DOE/OE Transmission Reliability Program

Advanced Synchrophasor Metrology

Paul D. Ewing, PE
Group Leader, RF, Communications, & Intelligent Systems
Oak Ridge National Laboratory
ewingpd@ornl.gov

Project Team

Mark Buckner, PhD, ORNL | **Eric Zhan, UTK**
Joe Gracia, PE, ORNL | **Yilu Liu, PhD, ORNL/UTK**

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Presentation Outline

- **Project Objective**
- **Looking Back** (accomplishments during the past year)
  - Collaboration with NIST and PNNL
  - Round robin testing with NIST
  - IEEE 1588 outreach efforts
- **Looking Forward**
  - Deliverables and schedule for activities in FY14
  - Risk factors
  - Early thoughts on follow-on work for FY15

Project Objective

- **Background** – Industry dependence on PMUs is expected worldwide as their use increases
  - 21 or more PMU manufacturers
  - More than 50 different models of PMU
  - PMU functions are being included in "multifunction devices" – protective relays, digital fault recorders, power quality meters, etc.[‡]
- **Consensus** – Conformance is necessary and metrology R&D needs to be addressed early on
- **Objective** – Identify emerging metrology needs and develop solutions in the form of tools, techniques, and procedures. A critical part of this project is developing a working relationship with NIST and PNNL.

[‡] NIST Framework for Smart Grid Interoperability Standards – Overview of PMU Performance Testing, NIST i-PCGrid Workshop, Jerry FitzPatrick and Tom Nelson, March 26, 2014

Collaboration with NIST and PNNL

- Conducting coordination meetings with NIST and PNNL regarding synchrophasor activities
  - ORNL/UTK participated in NIST PMU inter-laboratory comparison "round robin" testing (Liu)
  - Assisting NIST in evaluating and summarizing data (Buckner)
  - ORNL visited NIST (Buckner)
  - NIST and PNNL visited ORNL (NASPI Week)
- Identified new areas for collaboration – NIST/DOE Inter-Agency Agreement (Gracia)
- Sharing work progress and findings

NIST Round Robin

- ORNL/UTK was 1st participant in NIST PMU round robin testing
- Testing intended to provide verification of measurement capabilities of participating laboratories and to ensure the uniformity of the PMU calibration
- Ran over 600 tests (multiple configurations)

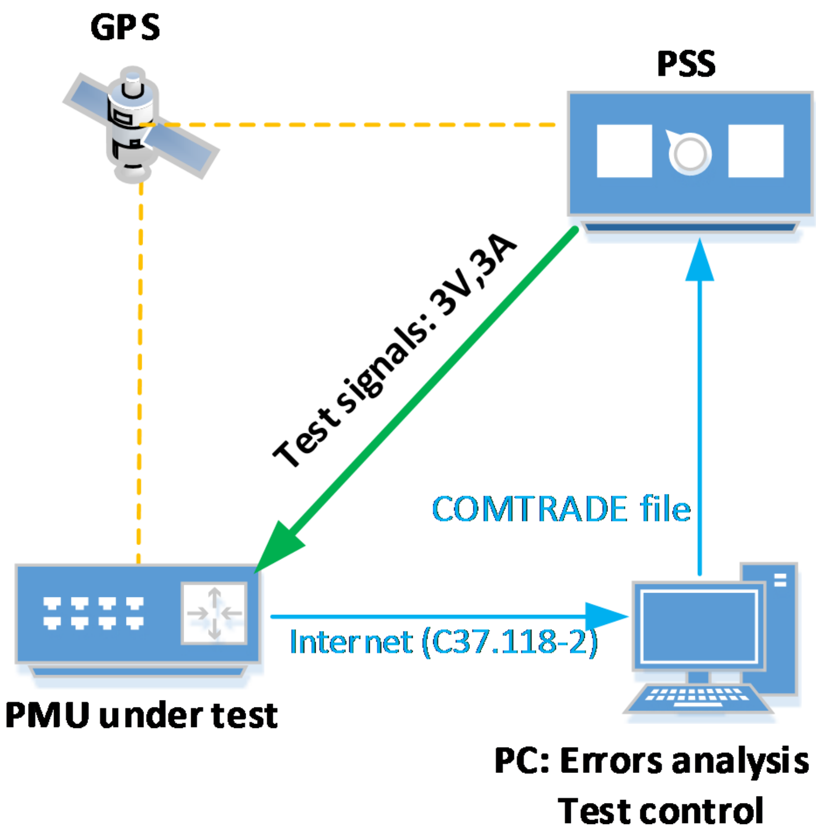
♦ BPA	♦ ORNL/UTK
♦ Fluke	♦ PG&E
♦ GE	♦ Quanta Technologies
♦ Georgia Tech	♦ Texas A&M
♦ METAS	♦ Virginia Tech

PMU Test Plan

- PMU under test – Model 1133A Power Sentinel manufactured by Arbiter Systems

- Preliminary test
  - Different nominal frequency (50Hz/60Hz)
  - Different reporting rate (10, 25, 50 for 50Hz nominal frequency; 10, 12, 15, 20, 30, 60 for 60Hz nominal frequency)
- Steady-state compliance test (30 fps and 60 fps)
  - signal frequency range, signal magnitude (voltage/current), harmonic distortion, and out-of-band interference
- Dynamic compliance test (30 fps and 60 fps)
  - magnitude modulation, phase modulation, frequency ramp, and step change in phase/magnitude

PMU Test Setup



- Power system simulator (PSS)
  - Doble F6150 PSS generates test signals (3-phase voltages, 3-phase currents, positive sequences) for PMU
- PMU under test
  - Measures the phasor; calculates frequency, and rate-of-change of frequency
  - Streams measurement data to PC through Internet
- GPS
  - Provides timing for PSS and PMU
- PC
  - Controls testing
  - Calculates the errors of measurement data

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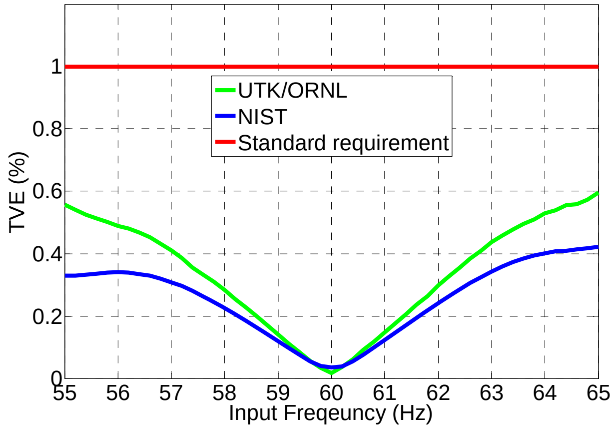
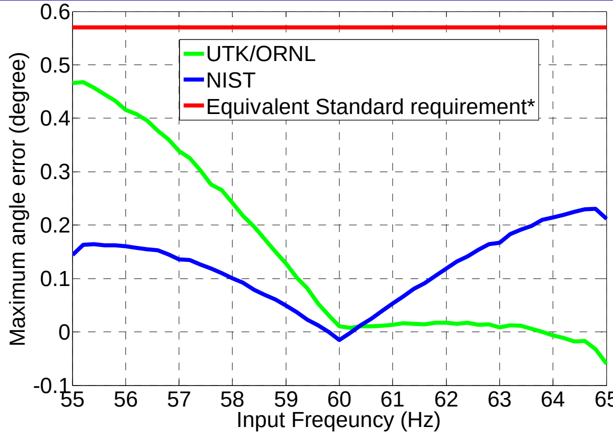
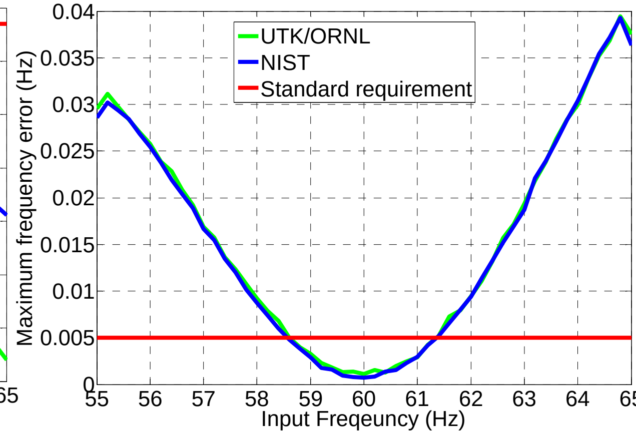
Pre-Calibration Test Results



TVE under frequency range test



Angle error under frequency range test



Frequency error under frequency range test

Frequency ramp test

	TVE (%)	Maximum angle error (degree)	Maximum frequency error (Hz)
UTK/ORNL	0.3275	0.4906	0.0513
NIST	0.2462	0.2487	0.0456
PMU Standard	**1**	**N/A**	**0.005**

- TVE errors could not accurately be calculated under off-nominal frequency conditions
- Both TVE and frequency errors could not accurately be calculated under frequency ramp condition

*PMU Standard has no requirement for angle, so 0.57 degree is used here to correspond to 1% TVE while assuming magnitude has no error.

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Problem with Test Setup

- PSS could not generate accurate signals for PMU

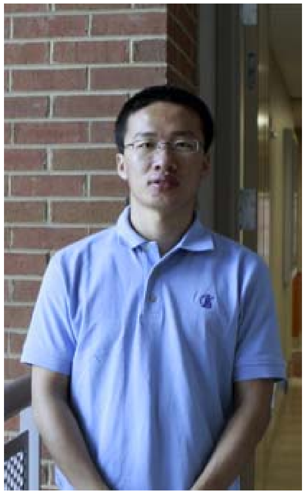
  Time delay of PSS: ~ 130 μs – voltage; ~ 115 μs – current

  True signal: $Sig = Acos(2\pi ft + \theta)$

  Actual signal: $Sig = Acos(2\pi f(t - t_d) - \theta_d + \theta)$

  The angle error caused by PSS is

$$Ang_E = -2\pi f t_d - \theta_d$$

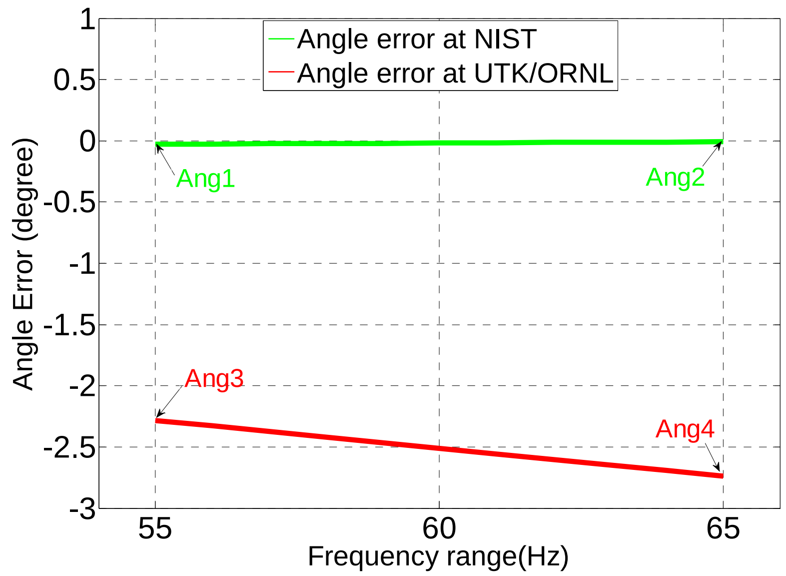


Eric Zhan

- The time delay of PSS will result in inaccurate TVE error analysis under steady-state conditions, and inaccurate TVE and frequency errors analysis under phase modulation and frequency ramp conditions
- t_d and θ_d must be compensated for

Compensation Method - t_d and θ_d

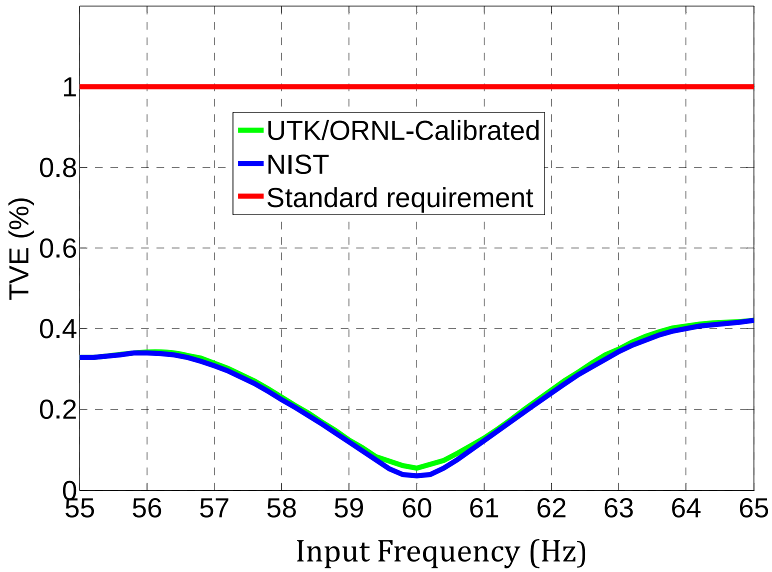
- Time delay will cause angle errors;
- Angle errors are a function of frequency
- The angle errors difference between ORNL/UTK and NIST under frequency range test are used to compute t_d and θ_d

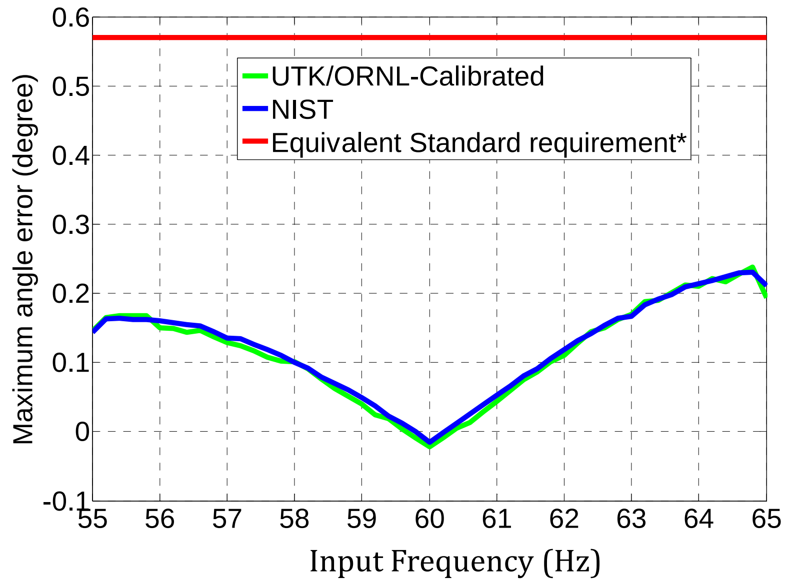


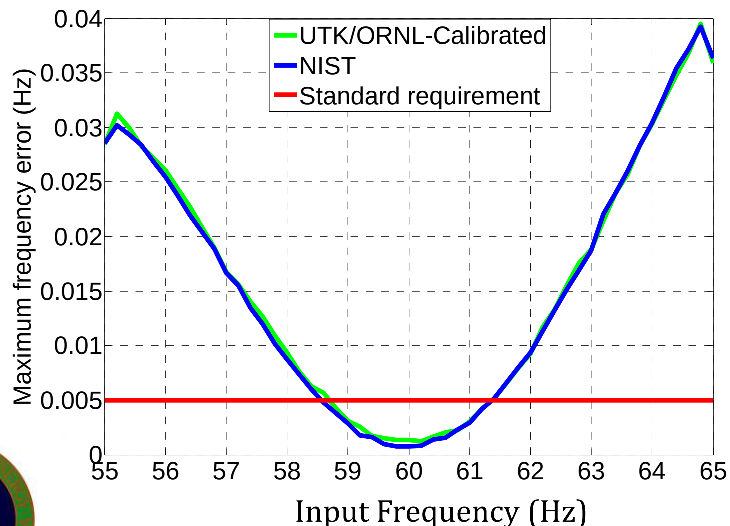
- Compensation equations -

$$\begin{cases} Ang4 - Ang2 = -2\pi 65 t_d - \theta_d \\ Ang3 - Ang1 = -2\pi 55 t_d - \theta_d \end{cases} \Rightarrow \begin{cases} t_{d\_cal} = \dfrac{(Ang3 - Ang1) - (Ang4 - Ang2)}{2\pi 10} \\ \theta_{d\_cal} = -\dfrac{65(Ang3 - Ang1) - 55(Ang4 - Ang2)}{10} \end{cases}$$

Frequency Range Test Comparison







TVE difference < 0.02%

Angle difference < 0.02 degree

Frequency difference < 0.0015 Hz

*PMU Standard has no requirement for angle, so 0.57 degree is used here to correspond to 1% TVE while assuming magnitude has no error.

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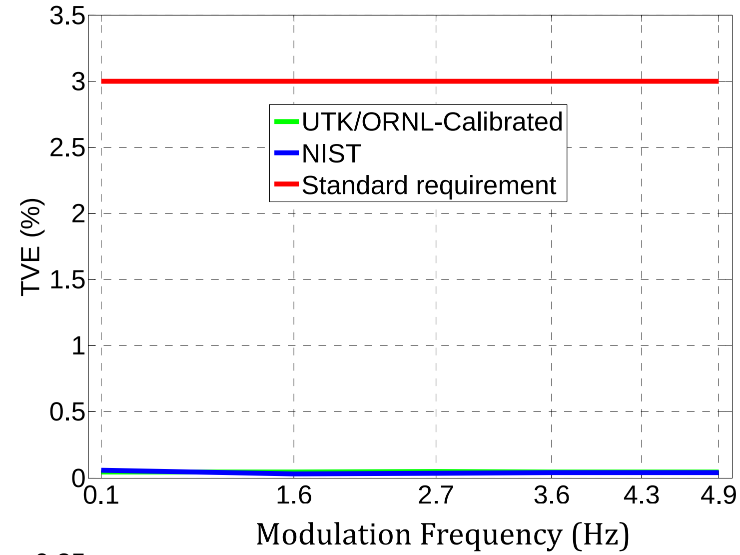
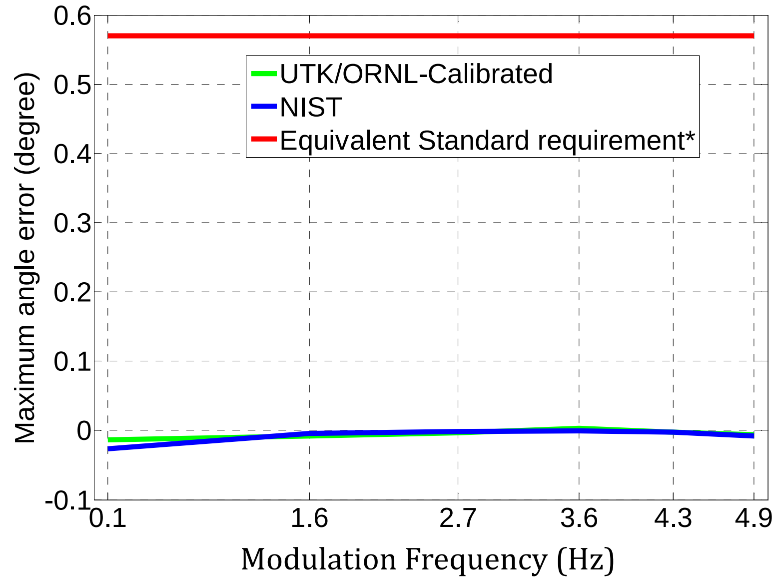
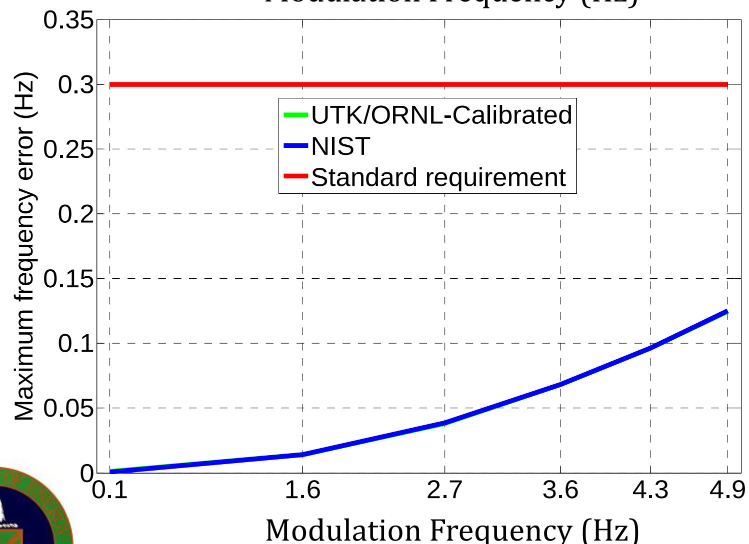
Phase Modulation Test Comparison







TVE difference < 0.015%

Angle difference < 0.015 degree

Frequency difference < 0.002 Hz

*PMU Standard has no requirement for angle, so 0.57 degree is used here to correspond to 1% TVE while assuming magnitude has no error.

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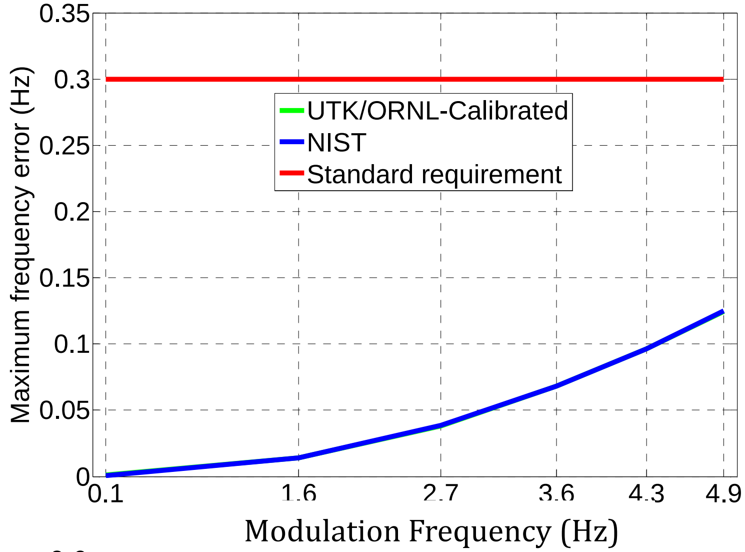
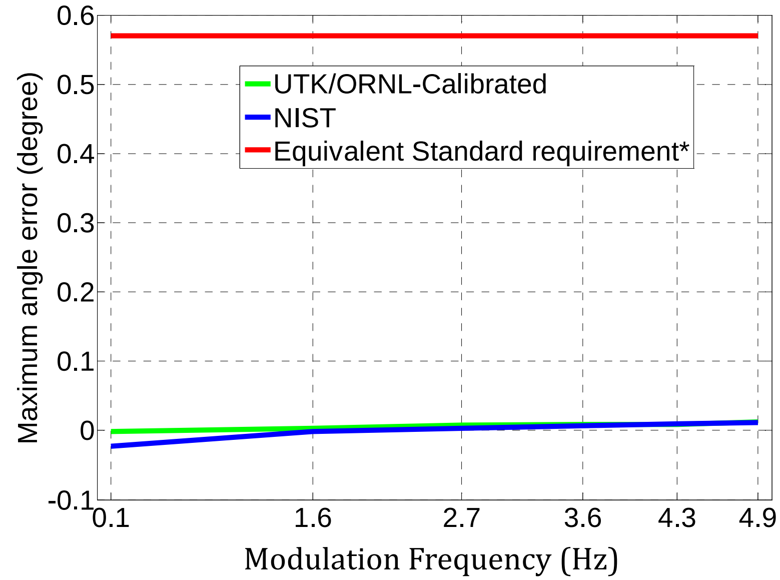
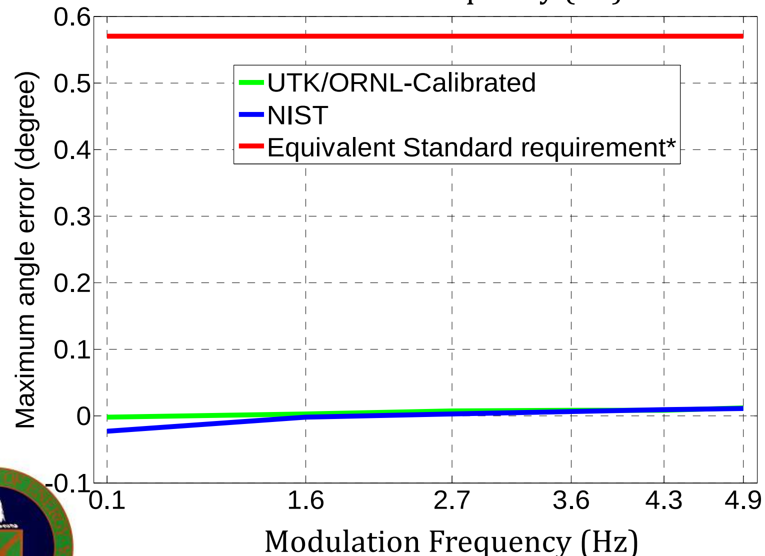
Magnitude Modulation Test Comparison







TVE difference < 0.025%

Angle difference < 0.025 degree

Frequency difference < 0.001 Hz

*PMU Standard has no requirement for angle, so 0.57 degree is used here to correspond to 1% TVE while assuming magnitude has no error.

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Frequency Ramp Test Comparison

	TVE (%)	Maximum angle error (degree)	Maximum frequency error (Hz)
NIST	0.2462	0.2487	0.0456
UTK/ORNL - Calibrated	0.2450	0.2407	0.0459
PMU Standard	1	N/A	0.005

TVE difference = 0.0012%

Angle difference < 0.008 degree

Frequency difference < 0.0003 Hz

Compliance of PMU Under Test

<table>
<tr><th rowspan="3">Class</th><th colspan="16">Steady State Test</th></tr>
<tr><th colspan="4">Frequency range test</th><th colspan="4">Signal magnitude test</th><th colspan="4">Harmonic distortion test</th><th colspan="4">Out of band test</th></tr>
<tr><th colspan="2">TVE</th><th>FE</th><th>RFE</th><th colspan="2">TVE</th><th>FE</th><th>RFE</th><th colspan="2">TVE</th><th>FE</th><th>RFE</th><th colspan="2">TVE</th><th>FE</th><th>RFE</th></tr>
<tr><td rowspan="2">M</td><td>V</td><td>P</td><td rowspan="2">Δf≤1.4: P
Δf>1.4: F</td><td rowspan="2">F</td><td>V</td><td>P</td><td rowspan="2">M=10%, 20%: F (UTK);
M=10%: F (NIST);</td><td rowspan="2">F</td><td>V</td><td>P</td><td rowspan="2">P</td><td rowspan="2">P</td><td>V</td><td>P</td><td rowspan="2">F</td><td rowspan="2">F</td></tr>
<tr><td>I</td><td>P</td><td>I</td><td>M=10%: F (UTK);
P (NIST)</td><td>I</td><td>P</td><td>I</td><td>P</td></tr>
</table>

<table>
<tr><th rowspan="3">Class</th><th colspan="15">Dynamic State Test</th></tr>
<tr><th colspan="4">Amplitude modulation test</th><th colspan="4">Phase modulation test</th><th colspan="4">Frequency ramp test</th><th colspan="3">Step test</th></tr>
<tr><th colspan="2">TVE</th><th>FE</th><th>RFE</th><th colspan="2">TVE</th><th>FE</th><th>RFE</th><th colspan="2">TVE</th><th>FE</th><th>RFE</th><th>RT</th><th>DT</th><th>OS</th></tr>
<tr><td rowspan="2">M</td><td>V</td><td>P</td><td rowspan="2">P</td><td rowspan="2">P</td><td>V</td><td>P</td><td rowspan="2">P</td><td rowspan="2">P</td><td>V</td><td>P</td><td rowspan="2">F</td><td rowspan="2">F</td><td rowspan="2">P</td><td rowspan="2">P</td><td rowspan="2">P</td></tr>
<tr><td>I</td><td>P</td><td>I</td><td>P</td><td>I</td><td>P</td></tr>
</table>

Nominal frequency: 60Hz; Reporting rate: 60Hz

P: Pass; F: Fail; Δf: frequency deviation; M: magnitude percentage

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Conclusions from Round Robin Testing

- Comparison of the ORNL/UTK and NIST test data are close, leading to a good result
- PMU under test passed many of the IEEE C37.118-1* tests, but failed a few
- Without compensation, the Doble F6150 PSS can't generate signals accurate enough for PMU testing
- The compensation/calibration method greatly improves the performance of the PMU testing system

* PMU standard requirements are expected to be relaxed soon since they are so strict and the PMU under test was not designed to pass the IEEE C37.118-1 Std.

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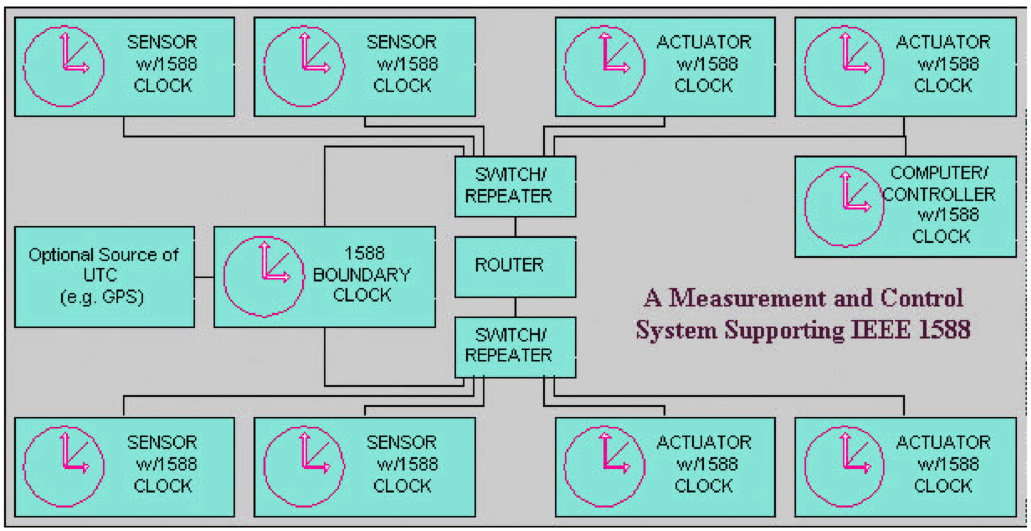
IEEE 1588 Std Outreach

- **Charter** – Issue new edition of IEEE 1588-2008, *Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*
- **Authorization** – PAR approved on June 14, 2013
- **Rationale** – Revision is needed to meet the requirements of various industries for a more secure precision clock synchronization protocol
  - Update existing Precision Time Protocol (PTP)
  - Work with both IPv4 and IPv6
  - Suitable for applications requiring sub-nanosecond timing

P1588 Working Group

- **Subcommittees** – 1) Architecture, 2) High Accuracy, 3) Security, 4) Management, and 5) Upkeep (maintenance)
- **Progress to Date** – Focus has been on re-defining the PTP architecture, specifying control messages and data formats for better functionality, and trying to maintain consistency with past definitions



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Deliverables and Schedule

- **Collaboration with NIST and PNNL**
  - Participation in scheduled discussions on how DOE technology and assets can support NIST's technical objectives (at least quarterly)
  - Distribution of minutes after each meeting
- **NIST Round Robin**
  - Test results provided to NIST - due 60 days after completion (status: complete)
  - Feedback on analysis and presentation of results - due Sept 2014 (status: complete)
- **IEEE 1588 Committee**
  - Meeting participation and technical input to working group – as scheduled (status: ongoing)
  - Provide updates – due 60 days after meetings (status: ongoing)

Risk Factors

Risk factors affecting the timely completion of planned activities, as well as movement through the RD&D cycle

There are no foreseen technical, fiscal, logistical, or organizational risk factors

Follow-on Work

Early thoughts on follow-on work that should be considered for funding in FY15

- Investigating the impact of PMU inaccuracy on synchrophasor-based PMU applications
- Pursuing additional PMU testing scenarios, such as a noise test and a composite signal test
- Investigating the possibility of magnitude compensation for PMU testing system
- Performing consistency testing on PMUs from different vendors
- Testing the new IEEE C37.118-1 compliant PMU (not yet released) when available

Follow-on Work (cont.)

Early thoughts on follow-on work that should be considered for funding in FY15

- Exploring solutions to timing synchronization redundancy
- Continuing support for IEEE 1588 Std committee work
- Streamlining instrumentation channels by standardizing the process bus, associated transducers, and merging units
- Researching and developing system integrity protection schemes (SIPS) for transmission and distribution systems
- Pursuing in-situ calibration techniques for field-installed PMUs

Q&A

World Metrology Day

Worldwide uniformity of measurement since 1875

Measurements and the global energy challenge

May 20, 2014

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