Protocol Agnostic Testing:** By focusing on "time impairments", the platform evaluates the unique **error signatures** of diverse synchronization sources—including **GNSS, IRIG-B, PTP, and White Rabbit**—quantifying their impact on grid stability regardless of the underlying transport layer.
- **Safety Margin Identification:** HIL platform can identify the ”threshold", where timing degradation leads to **Control Maloperation**.
- **Operational Readiness:** Moving from theoretical resilience to hardware-validated resilience, ensuring new timing sources meet the IEC 60255.118.1 / IEEE C37.118.1 performance standards.



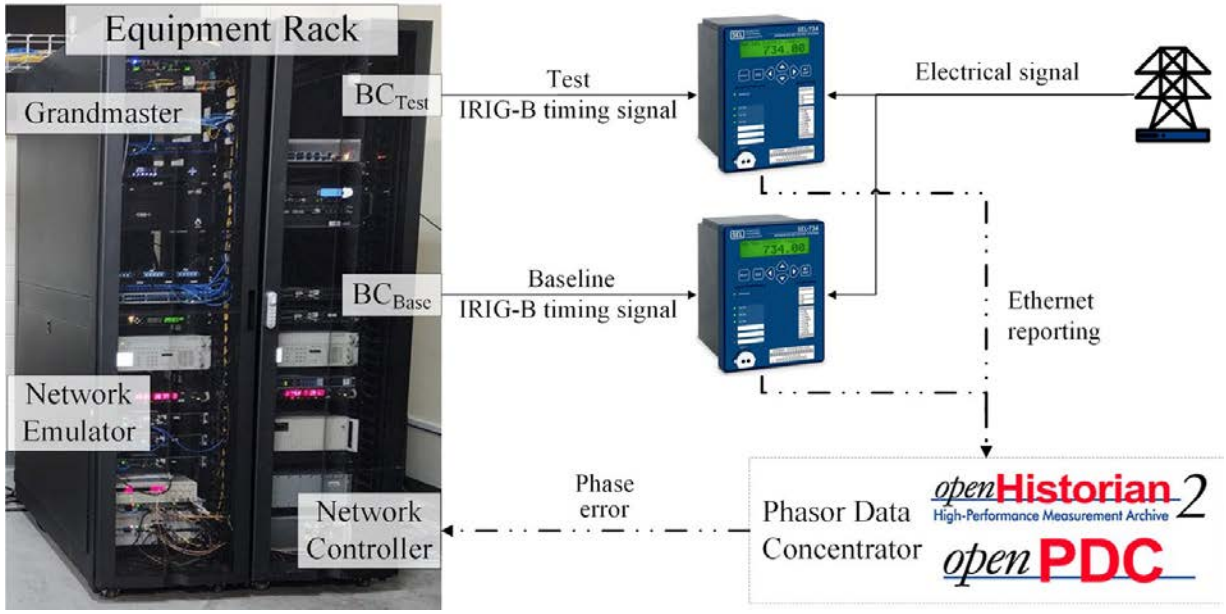
Architecture of Network Hardware-in-the-Loop Platform

- **Steady-state signal injection**:
  - Both PMUs receive the same 60 Hz steady-state signal to isolate timing-induced errors by eliminating power system transients.
- **Time reference & distribution**:
  - A UTC-aligned cesium atomic grandmaster distributes IEEE 1588 PTP to two boundary clocks (BCs).
  - A dual-chain compares a clean **Baseline Chain** (PMU #1) against an **Impaired Chain** (PMU #2).
- **Time impairment injection:**
  - A network emulator injects controlled PTP timing errors, quantifying how timing impairments propagate into synchrophasor measurements.



Architecture of Network Hardware-in-the-Loop Platform

- Hardware Integration:
  - A single equipment rack integrates the Cesium Grandmaster, Boundary Clocks, and the Network Emulator.
  - Two SEL-734 PMUs: Connected to respective chains; both monitor the same electrical signal.
- Data Management & Feedback:
  - OpenHistorian PDC: Aggregates Ethernet-based PMU reports for real-time analysis.
  - Closed-Loop Control: Calculated Phase Angle Error (PAE) is fed back to the network controller.



Time Error Analysis:
From PTP Packets to Timing and Measurement

- **PTP Clock Offset Estimation**:

$$\text{Path}_{\text{delay}} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2}$$

$$\text{T}_{\text{offset}} = (t_2 - t_1) - \text{Path}_{\text{delay}}$$

- **Network Impairment Injection**: The network emulator introduces an asymmetric delay ($\Delta\tau$) specifically to the t_3 or t_4.

$$\text{Path}'_{\text{delay}} = \text{Path}_{\text{delay}} + \frac{\Delta\tau}{2}$$

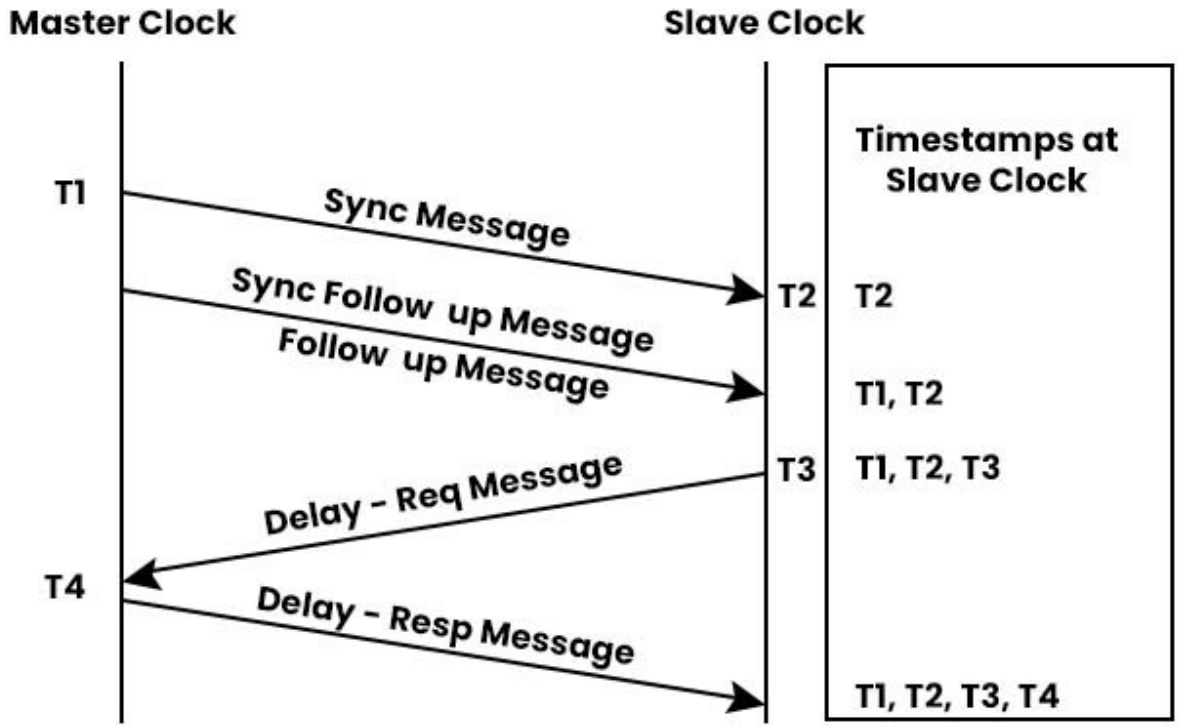
$$\text{TE} = \frac{\Delta\tau}{2}$$

- Phasor calculation according to the timestamp:

$$v[n] = V_m \cos(2\pi f(t + \text{TE}) + \theta_0)$$

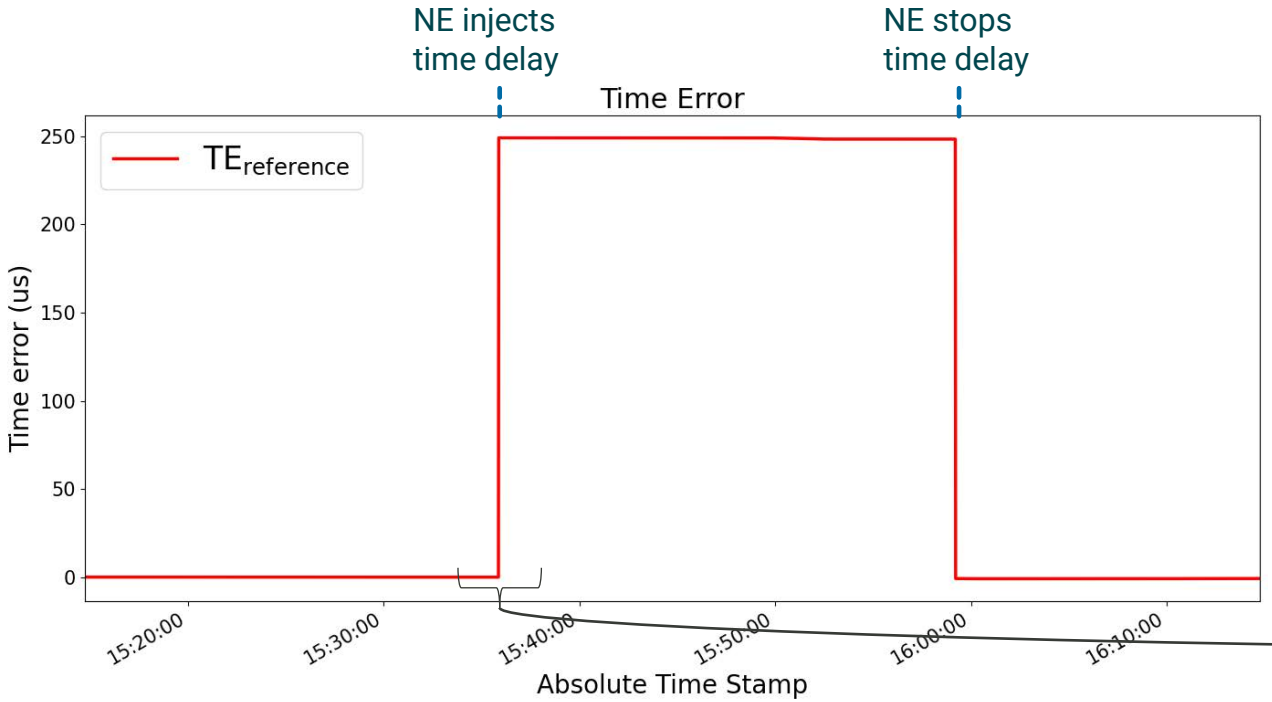
Leading to: $\text{Phase Angle Error} = 2\pi f \cdot \text{TE}$ (radian)

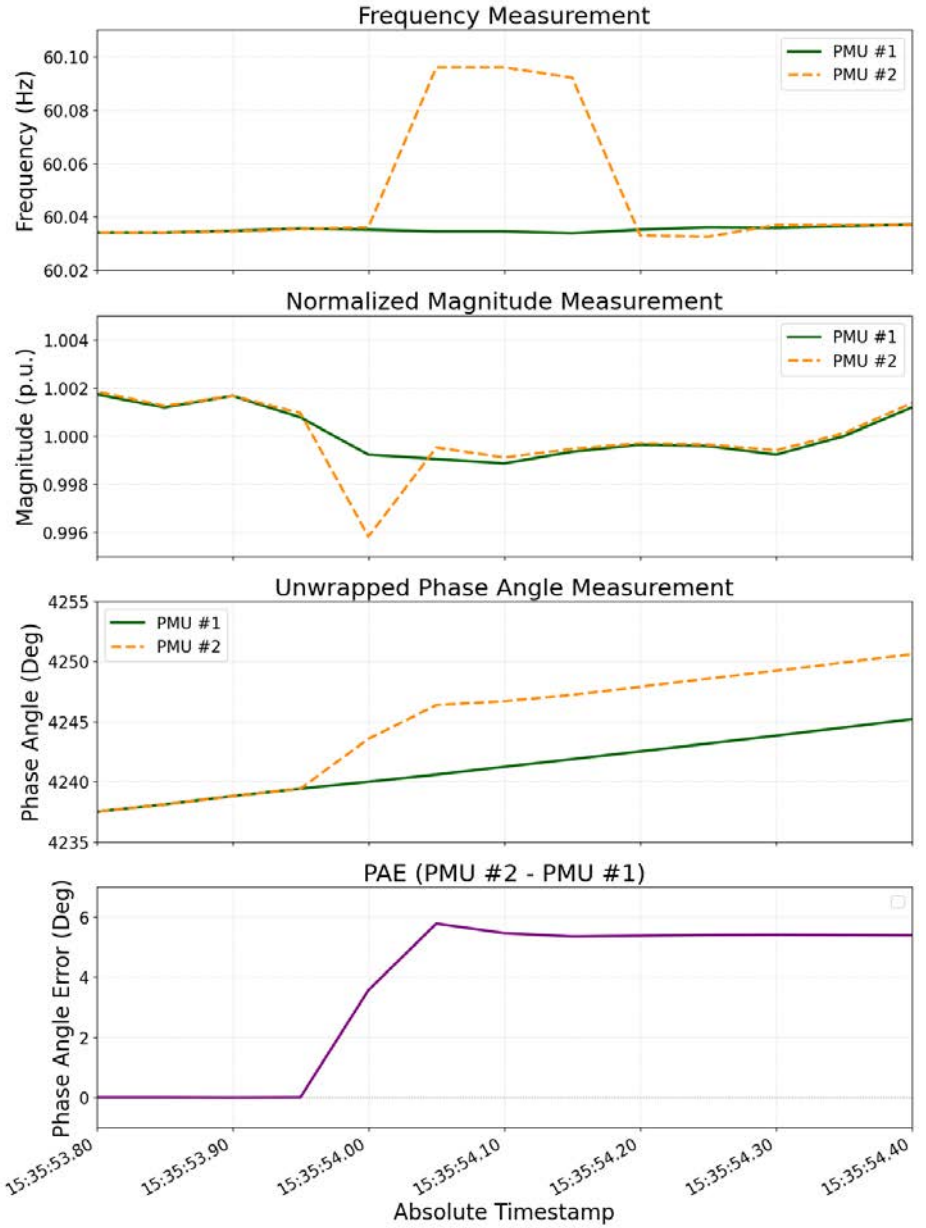
or: $\text{Phase Angle Error} = 360°f \cdot \text{TE}$ (degree)



Time Error Experiment: Constant Delay

- Experimental setup:
  - One-way time delay at 500us is injected by network controller.
  - $\mathrm{TE}_{\mathrm{reference}}$: extracted from the BC outputs.
    - 250 us time error is observed.





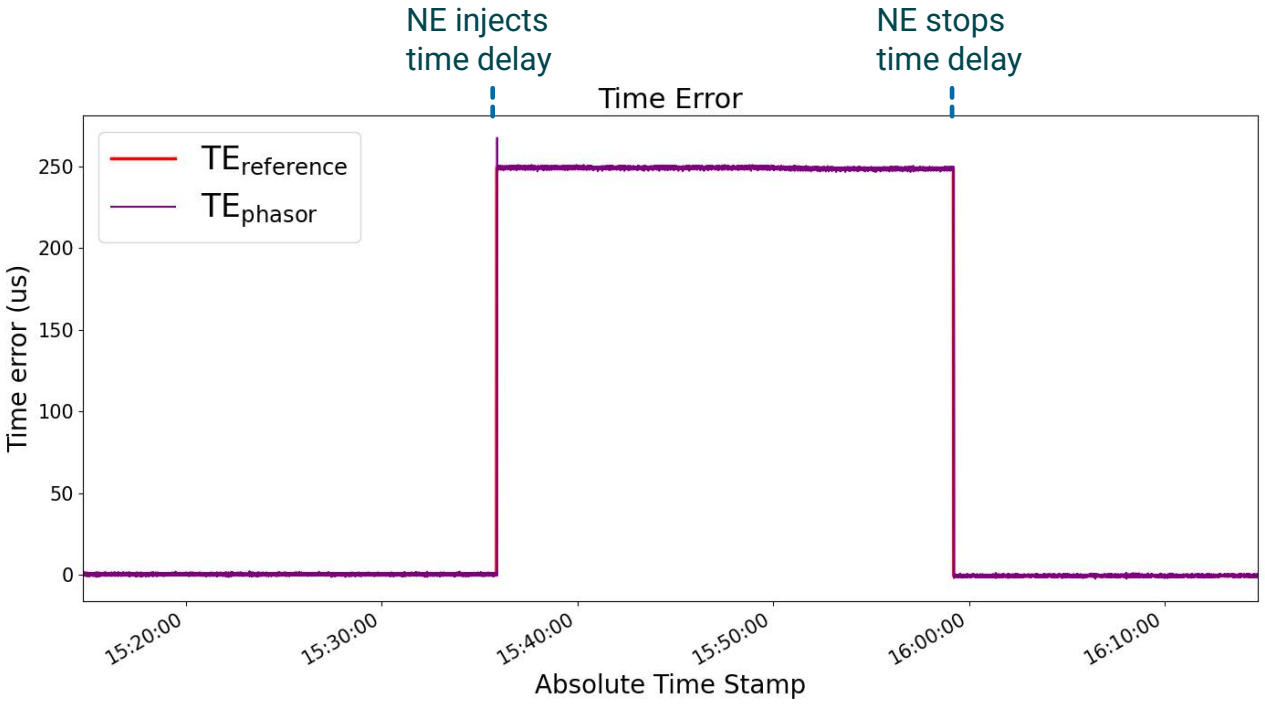
PMU measurements during transit (20 frames per sec)

Time Error Experiment: Constant Delay

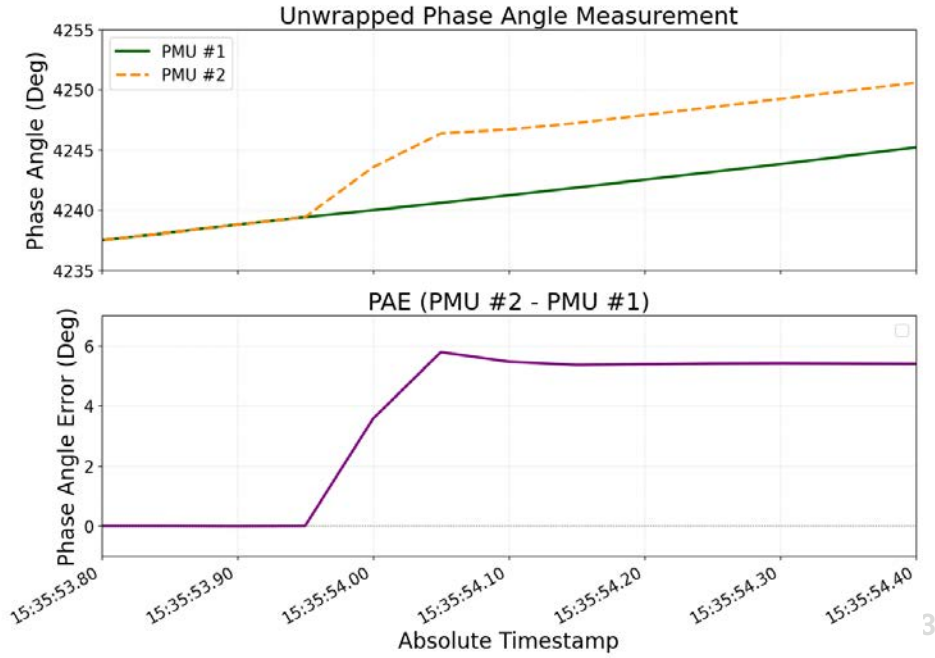
- Results comparison:
  - $\mathrm{TE}_{\mathrm{reference}}$: extracted from the BC outputs.
  - $\mathrm{TE}_{\mathrm{phasor}}$: estimated by the phasor measurement.

$$\mathrm{TE}_{\mathrm{phasor}} = \frac{\text{Phase Angle Error}}{360° f}$$

Injected one-way time delay (μs)	Average $\mathrm{TE}_{\mathrm{reference}}$ (μs)	Average $\mathrm{TE}_{\mathrm{phasor}}$ (μs)
10	4.58	4.47
100	49.69	49.81
500	248.87	249.11
1,000	499.52	499.83
5,000	2499.17	2499.55
10,000	5000.06	5000.47



$\mathrm{TE}_{\mathrm{phasor}}$ conversion

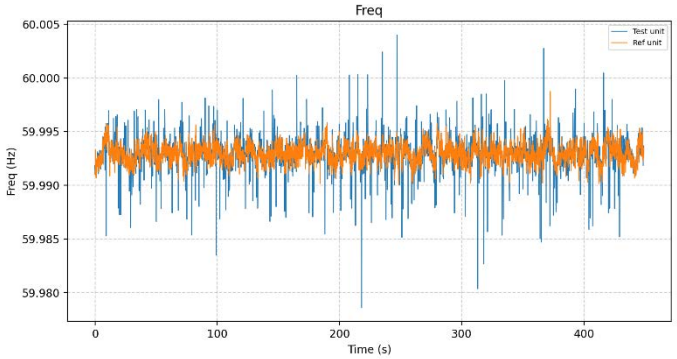


Time Error Experiment: Jitter Injection

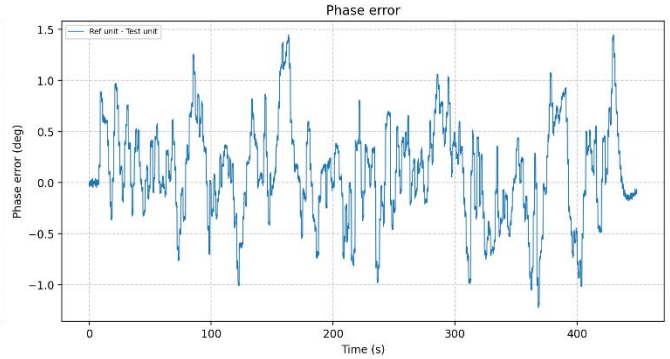
- The emulator injects correlated time error into the test signal path, while the reference unit provides a baseline.
- At injection onset, the measured $\mathrm{TE}_{\mathrm{phasor}}$ follows the reference $\mathrm{TE}_{\mathrm{reference}}$. The test unit also shows relative frequency and phase-angle fluctuations.

Jitter Injection Case

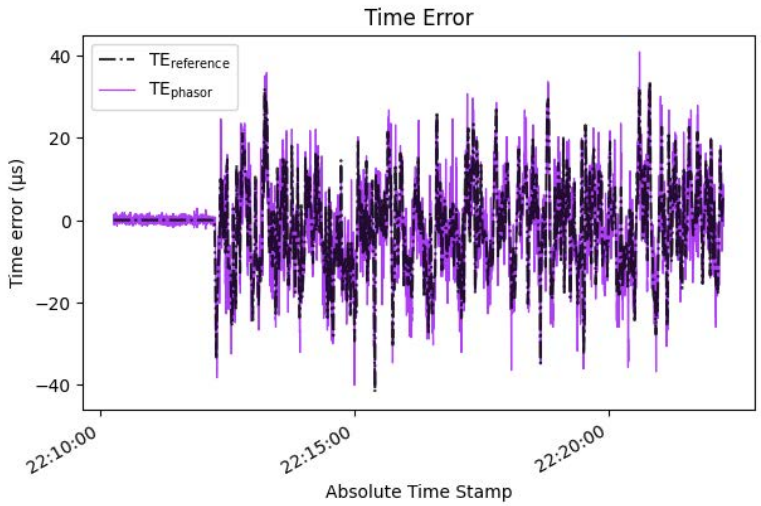
Frequency

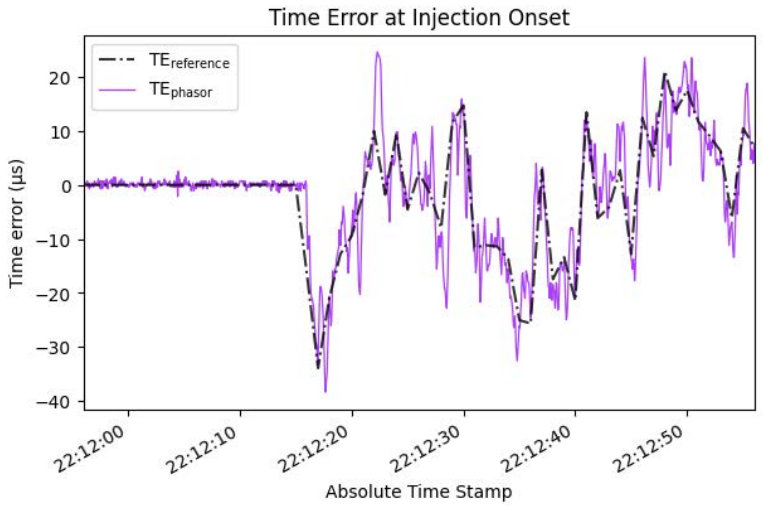


PAE



Time Error Comparison



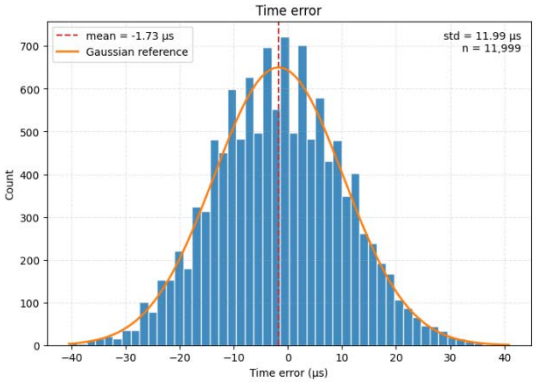


Time Error Experiment: Jitter Injection

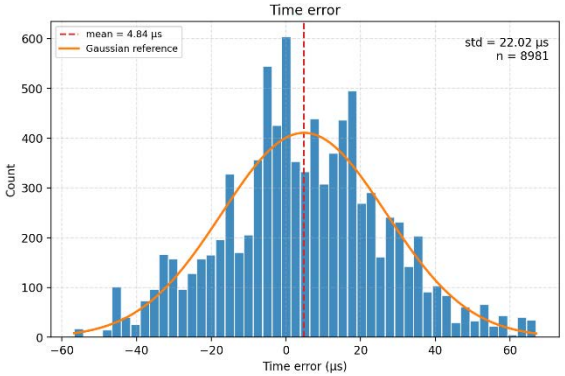
- Across four different jitter injection cases, the time error histograms follow the gaussian reference, with condition-dependent bias and spread.
- The table summarizes the input jitter, measured time error, and frequency excursions across the tested conditions.

Case	Input jitter TE_{ref} σ (μs)	Measured TE_{phasor} σ (μs)	Max |Δf| (mHz)
Case 1	12.18	11.99	7.16
Case 2	22.39	22.02	9.56
Case 3	26.30	25.58	13.02
Case 4	59.46	58.48	29.44

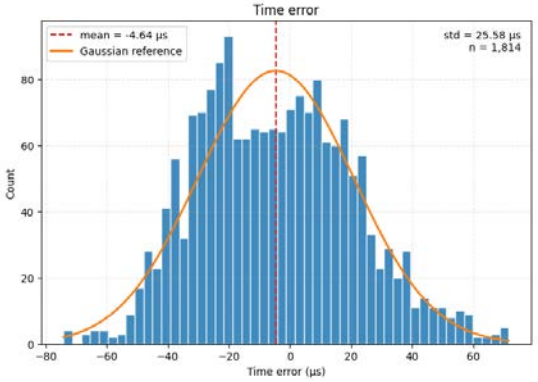
Case 1



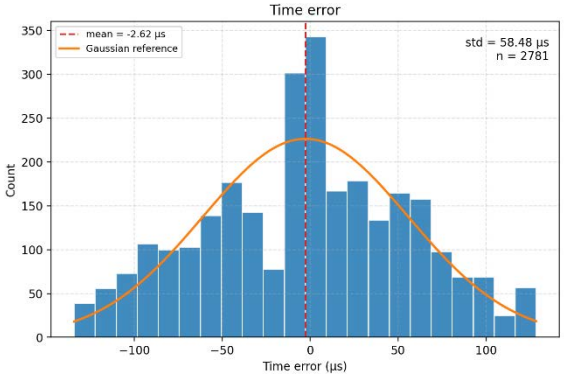
Case 2



Case 3



Case 4



Impact of Timing Error Injection on Power System Applications

- Timing threat in power system:
  - PTP packet-delay and path asymmetry create time-varying synchronization error.
  - GNSS loss or jamming can trigger holdover or source switching, while spoofing can introduce a plausible drifting timing offset.
- These timing mechanisms differ at the source, but all perturb the time reference received by a PMU or other synchronized device. The rapidly varying component of timing error appears as **jitter** and may be random or bursty. Slower timing error may appear as **drift or step changes**.
- **HIL experiment:** We inject bounded, zero mean timing jitter to represent controlled, rapidly varying timing error, then measure the differential timing error between the reference unit and test unit and the corresponding PMU response.
- Many power system applications are timing sensitive, including protection, control, fault location, and state estimation. Following study uses **double-ended traveling-wave fault location (DETWFL)** and **weighted least-squares (WLS) state estimation** as representative applications.

Critical Applications:
From Timing Distorted Measurements to Consequences

Timing jitter and delay can distort synchronized measurements. Their operational importance depends on how each application uses the affected measurement.

- **DETWFL**
  - **Purpose:** Rapidly locate a fault along a transmission line so that field crews can inspect the correct line section, isolate the fault, and restore service efficiently.
  - **Why timing matters:** Timing error directly biases the reported fault location.
  - **Consequence:** A biased location expands the patrol area or sends crews to the wrong line section, increasing the time required for fault verification, isolation, and restoration.
- **PMU-enhanced state estimation**
  - **Purpose:** Estimate the system wide voltage state from incomplete SCADA and PMU measurements, including unmeasured voltage, angle, and power flow information.
  - **Why timing matters:** Timing error rotates an affected PMU phasor before state estimation.
  - **Consequence:** A biased state can lead to an erroneous characterization of voltage stress, power transfer, and angle differences, thereby degrading the monitoring, security assessment, and stability decision.

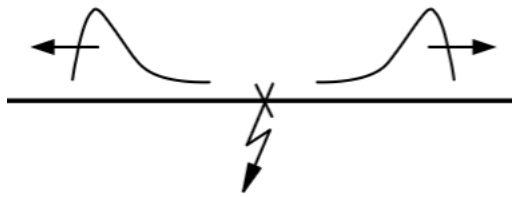
Double-Ended Traveling-Wave Fault Location: Differential First Wave Arrival

First-wave arrival at two terminals.

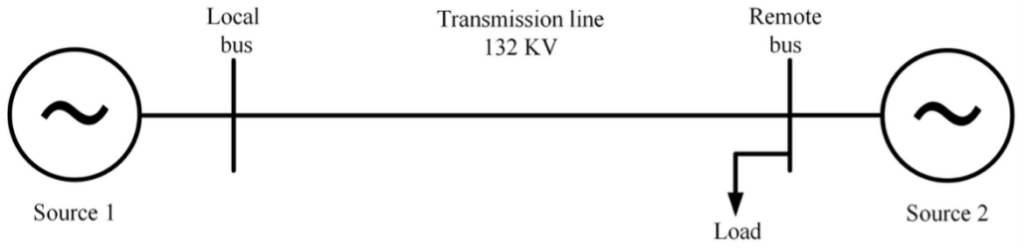
- A line fault launches high frequency traveling waves toward the local and remote terminals.
- First wave arrival times, t_L and t_R, are extracted from the terminal transient signals.
- The fault position is calculated from the arrival time difference

$$Fault\ location = \frac{l + (t_L - t_R)v}{2}$$

Where l is line length, v is traveling wave propagation speed.



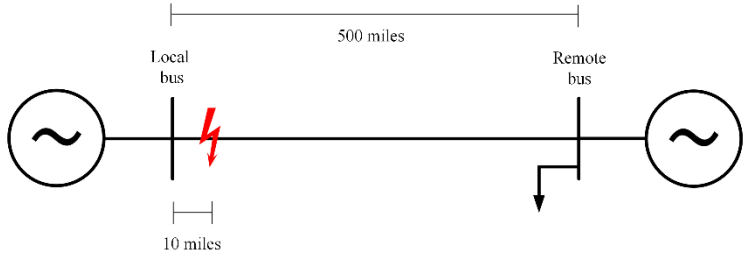
Propagation of the traveling waves



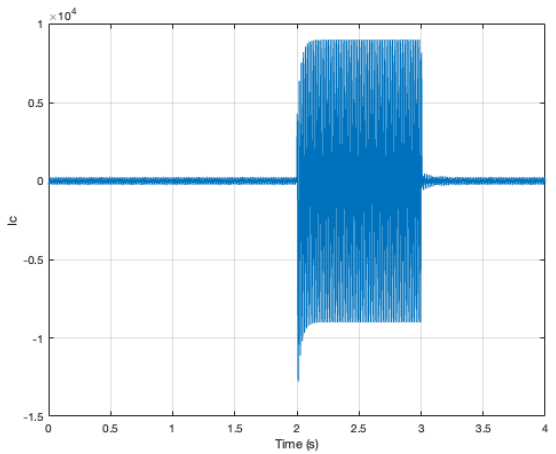
Two-terminal transmission line case used in the DETWFL study

TWFL Experiment: Double-Ended Traveling-Wave Fault Location

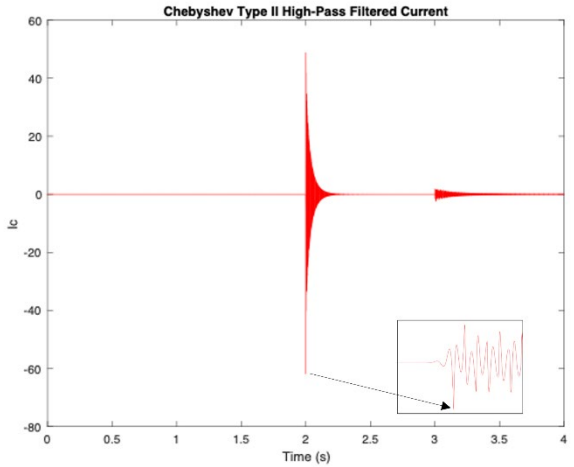
- The fault happens at 10-mile location launches traveling waves; the local terminal receives the first-wave before the remote terminal.
- The measured terminal current contains both the fault transient and fundamental-frequency content. A high-pass filter isolates the high frequency first-wave component.
- The insets identify the first-arrival times at the local and remote terminals. Their difference, $t_L - t_R$, determines fault location.



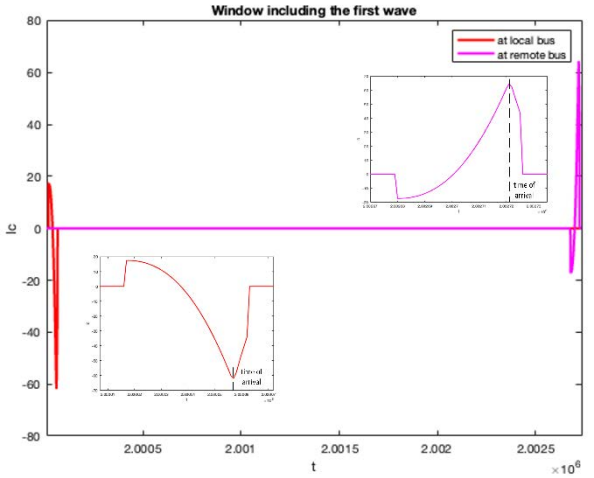
Fault location in the simulation



Fault transient current measured at the local terminal



High-pass filtered local terminal current used for first-wave detection



First-wave arrival time picks at the local and remote terminals

TWFL Experiment: Baseline Validation and Timing Error Sensitivity

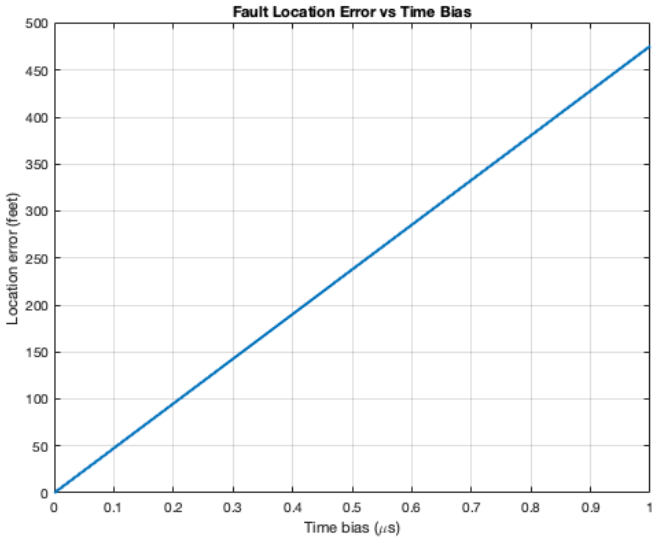
Baseline case:

- The simulated first-wave arrivals occur at $t_L = 2.000056$ s and $t_R = 2.00272$ s.
- Given a propagation velocity of v is 96.7% of the speed of light, the fault location as 10.00024 miles, consistent with the simulated fault location 10 miles.
- Other experiments show that, in the absence of timing errors, the location error due to calculation is less than **0.01 miles.**

Timing error sensitivity test:

- The sensitivity sweep shows that a 1 μs differential timing bias produces approximately 475 ft or **0.09 mile** of fault-location error.

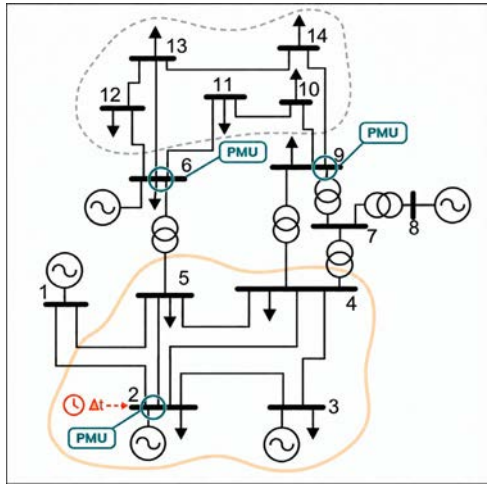
Actual Fault Location (miles)	SLG Estimated Location (miles)	SLG Error (%)
50	50.0002	0.0004
60	59.9901	0.016
70	70.00018	0.000257
80	79.99008	0.0124
90	90.00016	0.00018
100	99.99006	0.010



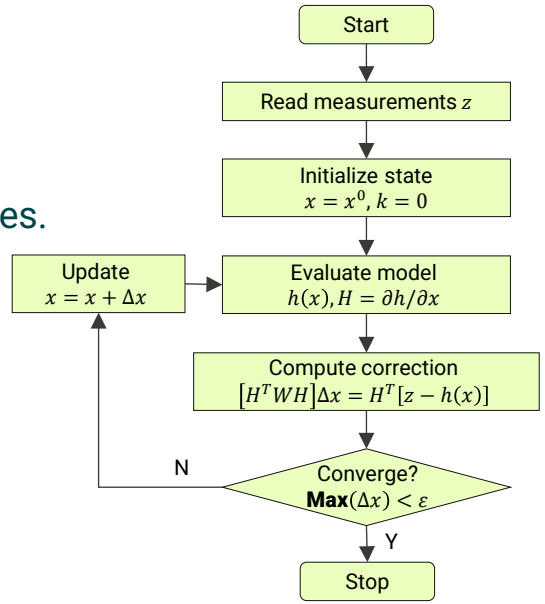
Location error under differential timing-bias injection

Power System State-Estimation: Nonlinear WLS Enhanced by PMU Data

- **Network and measurements:** The IEEE 14 bus system combines SCADA measurements with synchronized PMU phasors at buses 2, 6, and 9.
  - Stage 1 — Nonlinear SCADA WLS (flowchart at right):
    - Estimate $x_1 = [V, \delta]^{\mathrm{T}}$ from $z_s = h_s(x_1) + e_s$.
    - AC power injection and line flow equations define the predicted measurements. $x_1' = \arg\min_x [z_s - h_s(x)]^{\mathrm{T}} R_s^{-1} [z_s - h_s(x)]$
  - Stage 2 — Linear PMU fusion:
    - Combine the first-stage voltage estimates with PMU voltage and current-injection phasors in rectangular coordinates, then apply linear WLS to refine the voltage estimates.
  - Final estimate:
    - Linear WLS computes the final voltage state: $\tilde{x} = \left(H^{\mathrm{T}} R^{-1} H\right)^{-1} H^{\mathrm{T}} R^{-1} z$.
- Inject timing error into the PMU at bus 2 to impact the phasor measurement z.

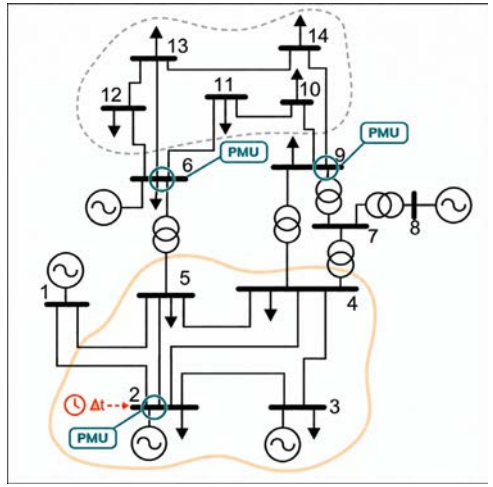


IEEE 14-bus system

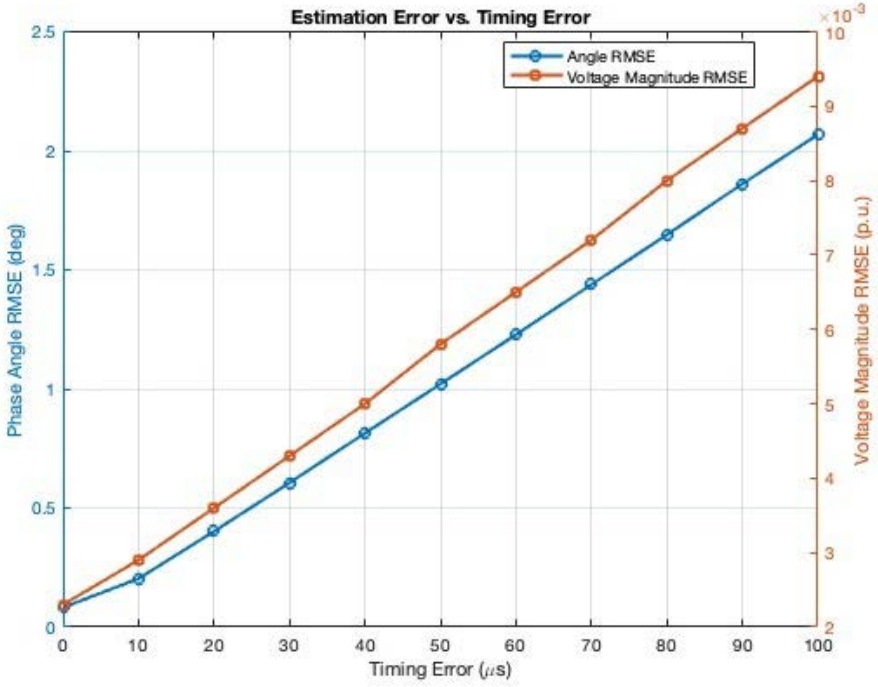


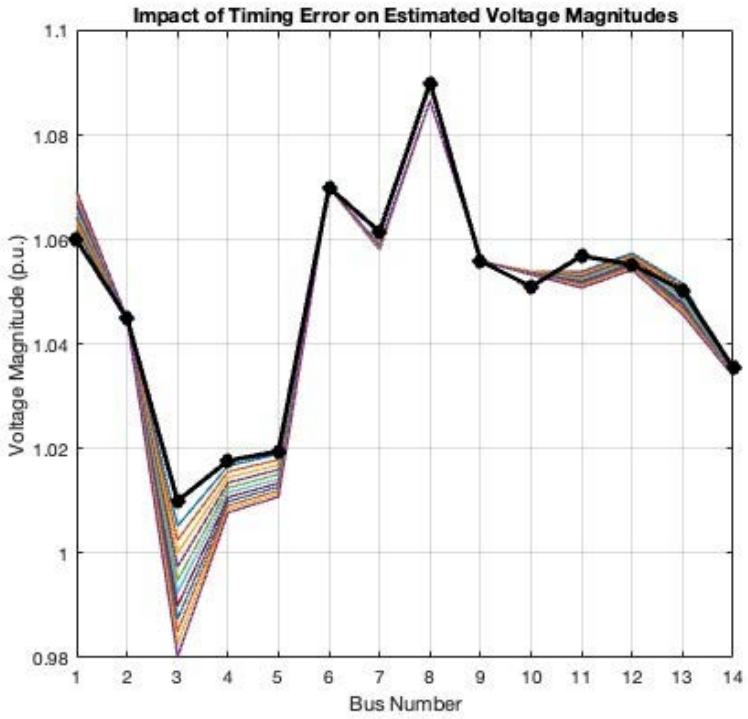
Non-linear WLS SE algorithm

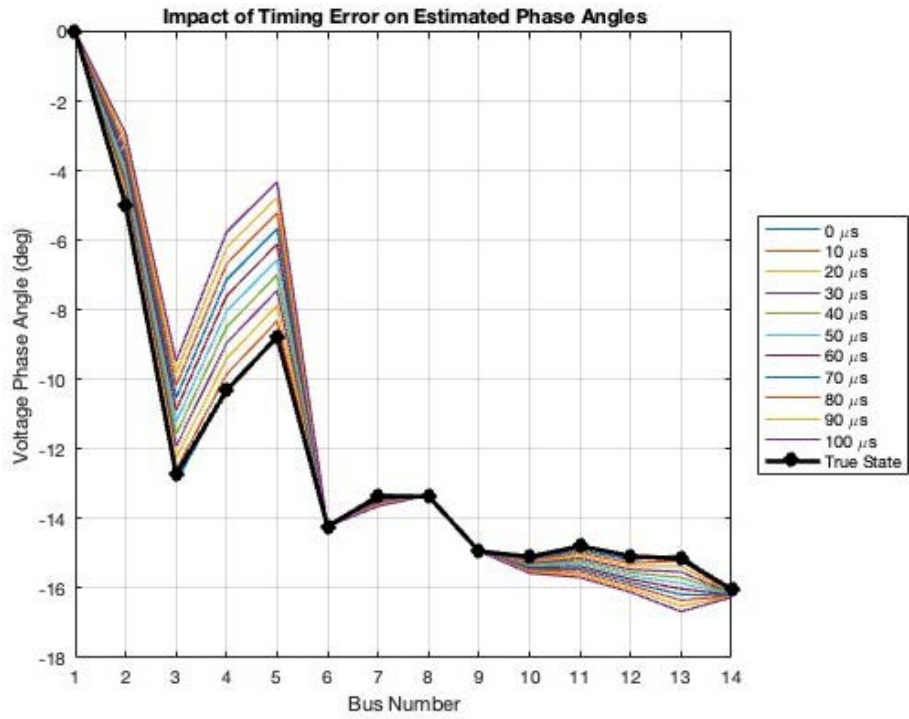
Power System State-Estimation Experiment: Time Error Sensitivity



- From 0 to 100us timing error injection into the PMU at bus 2. Voltage magnitude RMSE remains less than 2%, while the phase angle RMSE gets over 2.0^{o}.
- Buses 3–5 show the largest angle bias through direct electrical coupling to bus 2, while smaller bias persists at buses 10–14. the WLS estimator redistributes the inconsistent bus-2 phasor residual despite clean PMU measurements at buses 6 and 9







Summary and Conclusion

- This study demonstrated the high-fidelity capability of the NHIL testbed to evaluate PMU performance under controlled timing impairments, including time delays and timing jitter.
- The NHIL testbed emulated time delays ranging from 10μs to 10ms, as well as timing jitter from 10μs to 60μs. The results revealed a clear and quantifiable relationship between timing impairments and synchrophasor measurement errors.
- Such measurement degradation can compromise grid situational awareness. As demonstrated in the simulation, it could potentially lead to inaccurate power-system state estimation and line fault location
- Resilient synchronization is not merely a compliance requirement, but a fundamental enabler of reliable operation in increasingly automated power systems.


Questions?