DOE/OE Transmission Reliability Program

"New PMU" project

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Changing nature of work

- **Overall project objective**
  - Originally, figure out how to define “frequency” when it was changing
  - Later . . .
  - Implement a new kind of PMU
  - Understand theoretical performance limits

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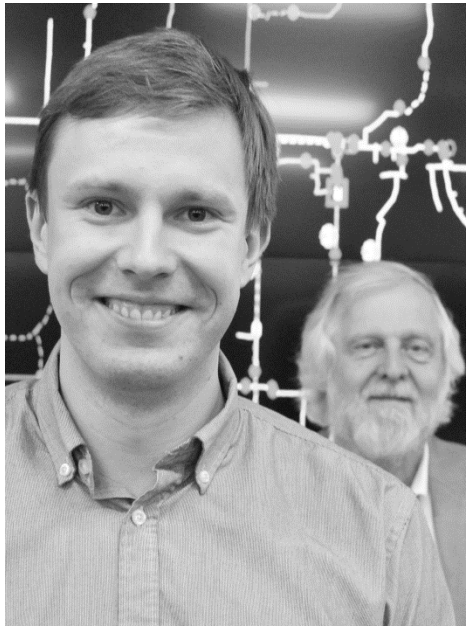
Collaborator



Artis Riepnieks

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Summary of accomplishments

- **New theory of measurement formulated**
  - **Theoretical limits of performance understood**
  - **Importance of noise established**
  - **ROCOF shown immeasurable by P-class PMU**
  - **(and, along the way, the Czarnecki/Budeanu issue resolved)**

- **“New PMU” simulated**
  - **Performs at theoretical limits**
  - **Errors in all params (inc ROCOF) at level of computer accuracy**
  - **Number of samples set by degrees of freedom of model**
  - **Controllable noise added to signals**

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Outline of rest of presentation

1. How we achieved this breakthrough
2. Some results from synthetic and real signals
3. A look at what is left to do

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Part 1: Measurement (*as reported in 2015*)

- Begins with notion, *concept*
- Concept refined to become *definition*
- Metrologists refer to this as the *measurand,* the thing that is to be measured
- Definition should be written as an *equation*

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Measurement (*as reported in 2016*)

- Equation is “model” of the real world
- Measurement is just process of finding parameters of model
- It can be regarded (and executed) as a *mathematical fitting problem*

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New Measurement Theory

Fitting produces a more complete framework for measurement

- It opens up *many* new possibilities for measurements
- Our work has philosophical/historical support

Let us review some history

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Rudolf Carnap, 1891-1970, philosopher

$$“L(a \circ b) = L(a) + L(b)”$$

Separates physical and conceptual domains

Physical world not treatable by mathematics

R. Carnap (1966), *Philosophical Foundations of Physics.* New York, NY: Basic Books.

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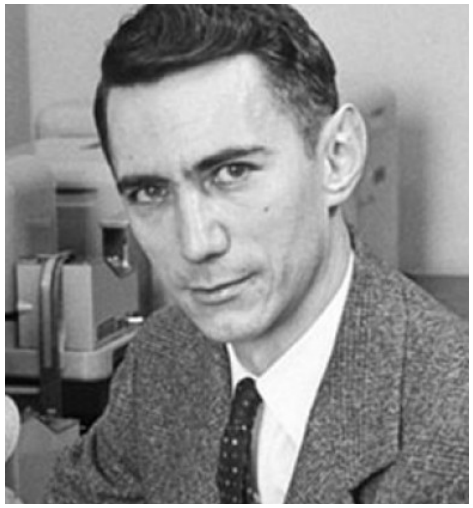
Claude Shannon, 1916-2001, Mathematician, Engineer

Wanted to find how to send messages over noisy channel



"Frequently the messages have *meaning*; that is they refer to or are correlated according to some system with certain physical or conceptual entities. These semantic aspects of communication are irrelevant to the engineering problem."

C.E Shannon (1948), A Mathematical Theory of Communication, The Bell System Technical Journal, Vol. 27, pp. 379–423, 623–656, July, October, 1948

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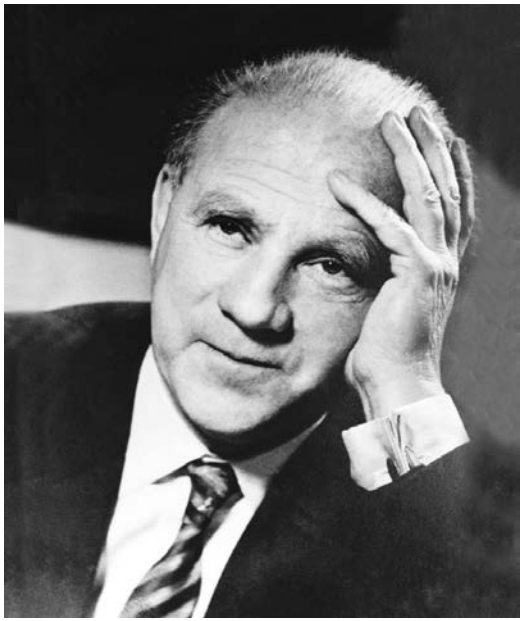
Werner Heisenberg, 1901-1976, Physicist

"Since the measuring device has been constructed by the observer, we have to remember that what we observe is not nature in itself, but nature exposed to our method of questioning"



W. Heisenberg, Physics and Philosophy: The Revolution in Modern Science, London: George Allen and Unwin, 1959.

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Carnap + Shannon + Heisenberg + Kirkham

Measurement is a process that uses information from the physical world to find the parameters of a model in the conceptual world, treatable by mathematics

The **information** – the meaning – is a semantic problem

The **model** is the specific question that we ask

The **method** can be solving a fitting problem

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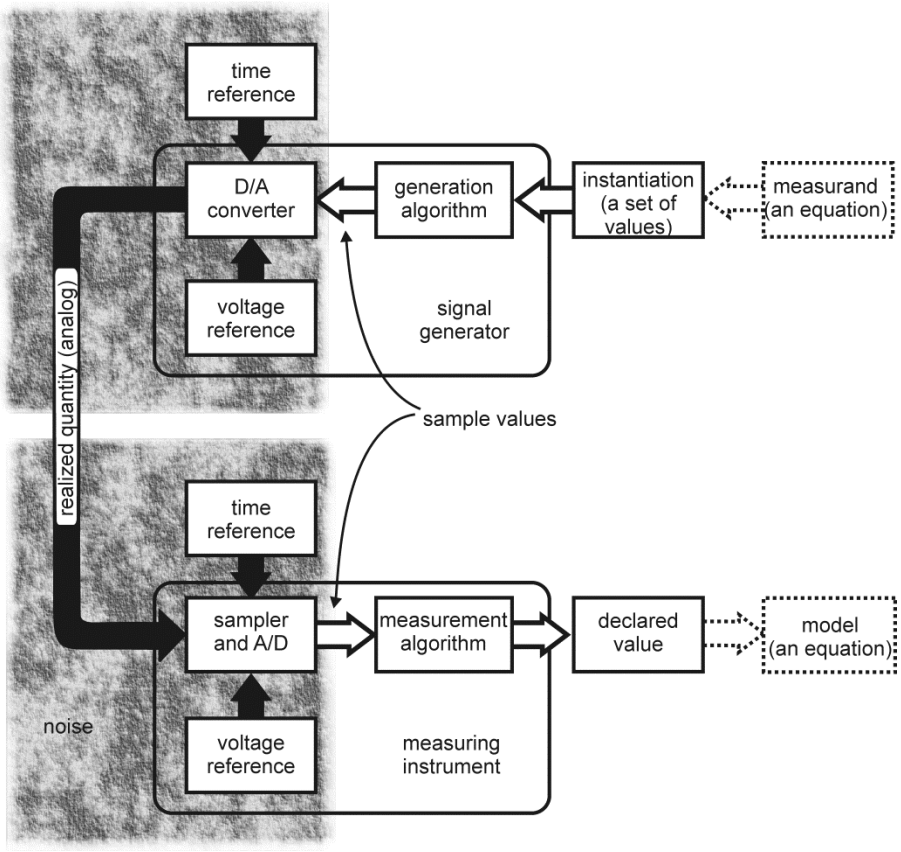
What has Kirkham's team been doing?



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Working with these equations

$$x(t) = X_{\mathrm{m}} \cos(\omega t + \varphi)$$

$$x(t) = X_{\mathrm{m}} cos\left\{\left(\omega + \frac{C_\omega}{2} t\right) t + \varphi\right\}$$

$$x(t) = X_{\mathrm{m}} \left(1 + \frac{C_x}{2} t\right) cos\left\{\left(\omega + \frac{C_\omega}{2} t\right) t + \varphi\right\}$$

$$x(t) = X_{\mathrm{m}} (1 + \varepsilon(t)) \cos(\omega t + \varphi + \Phi(t))$$

Less familiar, but better, think of these in the sample domain

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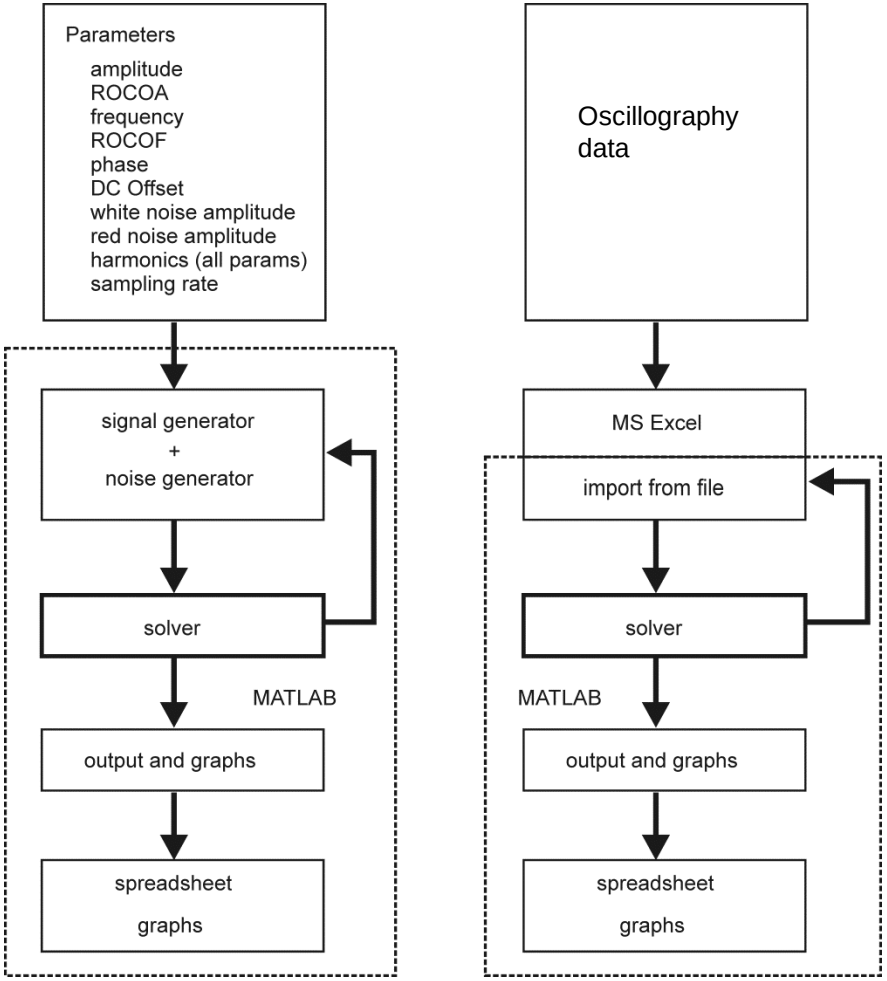
Implementation



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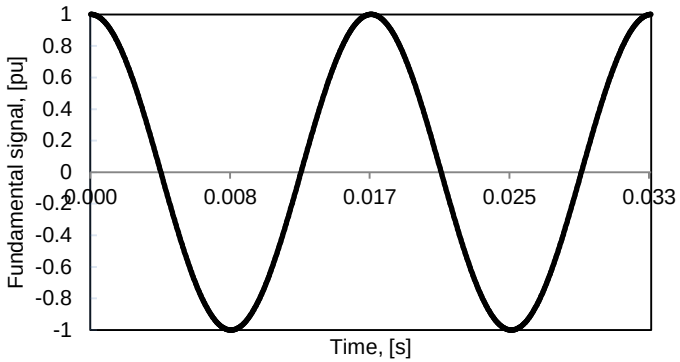
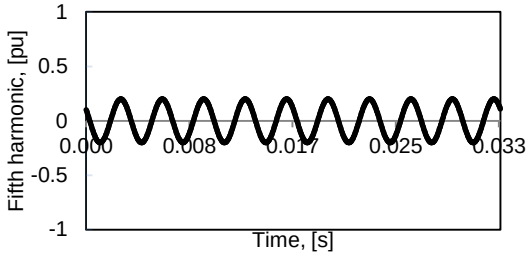
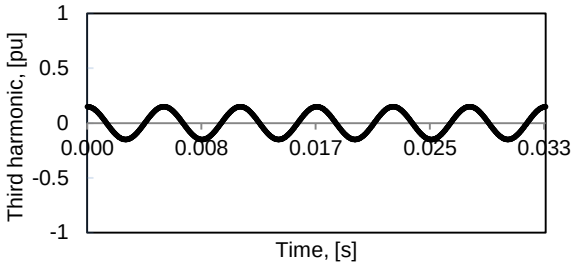
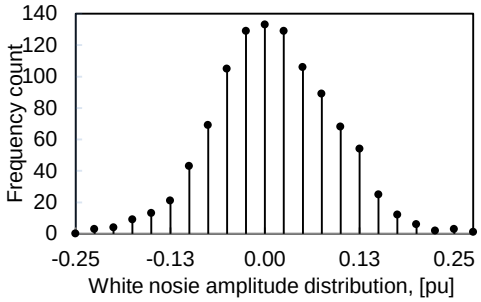
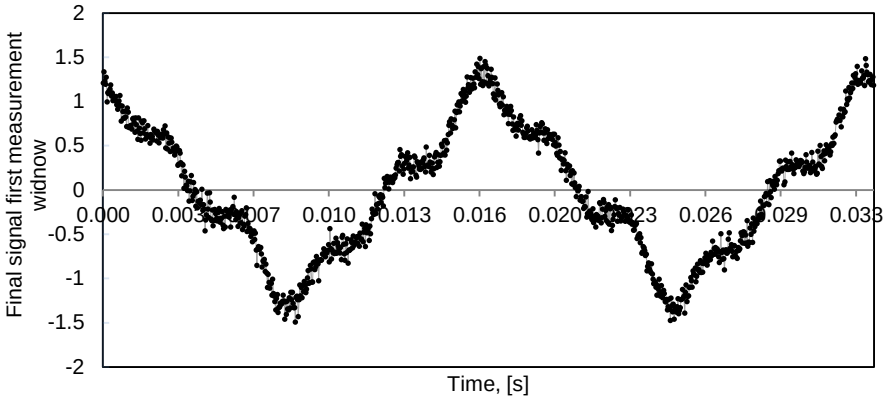
Part 2: Synthesis (white noise plus harmonics)











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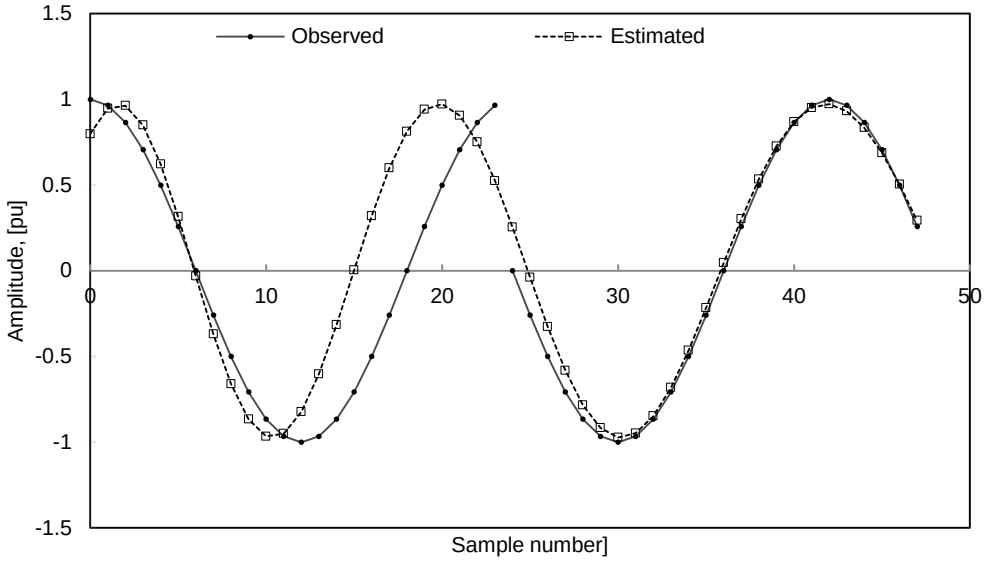
Synthesis + Analysis of phase jump



"Since the measuring device has been constructed by the observer, we have to remember that what we observe is not nature in itself, but nature exposed to our *method of questioning*"

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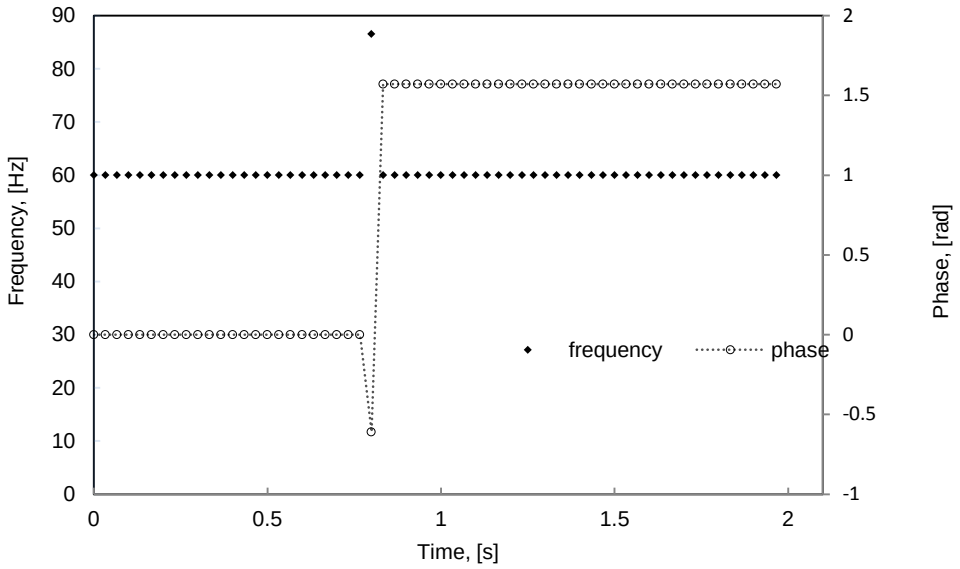
Measurement results

Phase jump



Note lack of filtering

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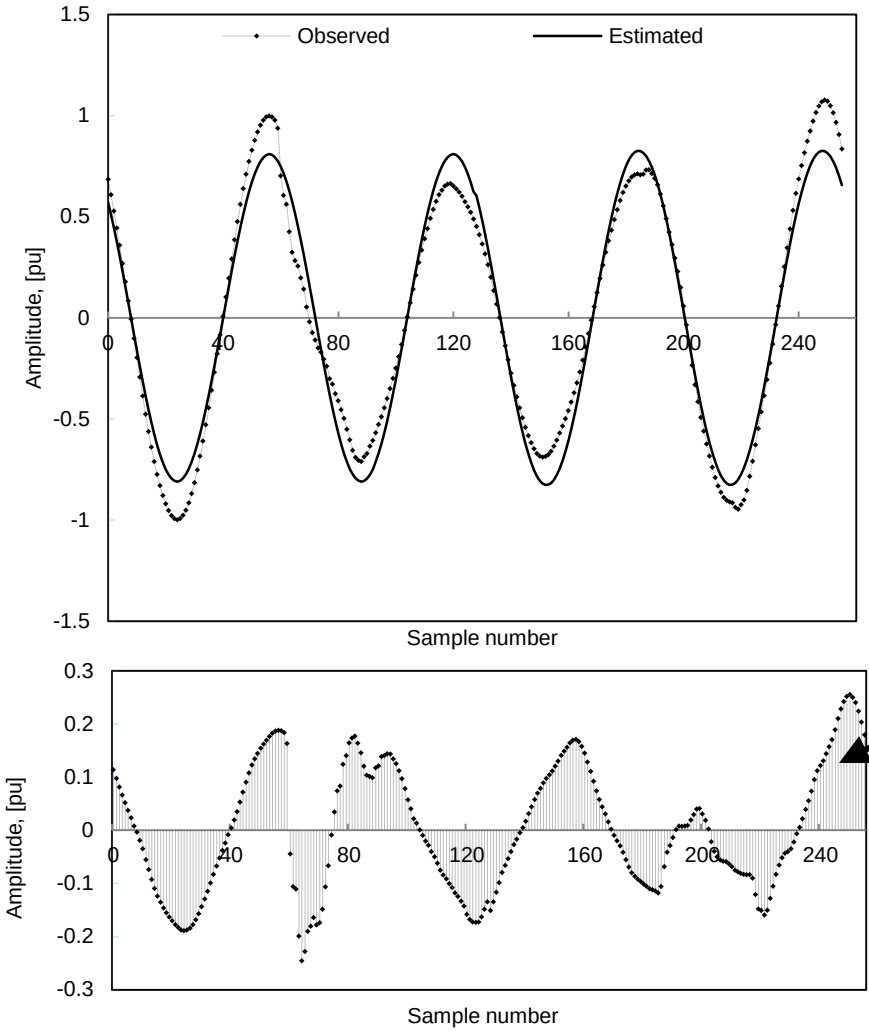
AEP (real-world) results



residuals

Goodness of Fit

Defined from the rms of the residuals

Calculable for *any* PMU

$$\mathrm{GoF} = 20 \log \frac{A}{\sqrt{\frac{1}{(N-m)} \sum_{k-1}^{N} (u_k - v_k)^2}}$$

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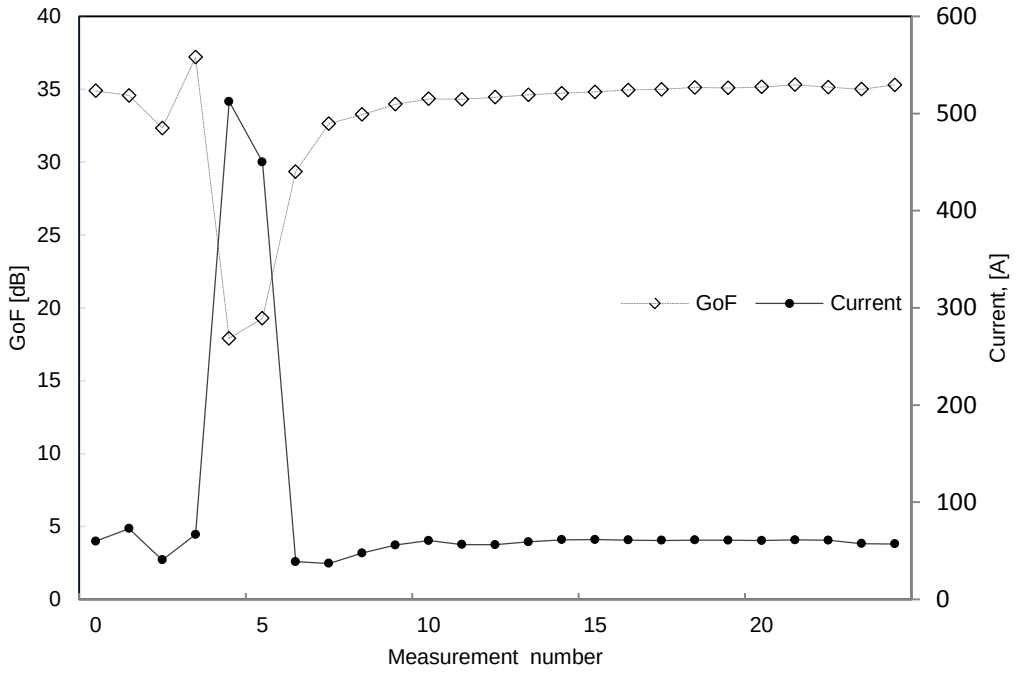
GoF for AEP data set



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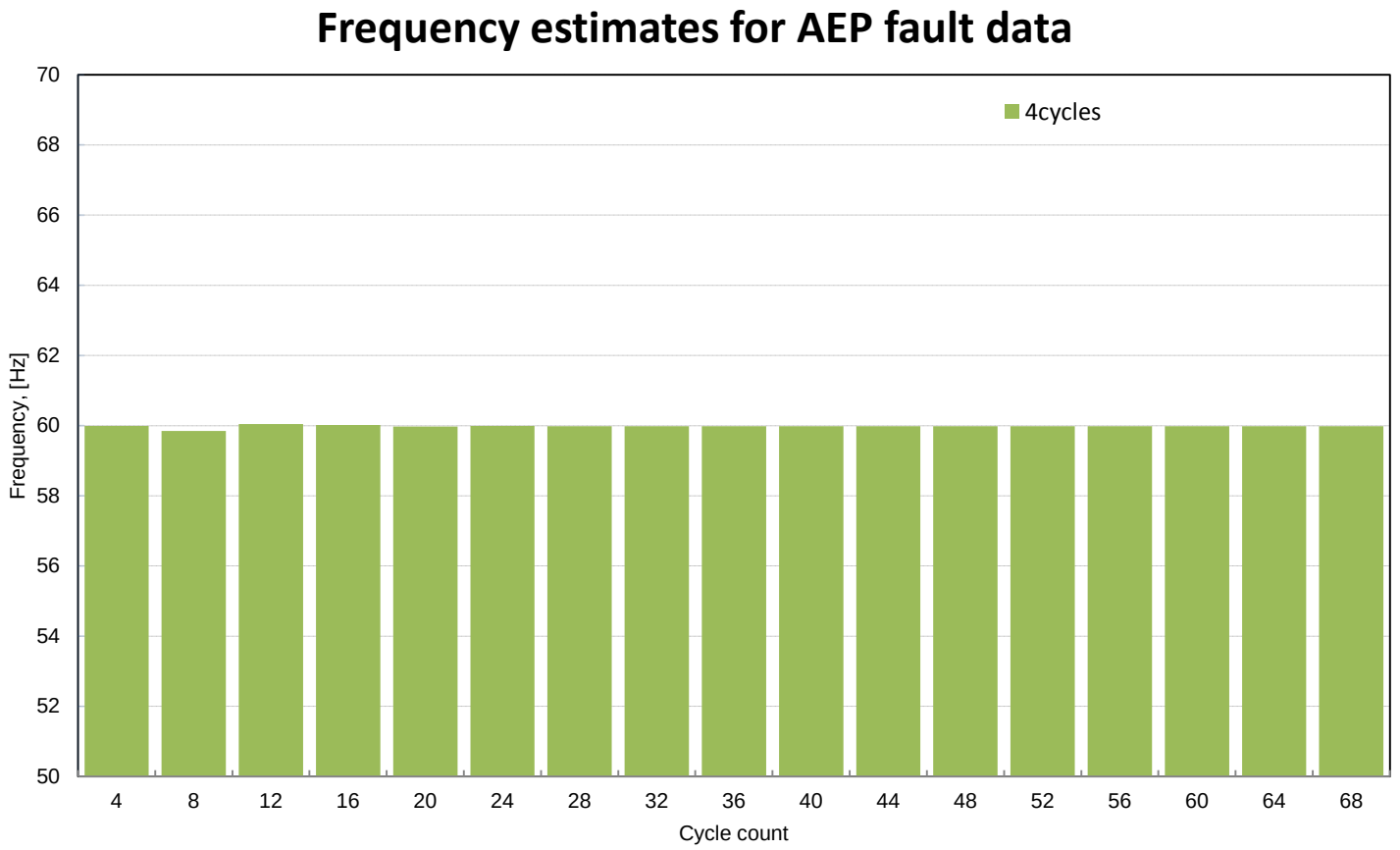
Window width study (1)



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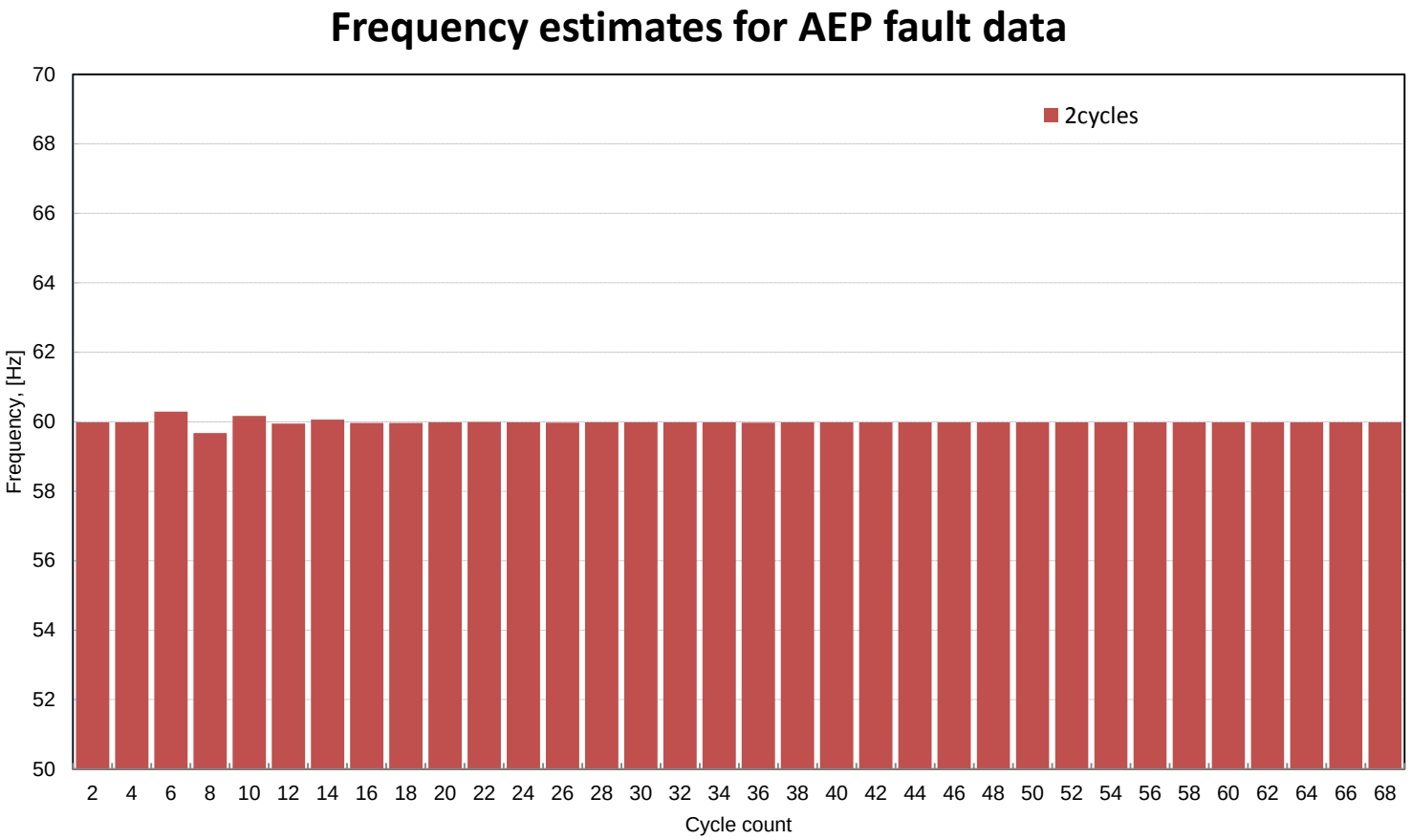
Window Width Study (2)



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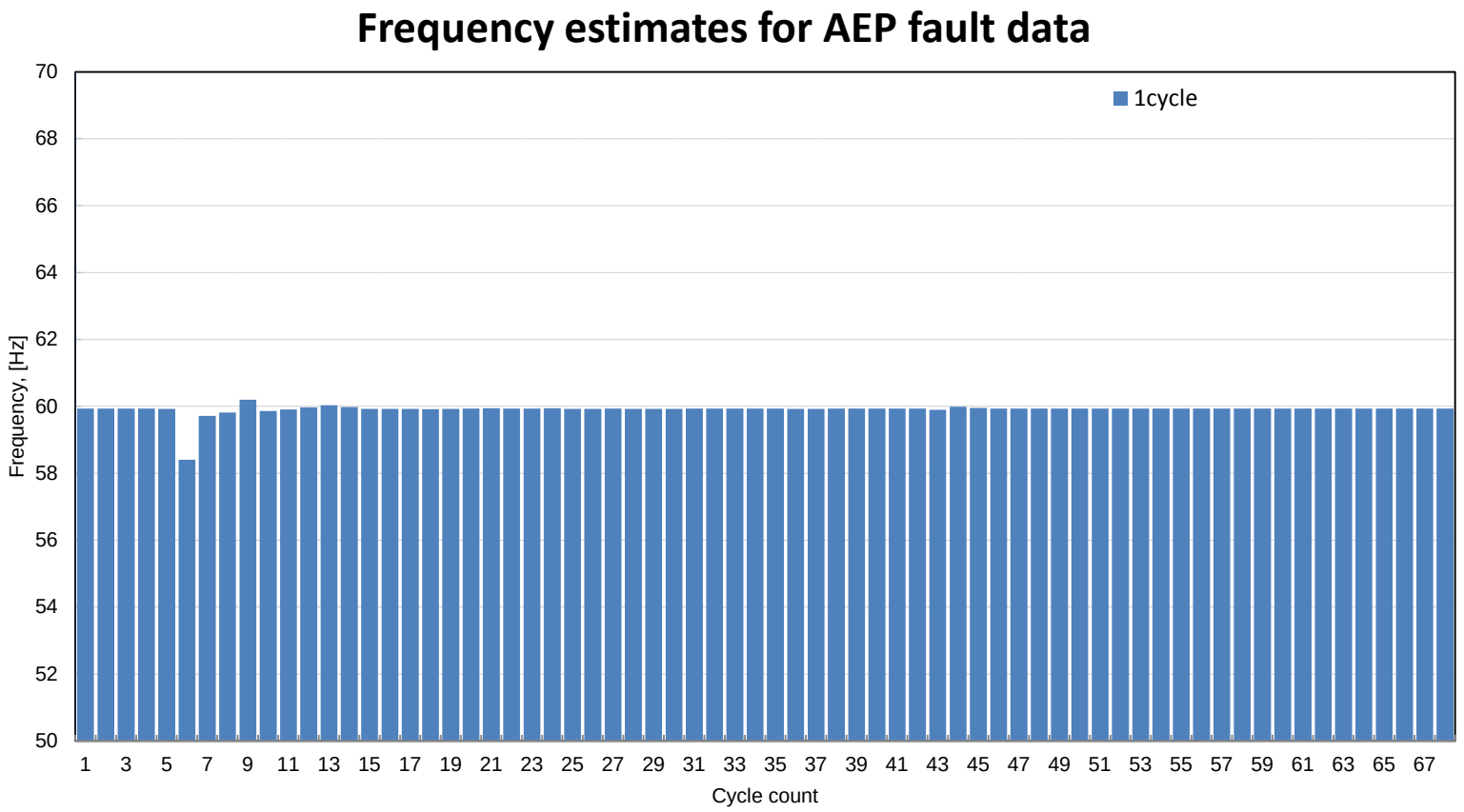
Window Width Study (3)



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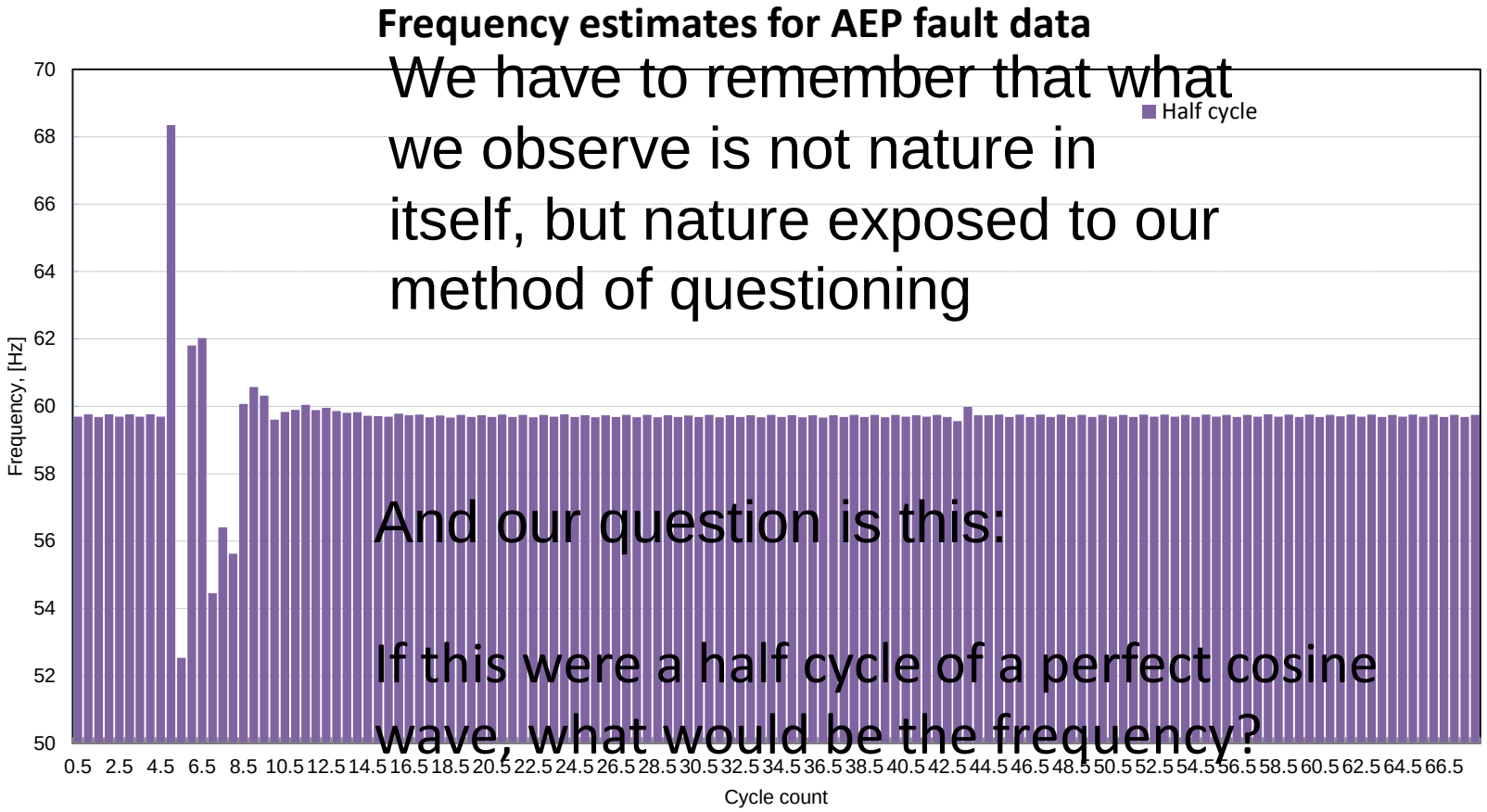
Window Width Study (4)



We have to remember that what we observe is not nature in itself, but nature exposed to our method of questioning

And our question is this:

If this were a half cycle of a perfect cosine wave, what would be the frequency?

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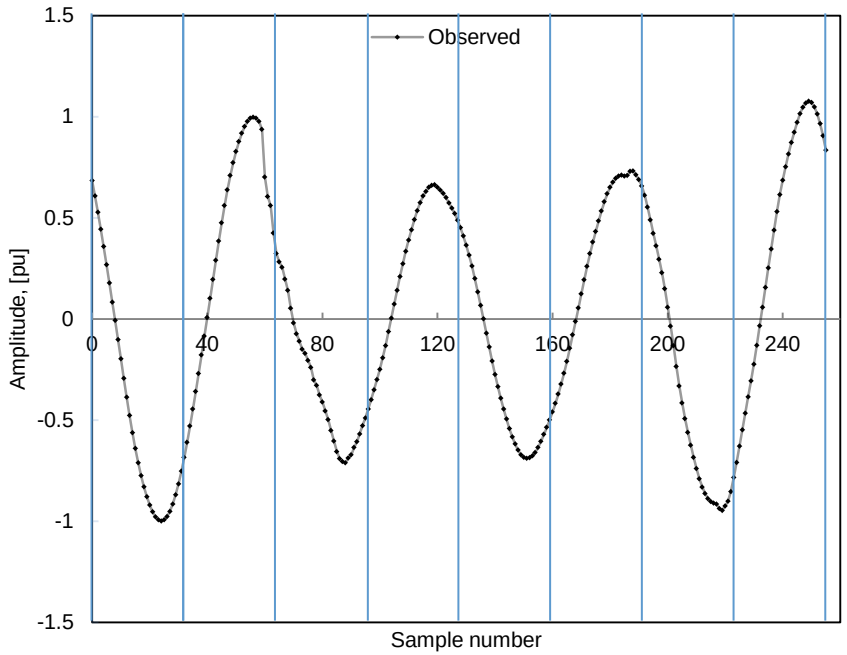
Significance of window width result



The window-width trend discloses:

- Not a *noise* problem
- A *model* problem
- The *question* is meaningless

Nature is not the same as our knowledge of nature, and just decreasing the window *does not improve our knowledge*!

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Summary of other work (1)

- Studied transitions
  - They are measurable
  - Acceptable GoF
- Defined changing frequency
  - Based on term in equation
- Studied noise
  - Without noise, results are “perfect”
  - Number of samples set by degrees of freedom
  - Beginning a study with Allan Variance
  - Best window width depends on parameter of interest
  - Beginning study of sampling rate – Riepnieks Variance

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Summary of other work (2)

- Wrote papers: these are accepted
  - NASPI (Goodness of Fit)
  - I & M Soc (The Measurand: the Problem of Frequency)
  - PES (Dealing with non-stationary signals: Definitions, Considerations and Practical Implications)
  - CPEM (Error Correction: a proposal for a Standard)

- These are in review
  - PES (Introduction to Goodness of Fit for PMU Parameter Estimation)
  - PES (Phasor Measurement as a Fitting Problem)
  - PES (Rate of Change of Frequency measurement)
  - PES (Students' Simple Method for Determining the Parameters of an AC Signal)

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Summary of other work (3)

- These papers are in process
  - Metrologia (Measurement as a fitting problem (maybe))
  - PES (The van der Pol problem)
  - I&M Soc (Allan Variance and phasor measurement)
  - I&M Soc (Riepnieks Variance)

- Artis Riepnieks has returned to Latvia and will pursue his PhD there

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Part 3: Looking Forward

- GoF being “trialed” by PSL
- Other commercial entities being approached

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Work to be done

- Improve the user interface on the PNNL system
  - Also, make a version that is not MATLAB-based
  - Investigate other solvers
- Understand power system noise
  - Adapt the PNNL system to measure amplitude and phase noise
  - Gather data from across time zones and times of day
- Apply method of Allan Variance
- Apply method of Riepnieks Variance
- Build real-time implementation

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