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CENTER FOR ULTRA-WIDE-AREA RESILIENT
ELECTRIC ENERGY TRANSMISSION NETWORKS

Inertia Estimation Techniques

NASPI-Recent trends in Inertia Monitoring, Estimation and impacts on the Grid
Oct. 2021

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Background

Accurate inertia estimation is important

Higher renewable penetration → lower inertia → lower frequency nadir

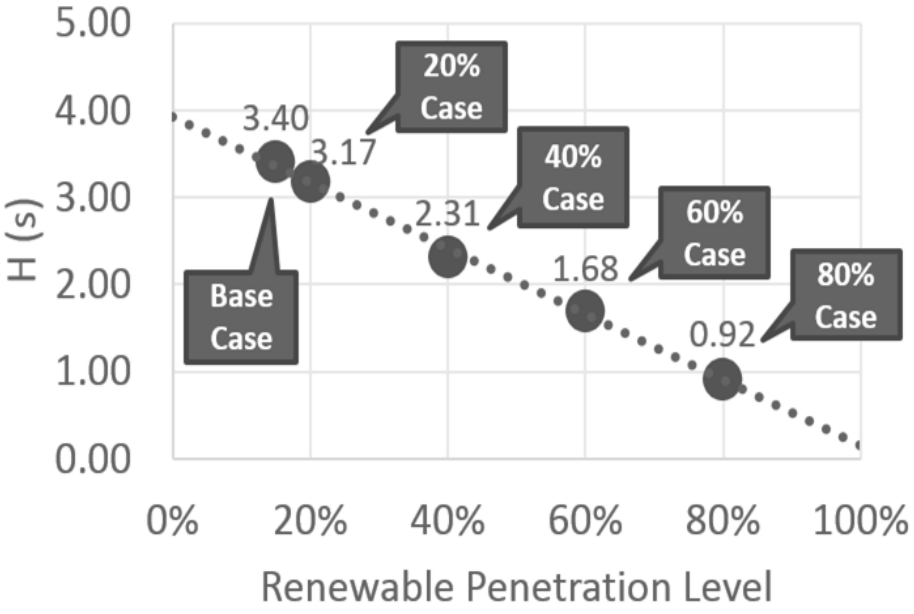
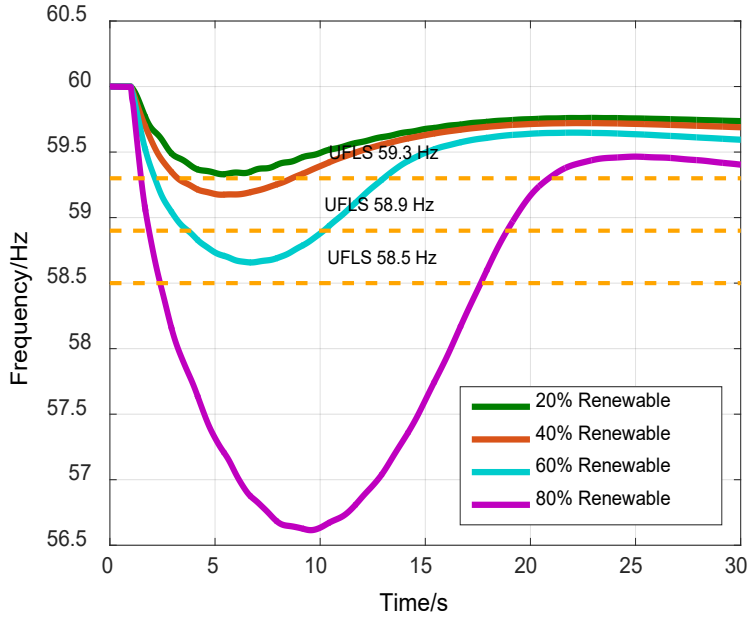
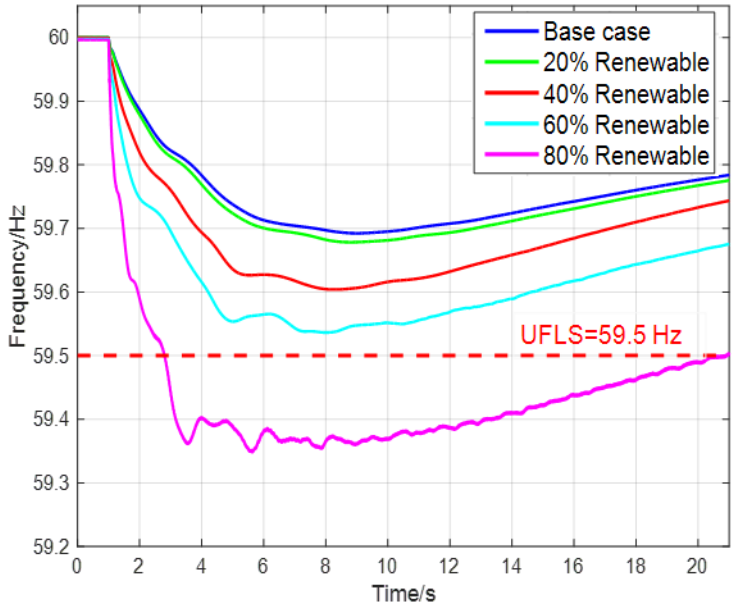


Fig. System equivalent inertia at different renewable penetration levels [SuNLAMP]



a. The ERCOT simulated frequency responses (2,750 MW generation loss)



b. The WECC simulated frequency responses (2, 625 MW generation loss)

Fig. Frequency response under different renewable penetration levels

Inertia Estimation Techniques - Overview

Inertia estimation methods overview

Methods	Input data			Performance		Comments
	EMS	PMU	Event information	Includes load, IBR, and other behind-the-meter inertia	Results impacted by FFR and load damping	
Dispatch-based	√	×	×	1	×	Easy to do, but IBR control, load, other artificial inertia may be lost
Event-driven	×	√	√	√	√	Most accurate, needs to wait for events, not real-time
Probing signal	×	√	×	√	√	Real time, invasive, added costs
Ambient signal	×	√	×	√	√	Real time, low cost, data processing has challenges

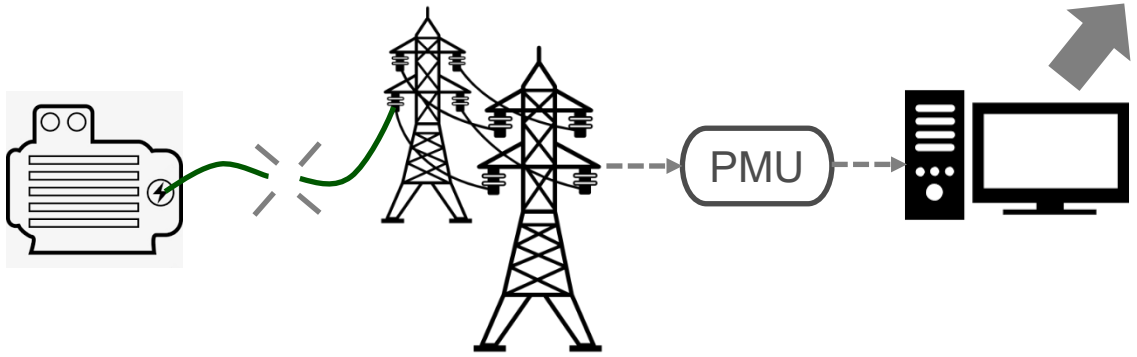
1 The dispatch-based inertia can include the behind-the-meter inertia by including correction factors, but these behind-meter inertias are not measured directly.

Ref:http://cigre.ru/research_commitets/ik_rus/c2_rus/materials/library/WBN022%20-%20C2.C4.41%20-%20Dec20.pdf

Inertia Estimation Techniques - Overview

Event-driven inertia estimation

1. PMU frequency monitoring
2. Data preprocess
3. Event detection
4. Event RoCoF extraction
5. Inertia calculation



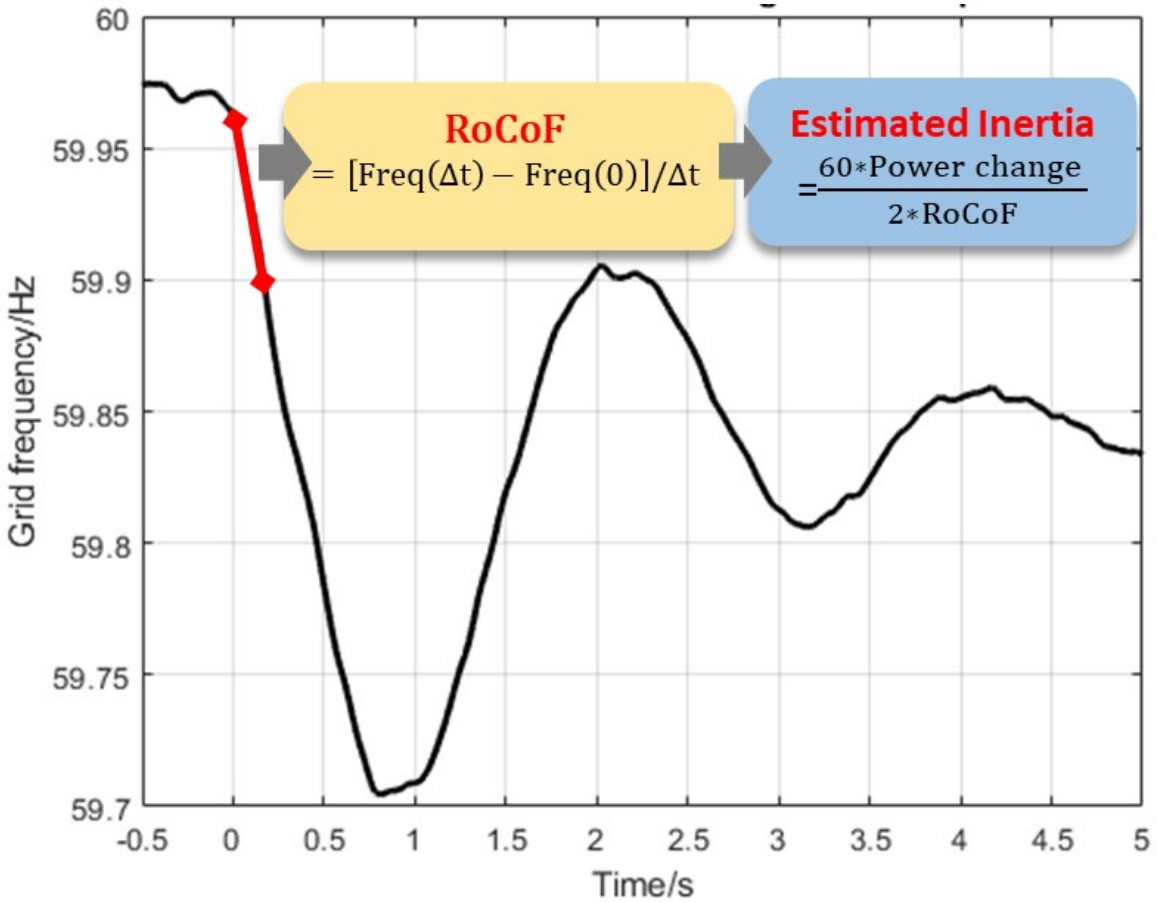


Fig. Process of inertia estimation based on an event

Inertia Estimation Techniques - Overview

Probing-signal-based inertia estimation

1. Inject a power signal
   - Pulse or other signal
2. Measure the response - frequency signal
3. Estimate inertia same way as the event case

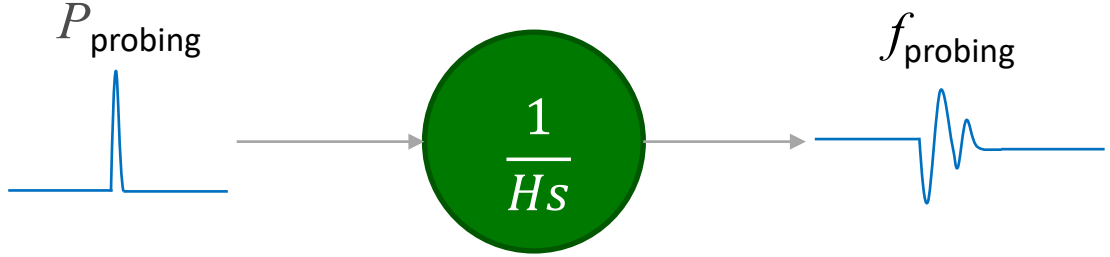


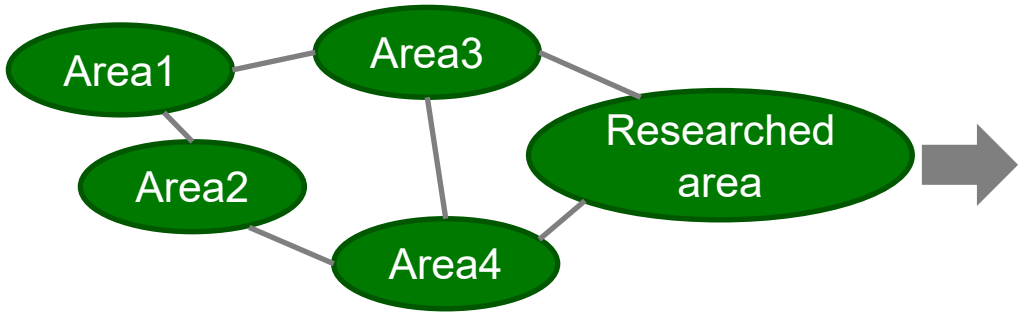
Fig. Example of probing signal method from Reactive Technologies

Source: https://www.reactive-technologies.com/grids/gridmetrix/

Inertia Estimation Techniques - Overview

Ambient-signal-based inertia estimation

1. Separate the system into areas (if needed)
2. Measure the power from boundary PMU
3. Measure the frequency inside of the research area
4. Extract noise like fast varying signals from power and frequency data
5. Estimate inertia by system identification



Example of multi-area power system

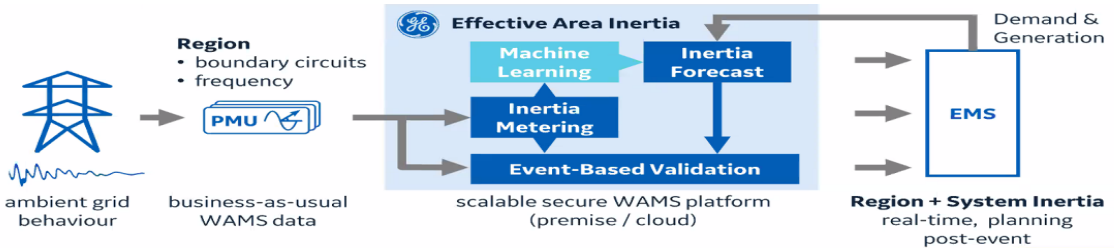
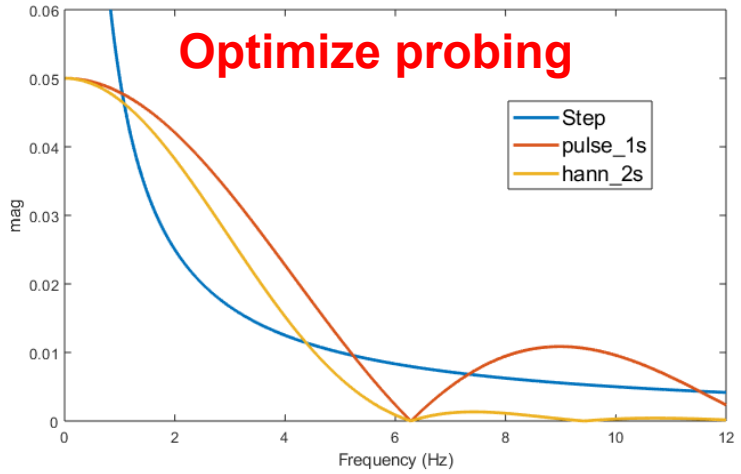


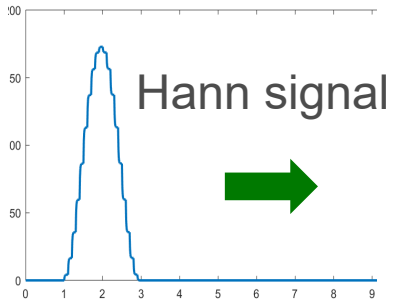
Fig. Example of GE Inertia Metering

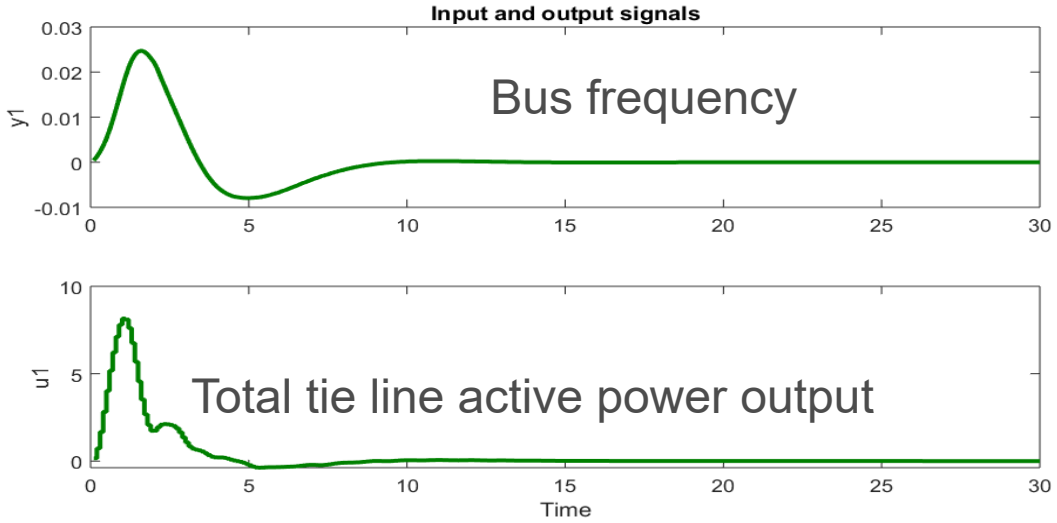
Source:http://www.epcc-workshop.net/images/Presentations/Session3/3-1%20GE%20D_Wilson.pdf

UTK Inertia Estimation Using Probing Signal

Case study using renewable as probing signal



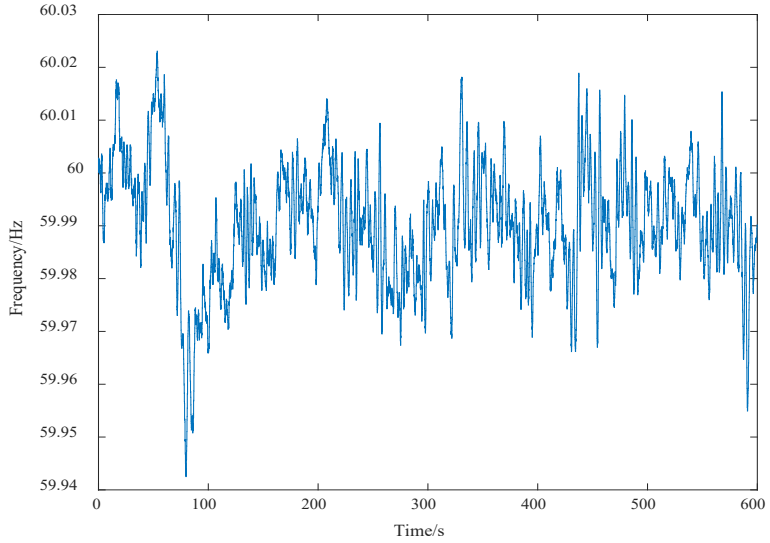




	Theoretical Inertia (MW·s)	Estimated Inertia (MW·s)	Error (%)
Area 1	7200	7328	**1.78**
Area 2	6125	6161	**0.58**
Area 3	3390	3553	**4.81**
All	16715	17012	**1.75**

UTK Inertia Estimation Using Ambient Frequency Signal

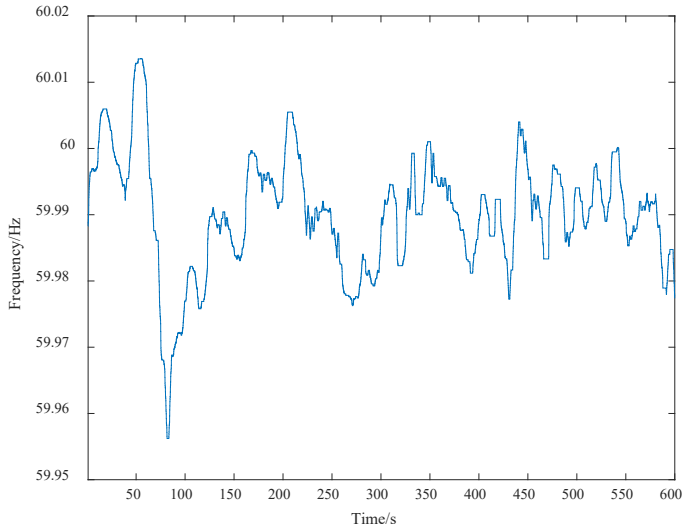
Extract ambient frequency signal



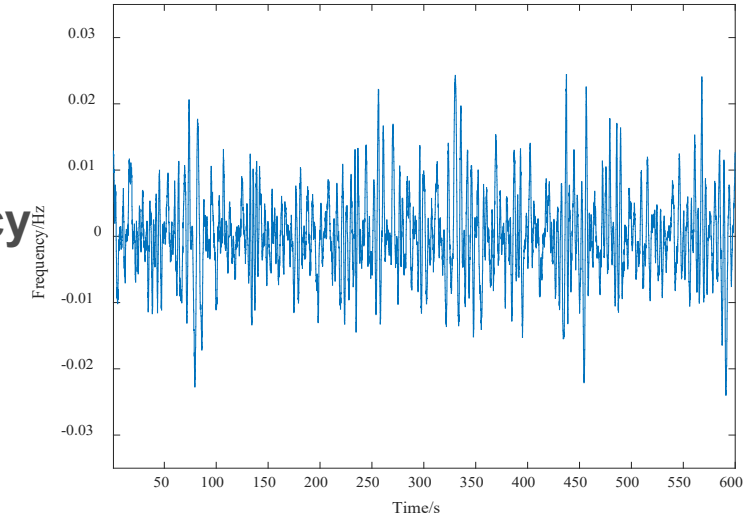
Raw data

Slow trend
(Moving window filter)

Ambient frequency signal
(Detrend data)



Slow



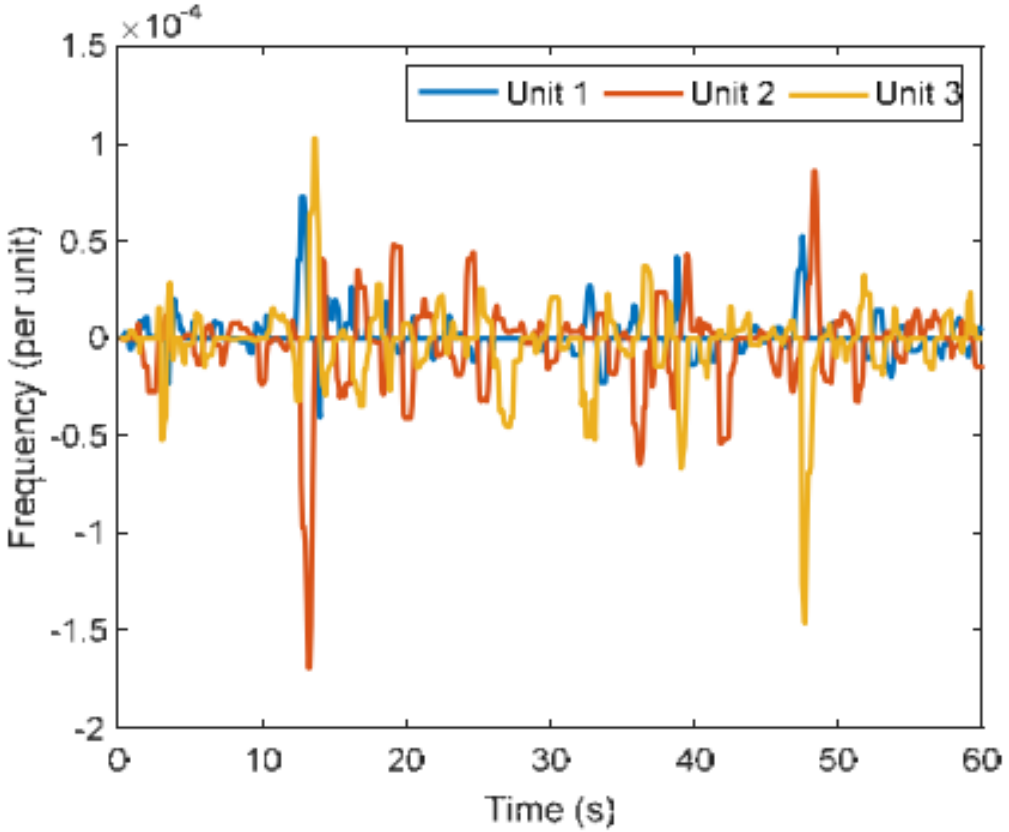
Fast

Fig. Ambient frequency signal extraction

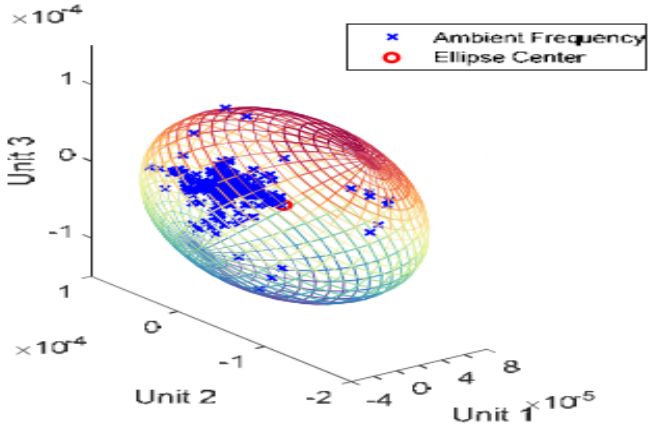
UTK Inertia Estimation Using Ambient Frequency Signal

Machine learning based method

- Minimum Volume Enclosing Ellipsoid (MVEE) from ambient-frequency features



MVEE



https://ieeexplore.ieee.org/document/9281662

Features	Dimension
Ellipsoid volume	1
Ellipsoid eccentricity	1
Ellipsoid centers	20
Projection of the longest axis	20
Daily average temperature	1
Load profile	1
Total dimension	44

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UTK Inertia Estimation Using Ambient Frequency Signal

Weather correlation

- Correlation Between Inertia and Weather Condition
- Average temperature of six cities in WECC: Los Angeles, Phoenix, Salt Lake City, Denver, Las Vegas and Seattle.

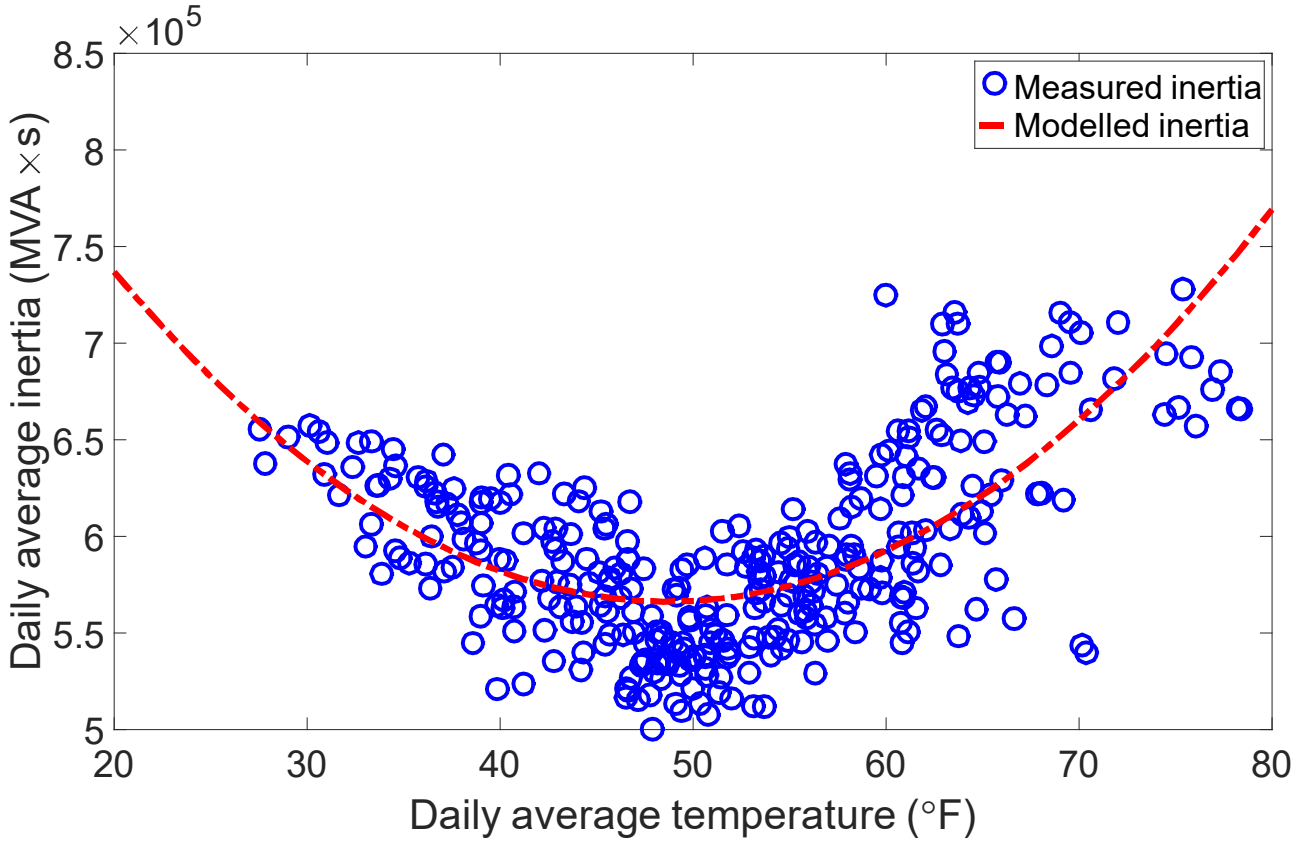

Fig. Correlation between daily average inertia and daily average temperature

UTK Inertia Estimation Using Ambient Frequency Signal

Machine learning based method

- AI tool to estimate WECC inertia by ambient frequency signal.

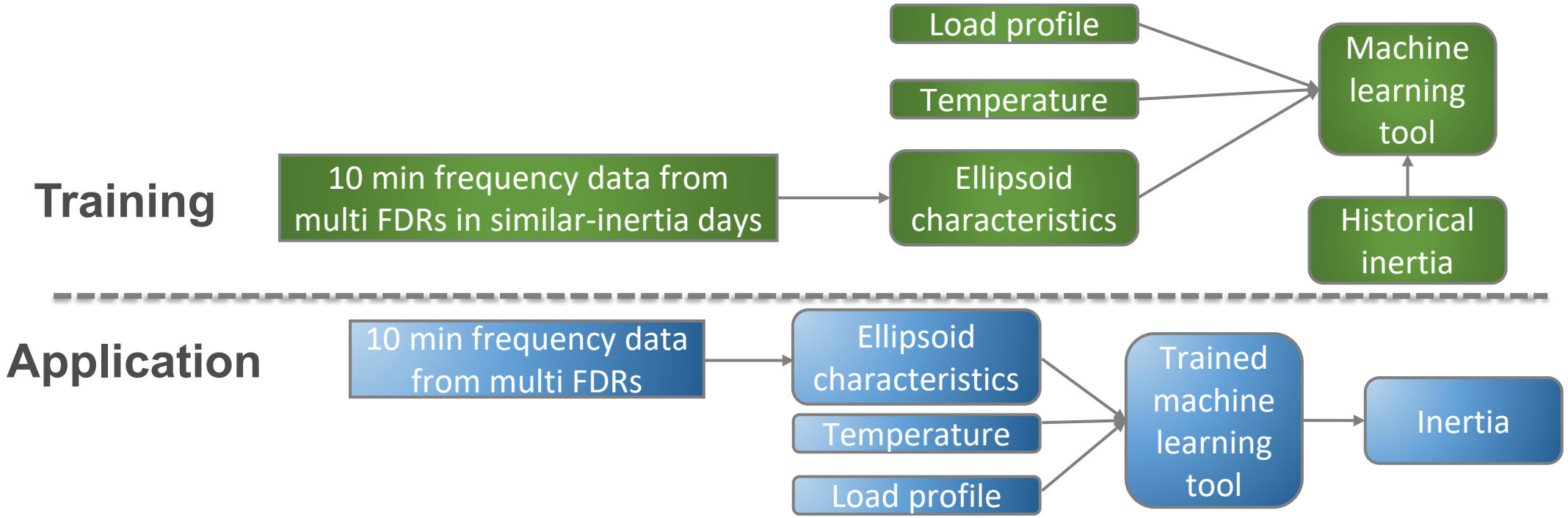

Fig. Process of the machine learning training and application

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UTK Inertia Estimation Using Ambient Frequency Signal

Machine learning based method – WECC test results

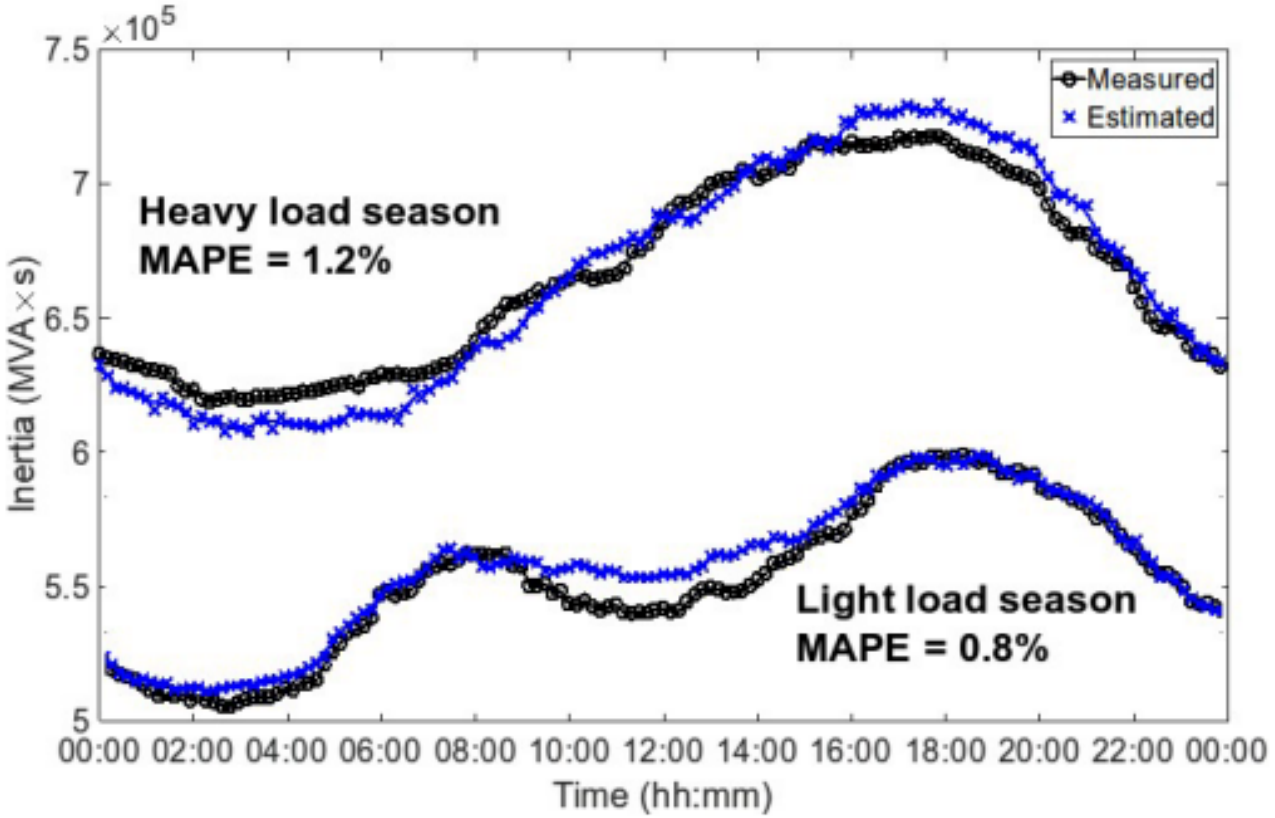


Fig. Performance of the machine-learning based inertia estimation using ambient frequency signal

UTK Inertia Estimation Using Ambient Frequency Signal

Data + Physics based method

- The process of calculating ambient frequency based ‘relative inertia’

$$2H\frac{df_{noise}}{dt} = P_{noise}$$

Integral to avoid RoCoF calculation

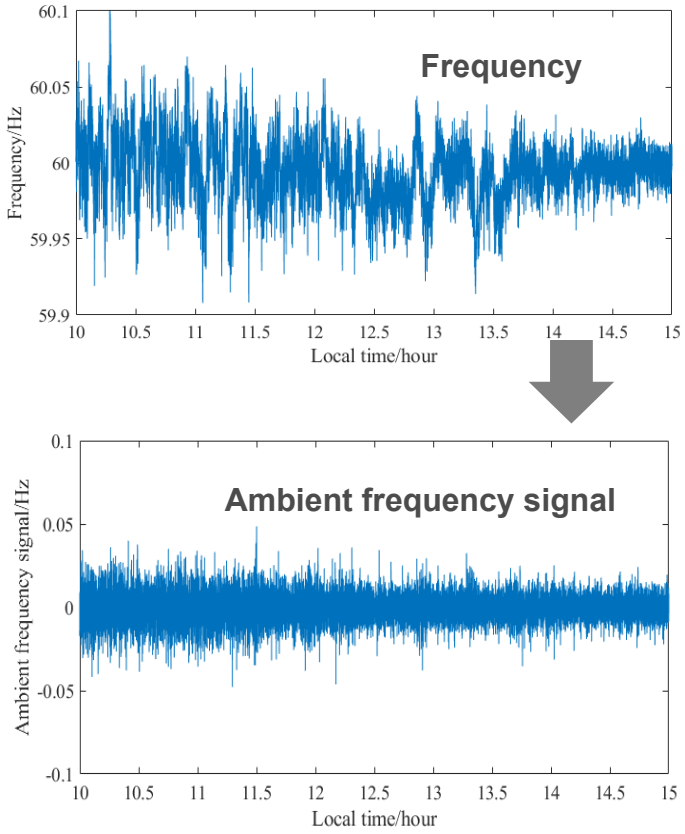
$$2Hf_{noise} = \int P_{noise}$$

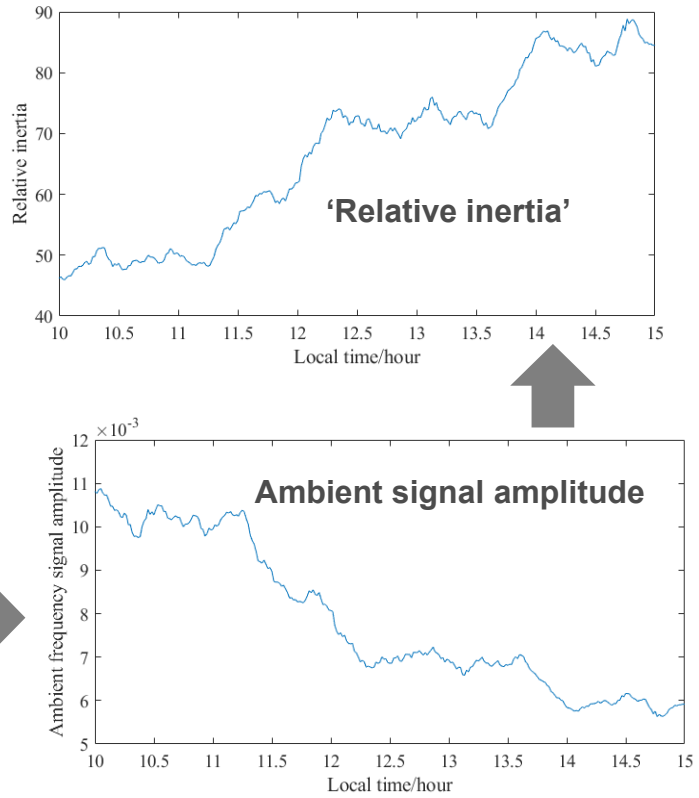
A() means amplitude within a time window.

$$2H * A(f_{noise}) = A(\int P_{noise})$$

$$H = \frac{1}{2A(f_{noise})} A(\int P_{noise})$$

‘Relative inertia’





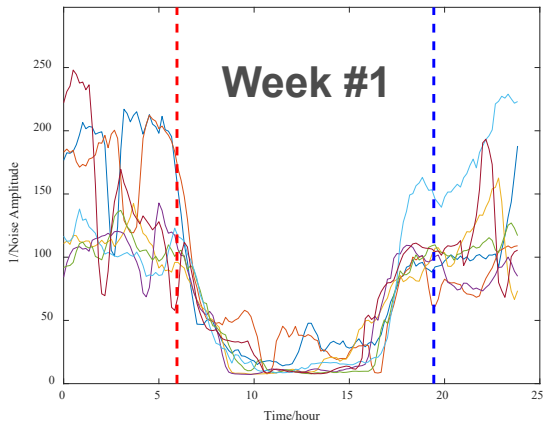
UTK Inertia Estimation Using Ambient Frequency Signal

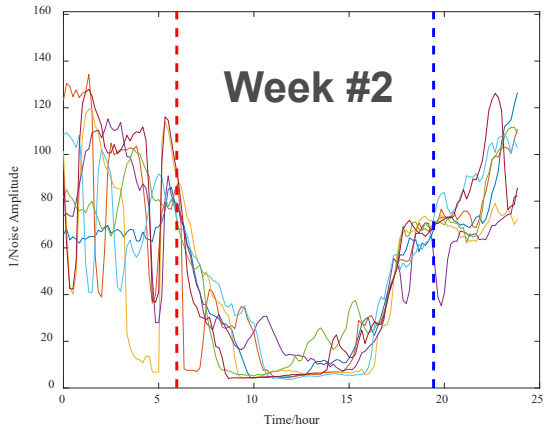
Data + Physics based method

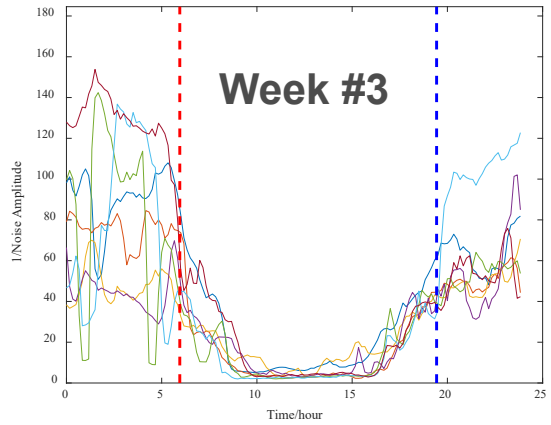
- 'relative inertia' results from island #1

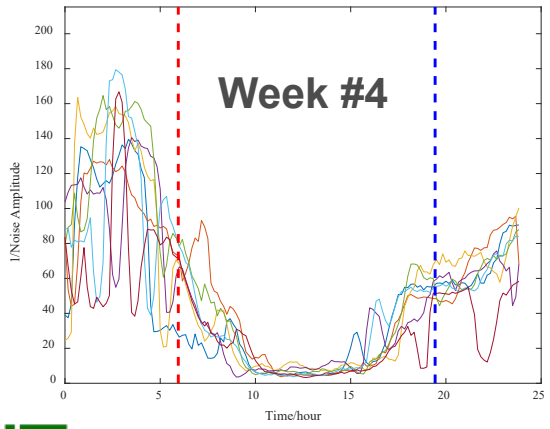
------ Local sunrise time

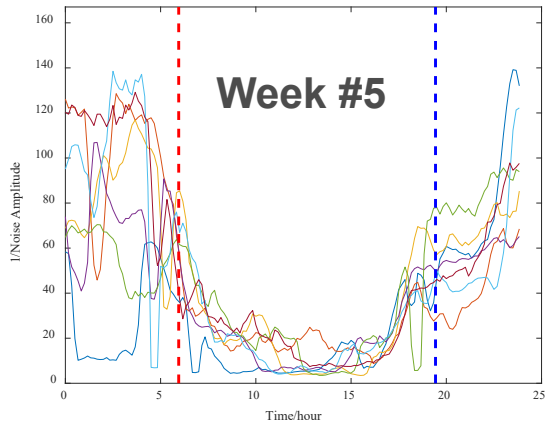
------ Local sunset time

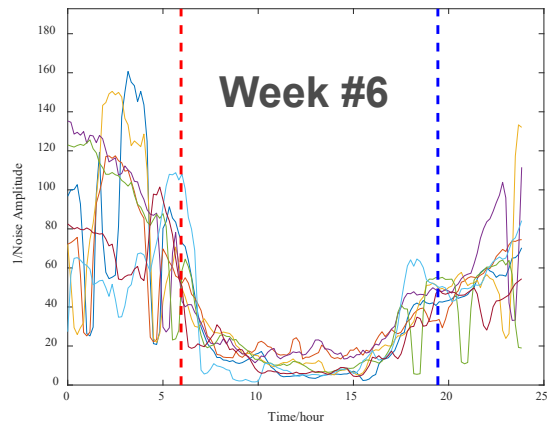












UTK Inertia Estimation Using Ambient Frequency Signal

Data + Physics based method

'relative inertia' results from island #2

------ Local sunrise time

------ Local sunset time