Micro-synchrophasors for distribution grids: ***instrumentation*** lessons learned (so far!)

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Acknowledgement

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Additional thank-you: ARPA-E projects assign Intellectual Property to the developers, so we have many patents at various stages. I will try to identify during my talk.

ARPA-E (Power Standards Lab) Micro-PMU

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Lesson Learned:
Expect moderately harsh environments, even at national labs in California.

ARPA-E (Power Standards Lab) Micro-PMU

Lesson Learned:
Mounting location in the field may be… er… unexpected.

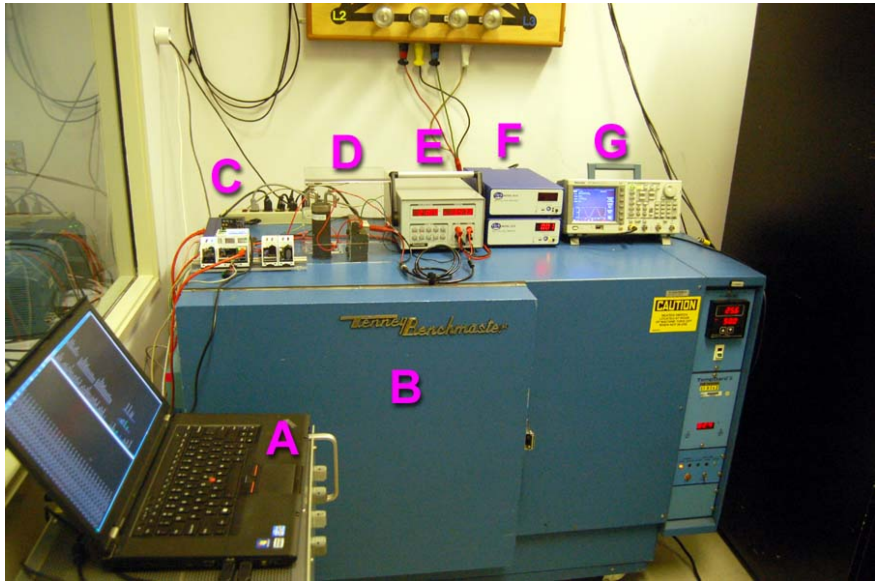
Micro-PMU requirements (1)

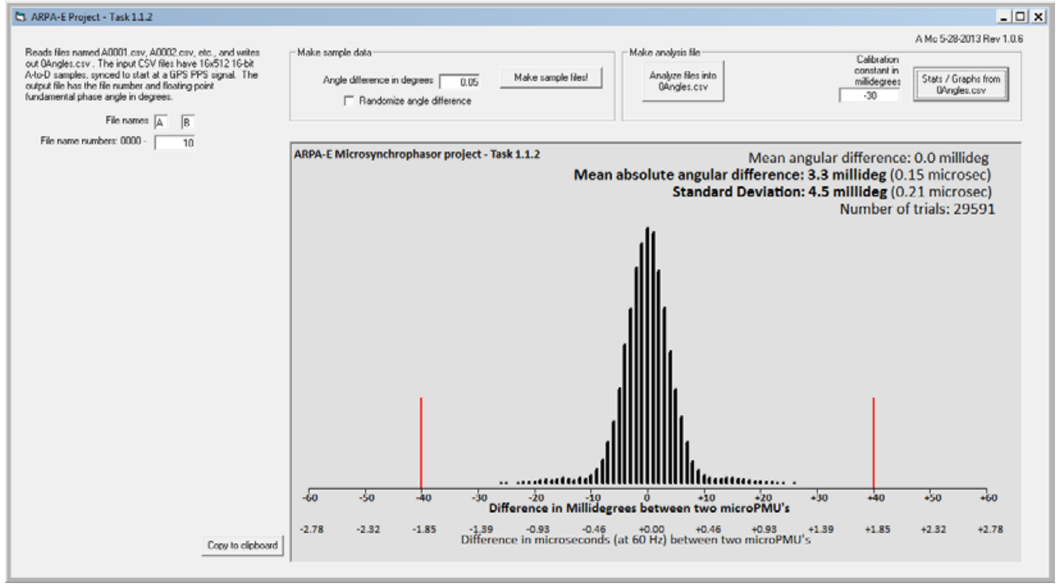
- 100V-690V applications: ±1,000V rating, ±6,000V measurement range, ±15,000V insulation test
- Ultra-precise CT's: 5-amp, individually calibrated to 50th harmonic, ±0.01%, ±0.001° (fundamental)
- Minimum 2-week data buffer, or 16 gigabytes. Drop-anywhere communications via cell phone Ethernet
- Harsh environments…

http://PQube3.com/tough

Micro-PMU requirements (2)

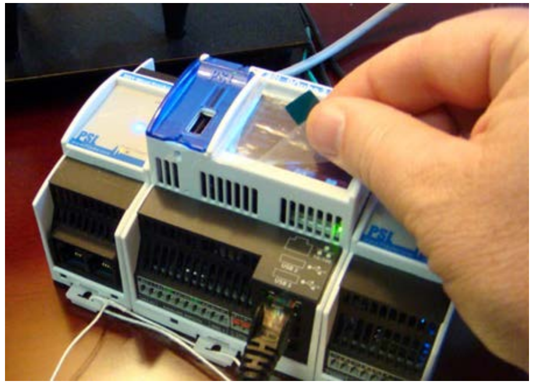
- **Lesson Learned: Accuracy is not as important as resolution, and short-term stability.**
- Micro-PMU resolution and short-term stability:
  - Magnitude measurements: ±0.01% (±0.00001% for some applications – 100 PPB)
  - Angle measurements: ±0.010° (±0.002° for some applications)
  - Roughly 2 or 3 orders of magnitude better TVE than transmission PMU specs…





Initial micro-PMU Field Installations

- **Lesson Learned: Line-to-ground or Line-to-Neutral voltage measurements?**
  - Standardized on phase-to-earth voltage measurements
- **Lesson Learned: Cyber probes almost immediately.**
  - Full Linux firewall built inside micro-PMU, and more coming
- **Lesson Learned: GPS orbital “surprises” -- to me, anyway**
  - No issues throughout the project, due to special GPS receiver(?)
- **Lesson Learned: always surprises!**



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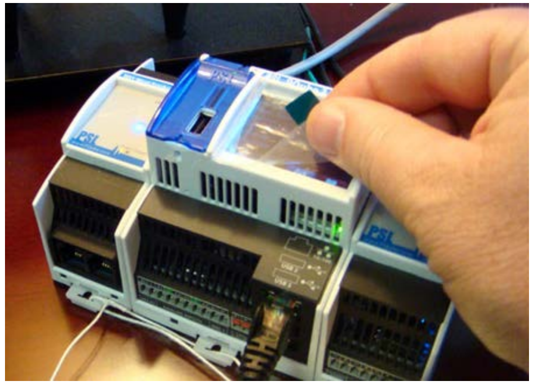


Technical instrumentation lessons learned (1)

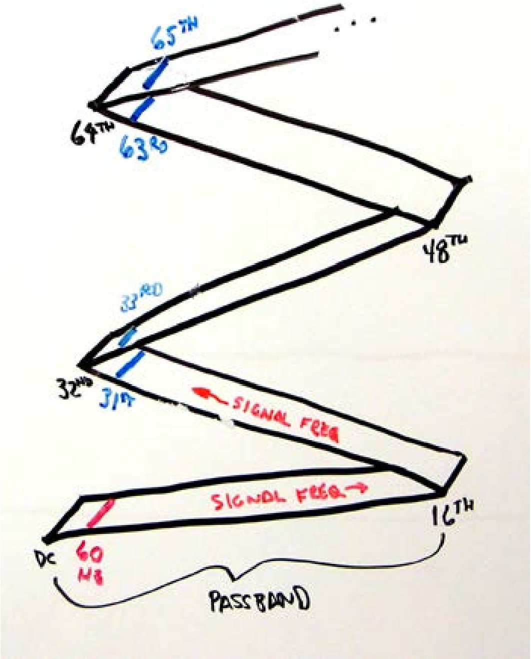
- **Example Lesson Learned: an anti-alias filter can use up your entire timing error budget.**
  - **At ±0.001° your total time error budget is 50 nanoseconds. (Remember, short-term stability!)**
  - **With 64 samples per cycle, your anti-alias filter has a cut-off frequency of 2 kHz ~ 500,000 nanoseconds.**
  - **So if the capacitors in your anti-alias filters can be are ±0.01% unstable in value…**
    there goes your entire timing-error budget.
  - **(Patent still in process on this one.)**

Technical instrumentation lessons learned (2)

- **Example Lesson Learned: A simple GPS cable shield can use up your entire magnitude error budget.**
  - **At ±10PPM, with a 3.0000V reference, your entire error budget is 30 microvolts.**
  - **With a 24-bit A-to-D converter, each tick is 0.13 microvolts.**
  - **With a 1 microamp cell-phone-RF-current flowing through your GPS antenna shield, then across your instrument ground through a 50-ohm path at 3 GHz, you've got a 50 microvolt problem.**
  - **(Patent issued this week! Only 4 years in process at USPTO… sigh.)**

Technical instrumentation lessons learned (3)

- **Example Lesson Learned: Higher samples-per-cycle can be a challenge too.**
  - **Eases anti-alias filter design, transferring it to digital domain.**
  - **Micro-PMU uses 512 samples-per-cycle at 50.000 Hz or 60.000 Hz.**
  - **But downsampling to synchrophasor calculation input must be done carefully.**
  - **Lesson Learned: simple decimation works in the lab, but sensitive to specific real-world harmonics.**



Technical communication lessons learned (1)

- **Example Lesson Learned: every time the distribution grid does something interesting, communication fails.**

  - **Streaming protocols, like C37, are not the best choice for distribution grid applications.**
    - **In most C37 implementations, all data is lost when comms is down.**
  - **Micro-PMU stores everything in an ordinary file structure, 2 weeks of backup.**
  - **UC Berkeley software (1) gathers, (2) confirms, then (3) remotely deletes.**
  - **Optimal for research, but not optimal for control.**

Technical communication lessons learned (2)

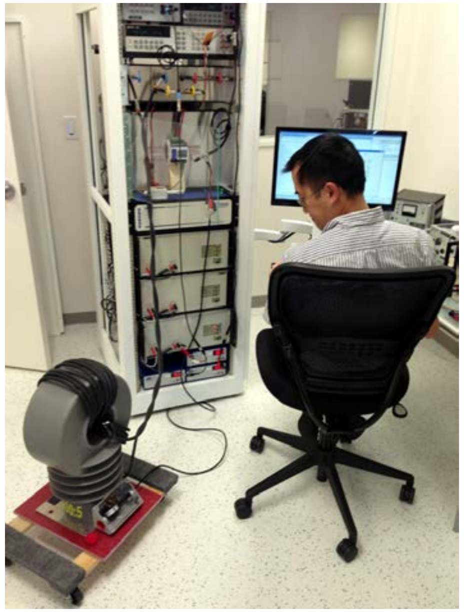
- **Example Lesson Learned: C37 streaming is pretty good for adding micro-PMU measurements to control loops.**
  - **Local network, and unlikely to go down.**
  - **OK if network fails when power fails.**
  - **In control loops, the meaning of time-stamps becomes important, and confusing.**
  - **Kirkham's goodness-of-fit could become important.**

Technical communication lessons learned (3)

- **Example Lesson Learned: *Some* C37 receivers struggle with 120 samples per second.**
  - **120 samples per second is the slowest a micro-PMU can go.**
  - **Roughly 500 megabytes per day from each micro-PMU, or for a smallish set of 60 micro-PMU's:**
    - **1 terabyte of raw data per month**
    - **4 terabytes of "interesting" calculated data per month.**

Distribution grid lessons learned (1)

- **Example Lesson Learned: PT's and CT's are not accurate, but they are stable.**
    - **Can be calibrated to some extent – an order of magnitude better.**
- **Important to choose algorithms that are sensitive to stability, not accuracy.**
- **Distribution grid sensors exist that should not be used for uPMU measurements.**
    - **Poor stability of capacitive-coupled voltage sensors, lay-in current sensors**



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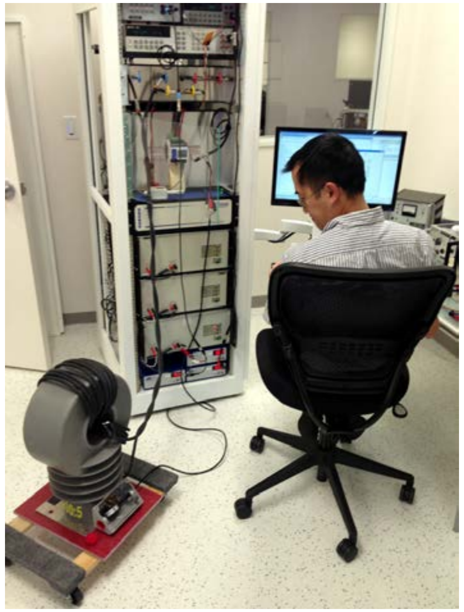
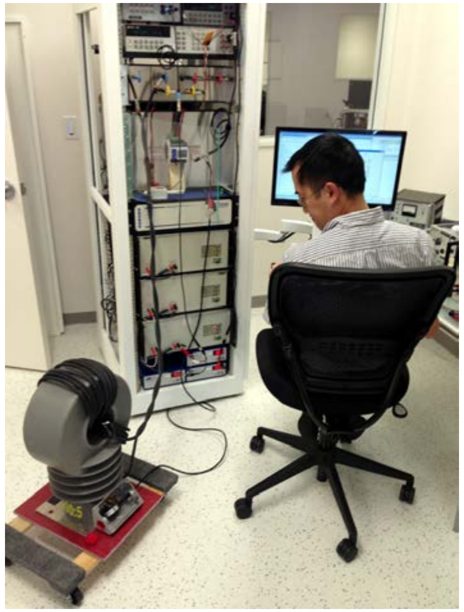
Distribution grid lessons learned (2)

- **Example Lesson Learned: Distribution grid models can be quite wrong.**
  - **Example: assumed lengths of conductors, assumed configuration**
  - **Example: the impedance of a 3-phase run is NOT the same on all three phases.**
  - **Example: simplifying assumptions may not match the real world measurements.**
  - **Good news: use micro-PMU measurements to update grid models.**

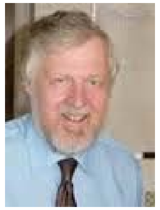


Distribution grid lessons learned (3)

- **Example Lesson Learned: For distribution, costs matter.**
  - **ARRA: $340 million, 1100 transmission PMU’s installed: $40k(?) per point**
    - **Includes instrument development, software dev, installation, coms**
  - **ARPA-E: $4 million, 100 distribution microPMU’s installed: $10k(?) per point**
    - **Includes instrument development, software dev, installation, coms**
    - **Factor of 10, but two more factors of 10 would be useful…**



Lessons learned: synchrophasor domain *vs.* time domain or frequency domain



Harold Kirkham – I'm paraphrasing – pointed out to me that synchrophasor measurements answer the question "if – IF! – the underlying signal were a cosine wave, what would its amplitude be, and what would its phase angle be relative to a timing pulse?"

THIS IS IMPORTANT.

1. **On distribution grids, the underlying signal is NOT a cosine wave.**
    a. **In steady state, both voltages and currents have significant <u>harmonics</u>.**
    b. **During any interesting event, the voltages and currents are <u>rapidly changing</u>.**
2. **For <u>harmonics</u>, you're often better off measuring in the frequency domain, not the synchrophasor domain.**
3. **For <u>rapidly changing</u> voltages and currents, you're often better off measuring in the time domain, not the synchrophasor domain.**
4. **Maybe we should reserve the synchrophasor domain for quasi-steady-state fundamental analysis: grid control-loop stability, grid impedances, and the like?**

Good news: we can flip the micro-PMU back and forth between synchrophasor recording, or frequency domain and triggered-time-domain recording

Internally, it's all the same commercially-available instrument: micro-PMU, or PQube 3 (http://PQube3.com).

- **Slightly different calibration procedure, but merging now**
- **Not even a firmware change – but it runs one function, or the other**
- **ARPA-E project requirements:**
    - **Ultra-precise microPMU measurements, and**
    - **IEC 61000-4-30 Class A power quality triggered measurements, and**
    - **IEC /ANSI Class 0.2 Certified revenue measurements, and**
    - **UL-recognition**
- **Some projects putting in both instruments, side-by-side (DARPA, NSA, etc.)**

PQube 3: time domain and freq domain

Lesson Learned:
Time domain data and Frequency domain data nicely supplement Synchrophasor data.

Example PQube 3 / microPMU triggered-time-domain recording

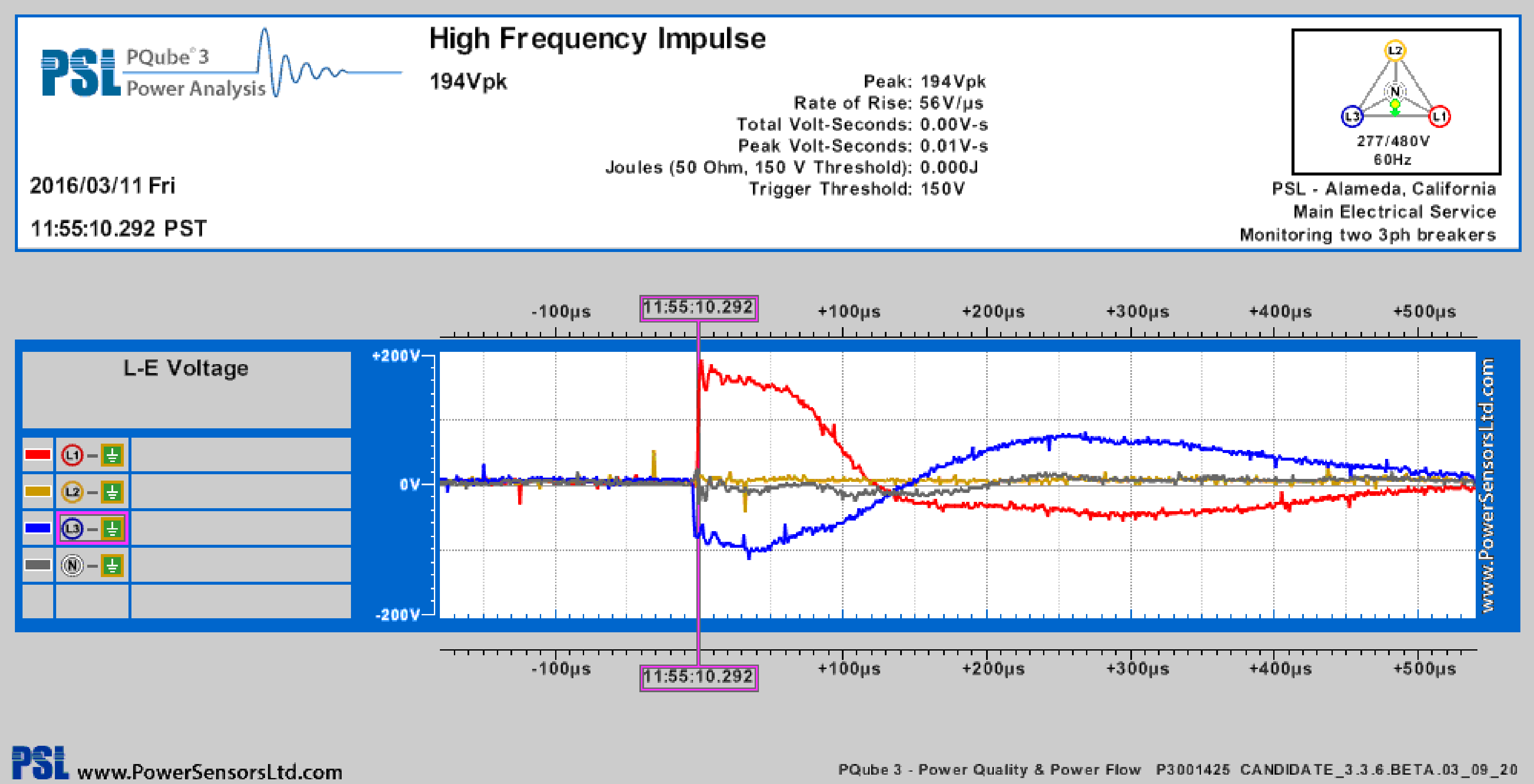
512-samples-per-cycle, "Waveshape change" trigger:

No software required – Instrument emails this GIF, plus Microsoft Excel files…

Example PQube 3 / microPMU triggered-time-domain recording

4-million-samples-per-second, "Impulse" trigger:

No software required – Instrument emails this GIF, plus Microsoft Excel files…



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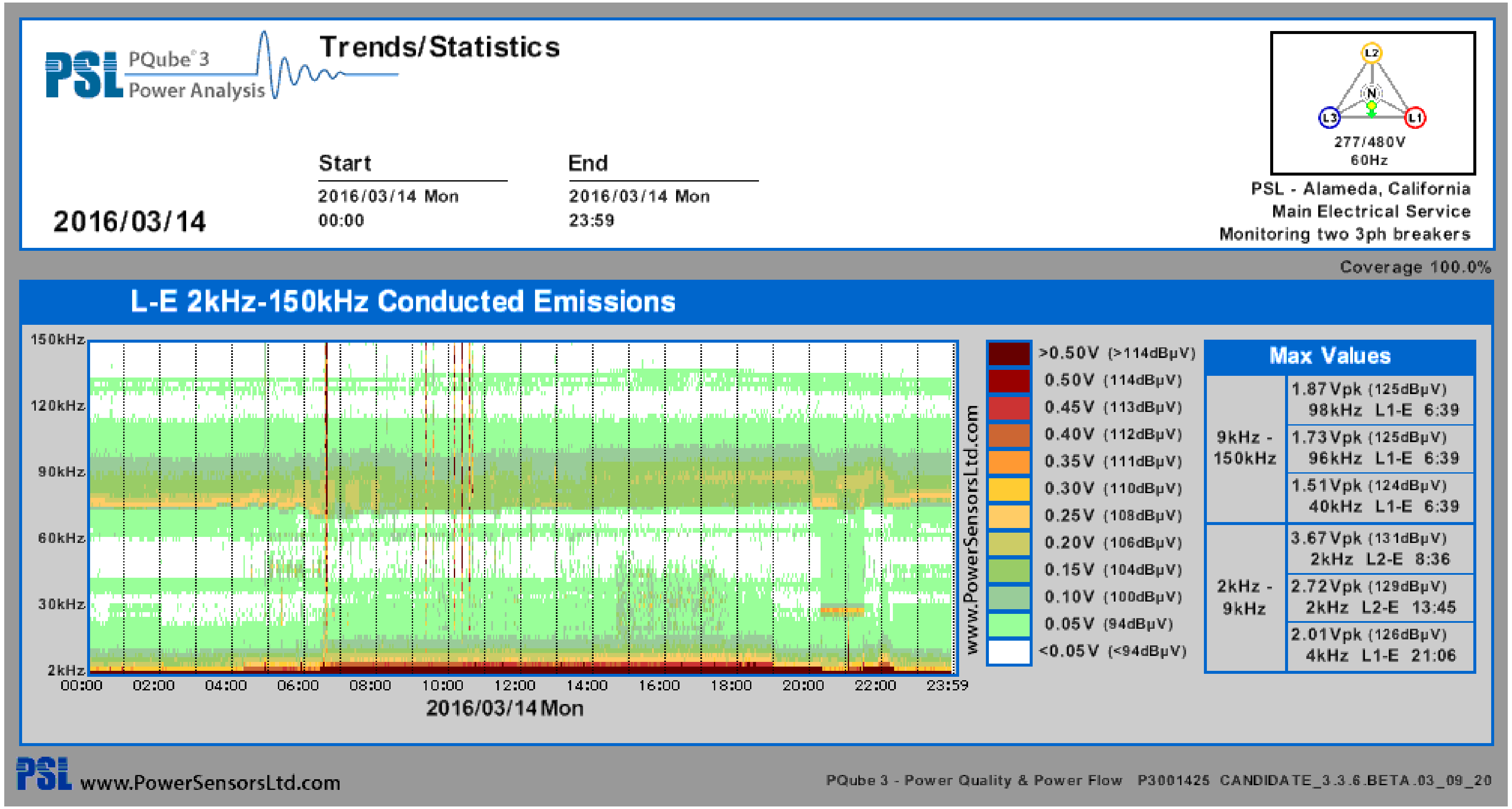
Example PQube 3 / microPMU frequency-domain recording

1-million-samples-per-second, 2kHz-150kHz voltage

No software required – Instrument emails this GIF, plus Microsoft Excel files…



ARPA-E lesson learned: MicroPMU Quick Start Kit

Fast and easy way to get started on Micro Synchrophasors

Description

PSL's Complete Quick Start package includes everything you need to get started!

1. **Four pre-configured ARPA-E micro-synchrophasor instruments**:
   a. 1-phase or 3-phase 10-volt - 1000-volt voltage input channels, 50/60 Hz
   b. 5-amp snap-on current transformers for current input channels
   c. Calibrated, certified, isolated GPS receiver for each instrument
2. **Cables** - every cable you need to connect-and-go, with both ends of each cable carefully labeled
3. **Powerful Dell Blade server**
   a. pre-loaded with research-gradesupport software, including the amazing BTrDB uPMU package
   b. Configured to support up to 15 micro-PMU instruments
   c. 64 gigabytes of RAM, y terabytes of disk storage
   d. 16-port switch

Wireless router (optional)

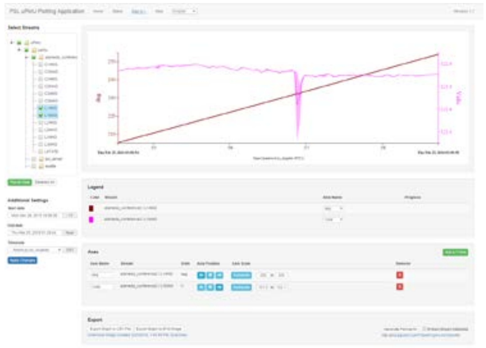
Highlights

- The Quick Start Kit comes with a private, physically-isolated, lab-bench LAN (local area network)
- No need for IT Department approval or support – does NOT connect to your institution's internet
- No need for internet connections
- Later, you can easily expand to internet-based connections to your uPMU's ... but get started quickly with local connections

Setup Instructions

Here are the complete, step-by-step instructions for getting a **4-uPMU Quick Start Kit** up and running on your lab bench:

1. Unpack your uPMU Starter Kit boxes.
2. Plug in your pre-labeled cables - just read the labels on each end of every cable, and pop them in!
   1. plug into a 100V-240V mains socket.
   2. position the GPS receivers near a window, so they can see the sky.
   3. Connect your laptop to the Quick Start Kit Wi-Fi router.
   4. Type the router's Gateway IP (usually 192.168.1.1 or 10.0.0.1) into your browser.
   5. Start plotting, reviewing, studying the measurements from your uPMU's!



Thank you.

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