Extracting Dynamical Models From PMU Data

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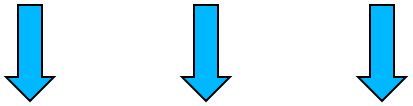
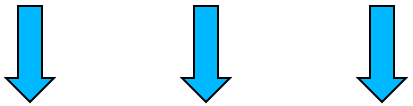
Future—Dynamic Stability Will Be More Difficult to Predict

- **Faster market clearing + more time-intermittent renewable generation**



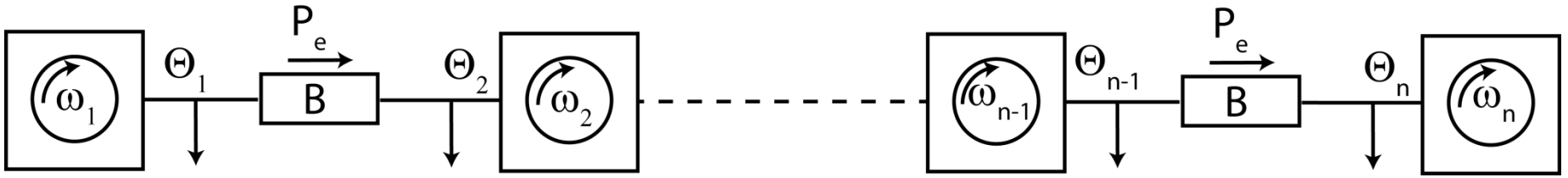
- **Generation and power flow patterns will change faster and be less predictable**

- **Less time for detailed, direct numerical simulation of transient and small signal stability**
- **Dynamical model accuracy becomes more suspect**
- **Load dynamics are becoming more important to stability**



- **We seek a data-driven method that can provide model-independent predictions of grid dynamics**

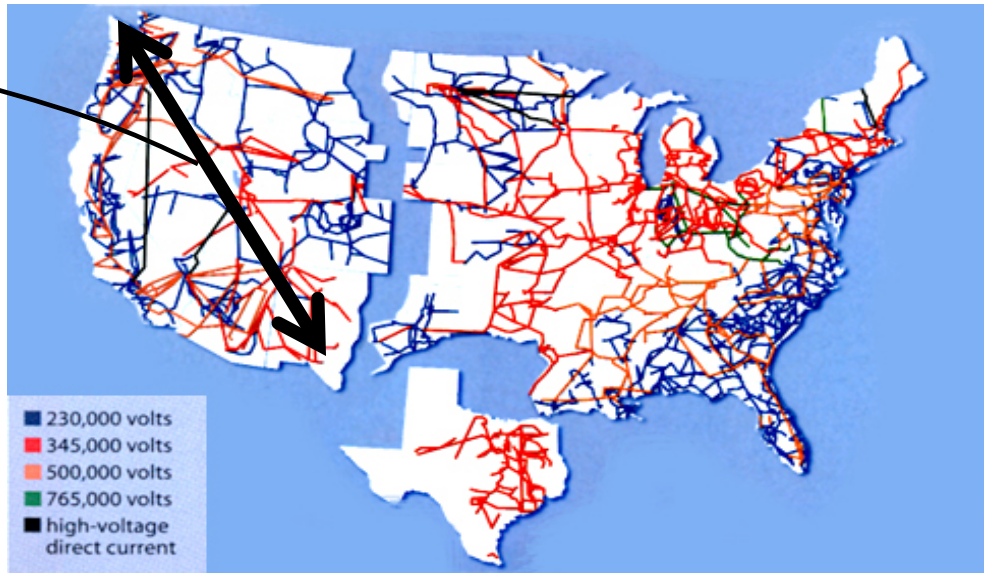
Intuitive Grid Dynamics—N-Bus System—Extended Waves



$$c = \text{Phase speed} \approx \sqrt{\frac{V^2 b}{\omega_0 h}} \approx 1{,}000\ km/s$$

$$L = \text{Interconnection size} \approx 2000\ km$$

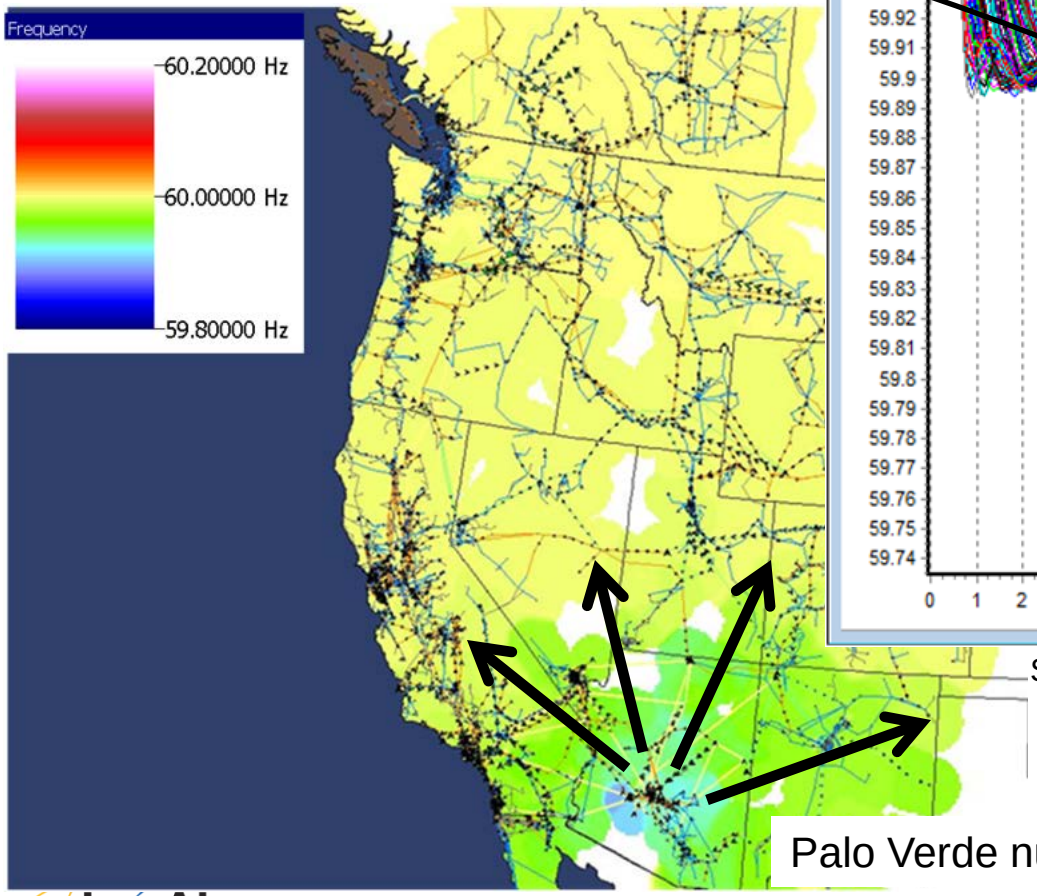
$$\text{time scales} \approx L/c = 2\ \text{sec} \rightarrow 0.5\ \text{Hz}$$

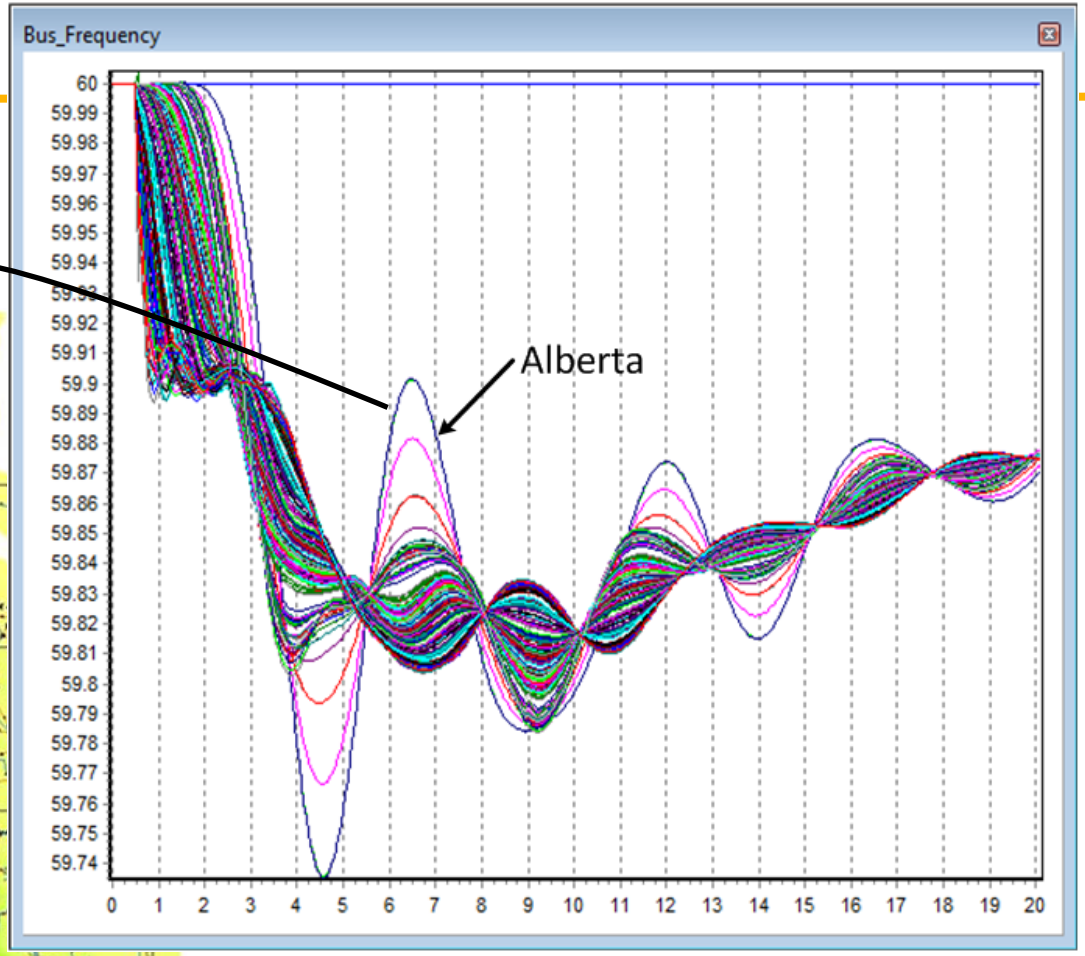


Just like any wave system, it can support traveling and standing waves

EM Traveling Waves

Wave nature apparent in the reflection of the grid edge



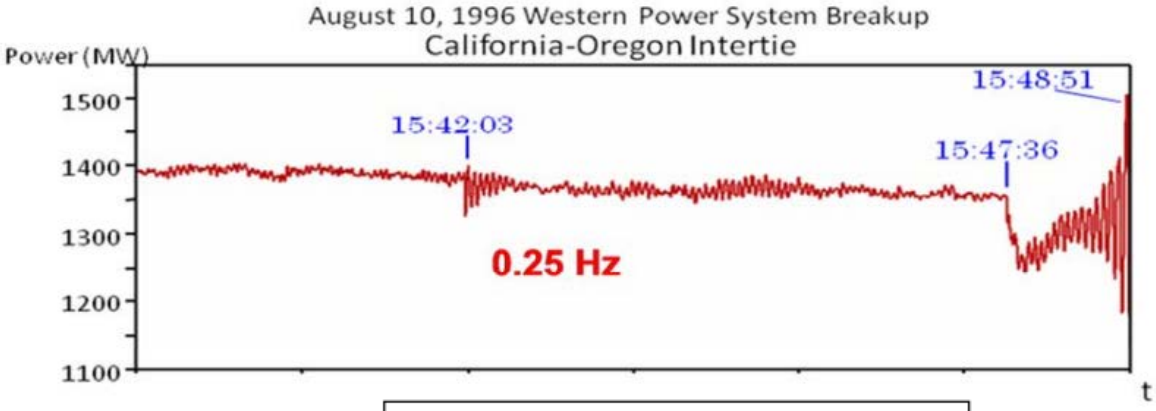


Source: Tom Overbye, Univ. of Illinois Urbana-Champaign

Palo Verde nuclear station trip

$$c \approx \sqrt{\frac{V^2 b}{\omega_0 h}}$$

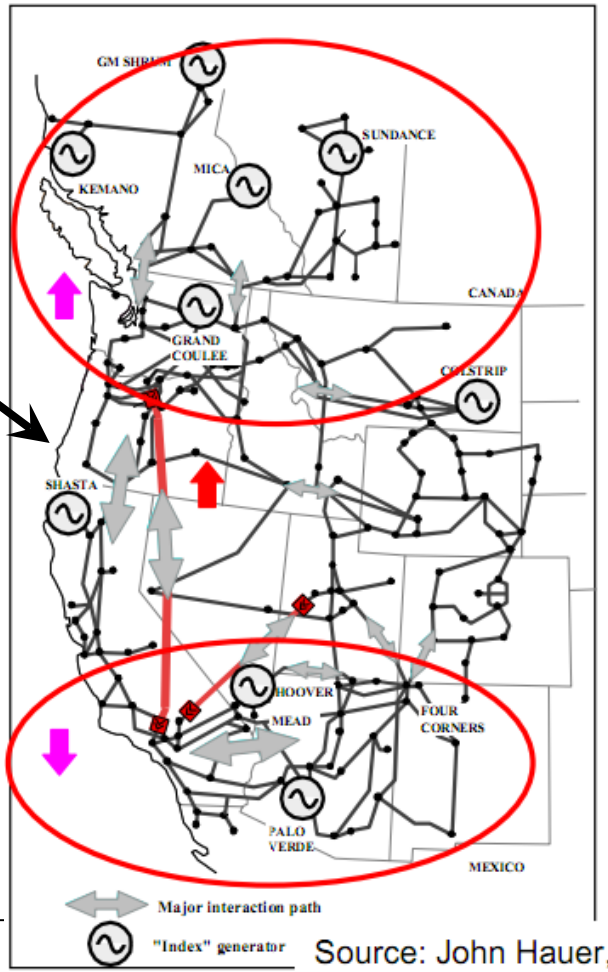
EM Standing Waves



- Inter-area modes
- Weak transmission/heavy loading results in low dynamic susceptance
- Lowering the phase speed

$$c = \text{Phase speed} \approx \sqrt{\frac{V^2 b}{\omega_0 h}}$$

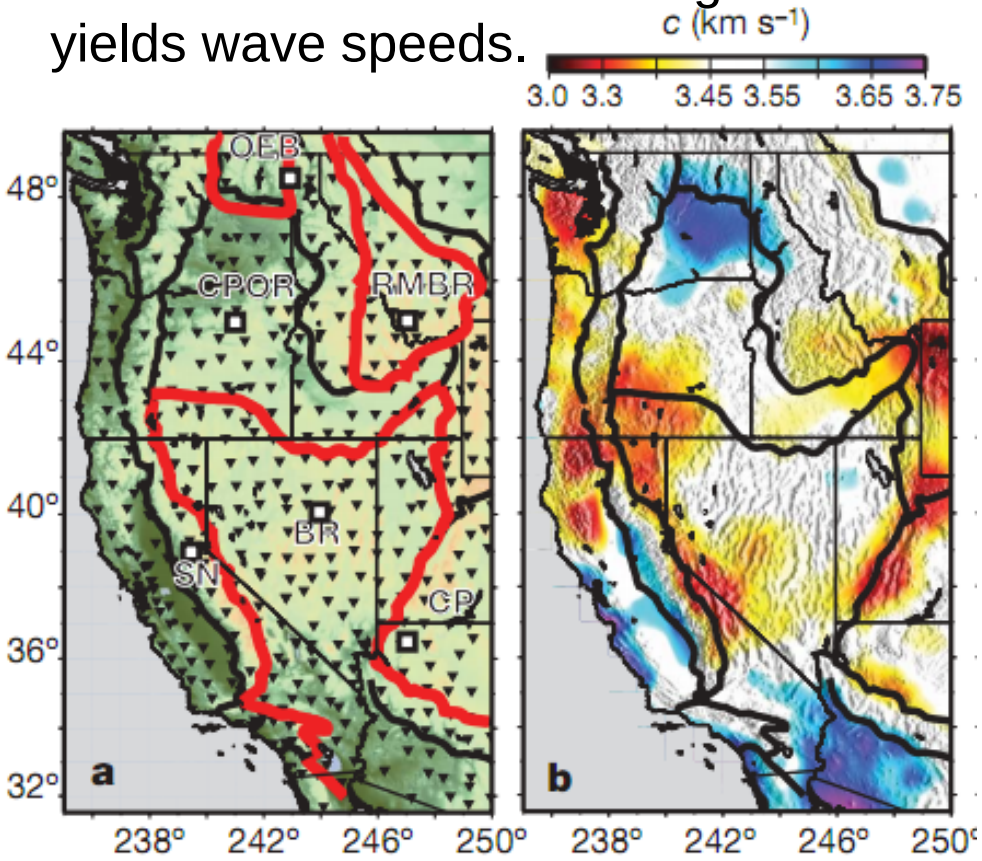
- Regions of low phase speed define the mode shape



Source: John Hauer, PNNL

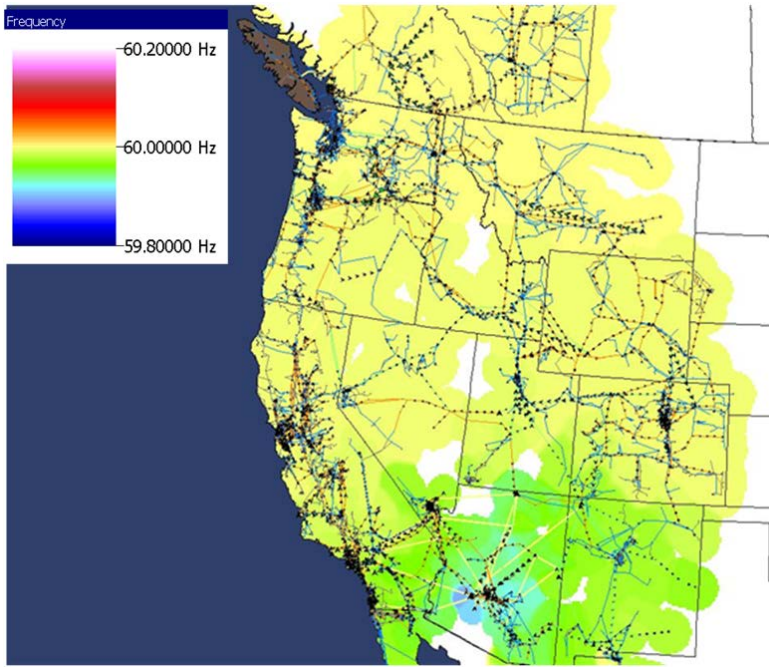
Noise Tomography/Imaging of Wave Propagation

Cross correlations of seismic noise over a network of monitoring stations yields wave speeds.



M. P. Moschetti, M. H. Ritzwoller, F. Lin and Y. Yang
Nature Vol 464 (2010) doi:10.1038/nature08951.

Can we do the same thing here?
And can we do even more?

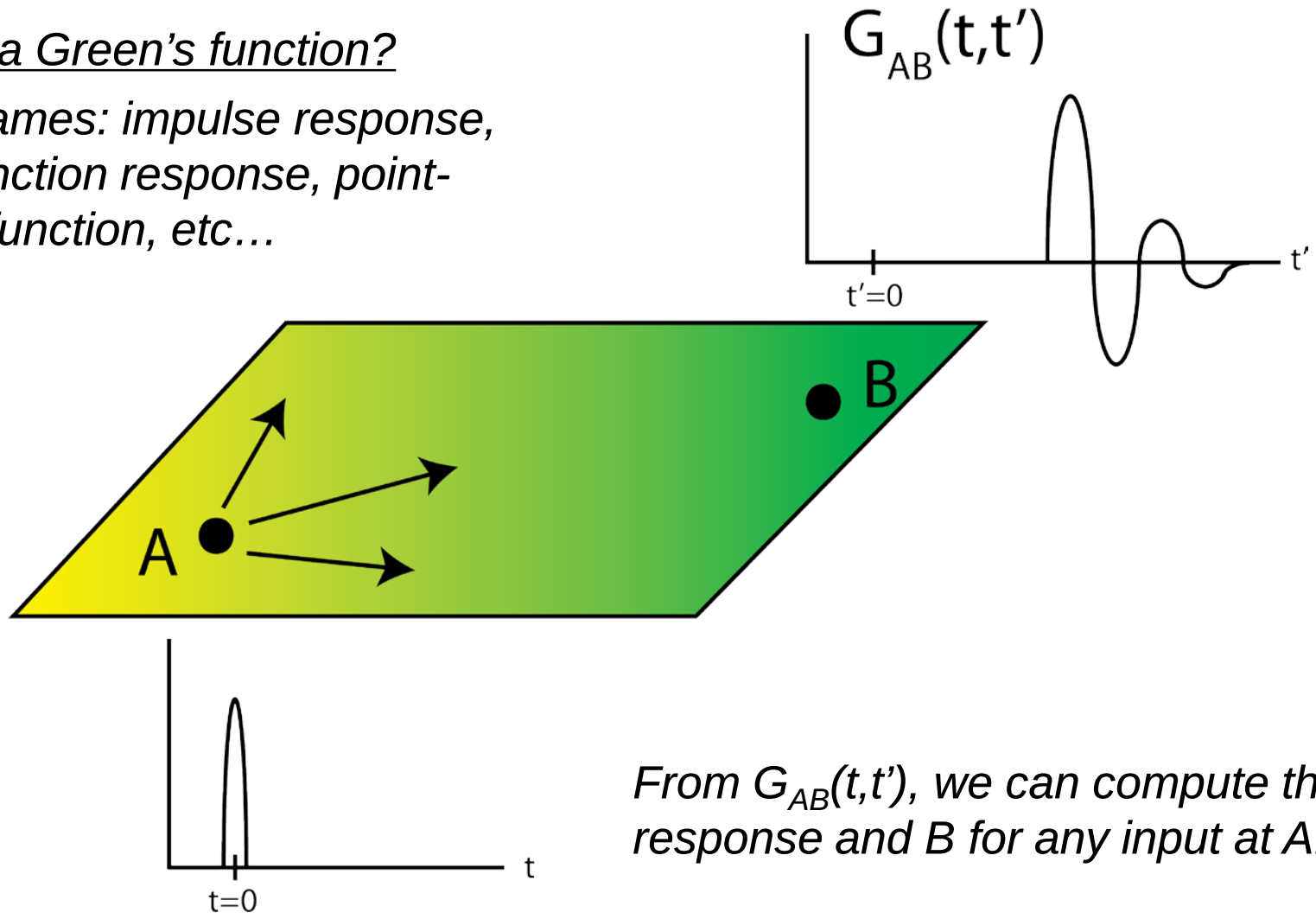


Source: Tom Overbye, Univ. of Illinois Urbana-Champaign

Green's Functions—The Fundamental Wave Response

What is a Green's function?

Other names: impulse response, delta-function response, point-spread function, etc…

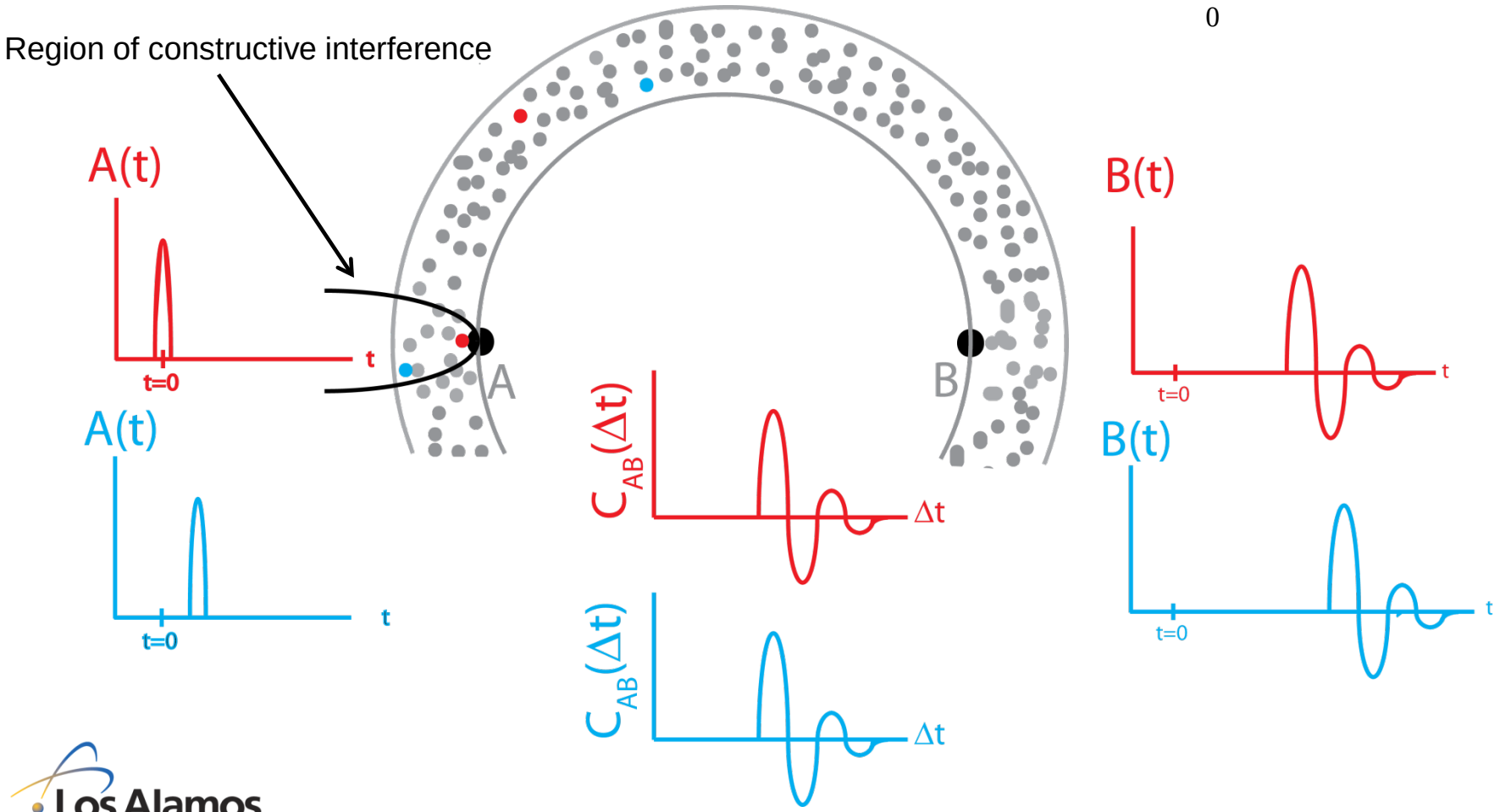


From $G_{AB}(t,t')$, we can compute the response and B for any input at A.

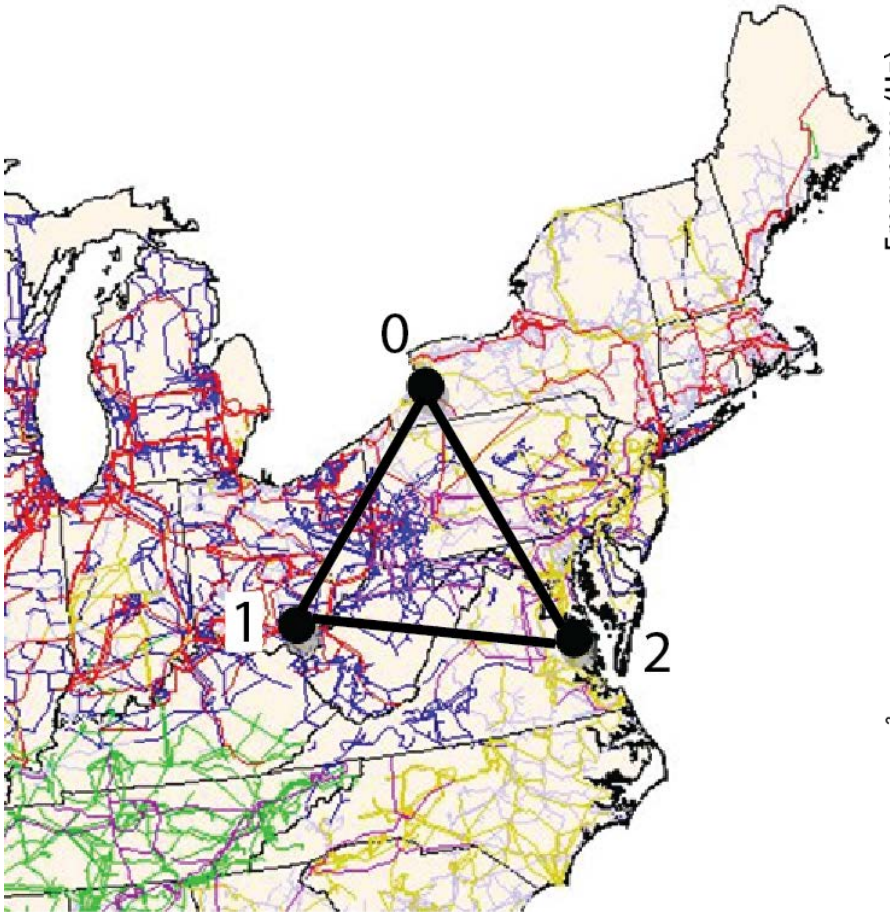
Extraction of EM-Wave Green's Functions From Noise

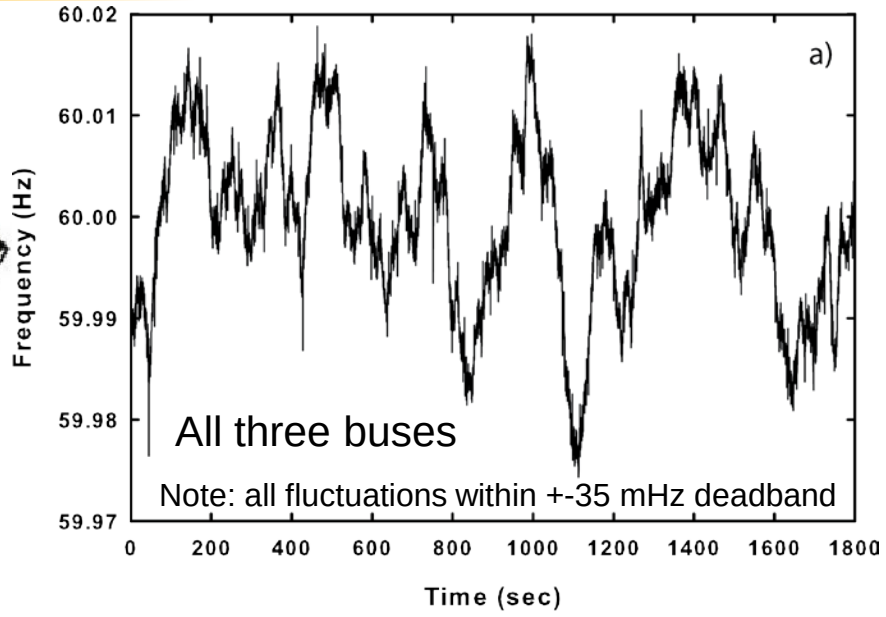
How is a Green's function related to noise?

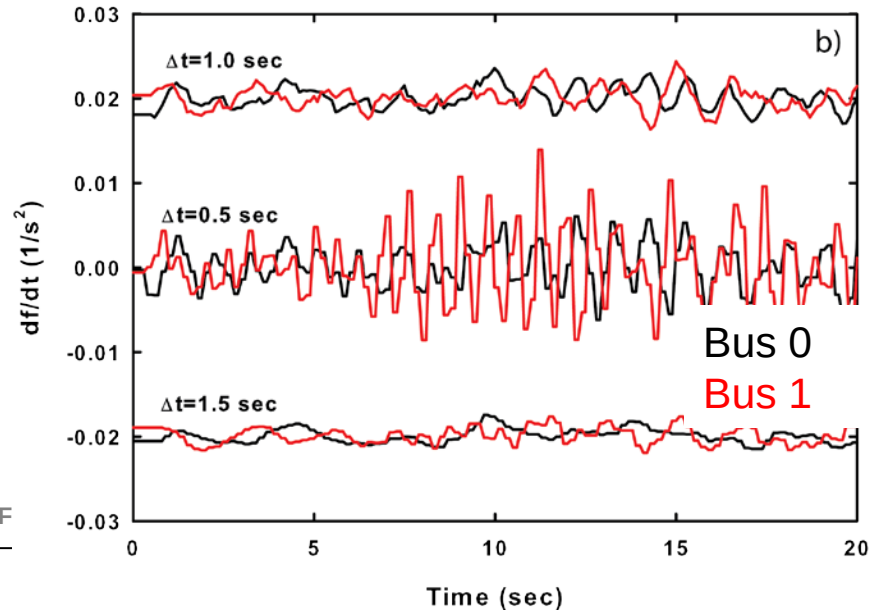
$$C_{AB}(\Delta t) = \int_0^{\infty} A(t+\Delta t)B(t)dt$$



Extraction of EM-Wave Green's Functions From Grid Noise







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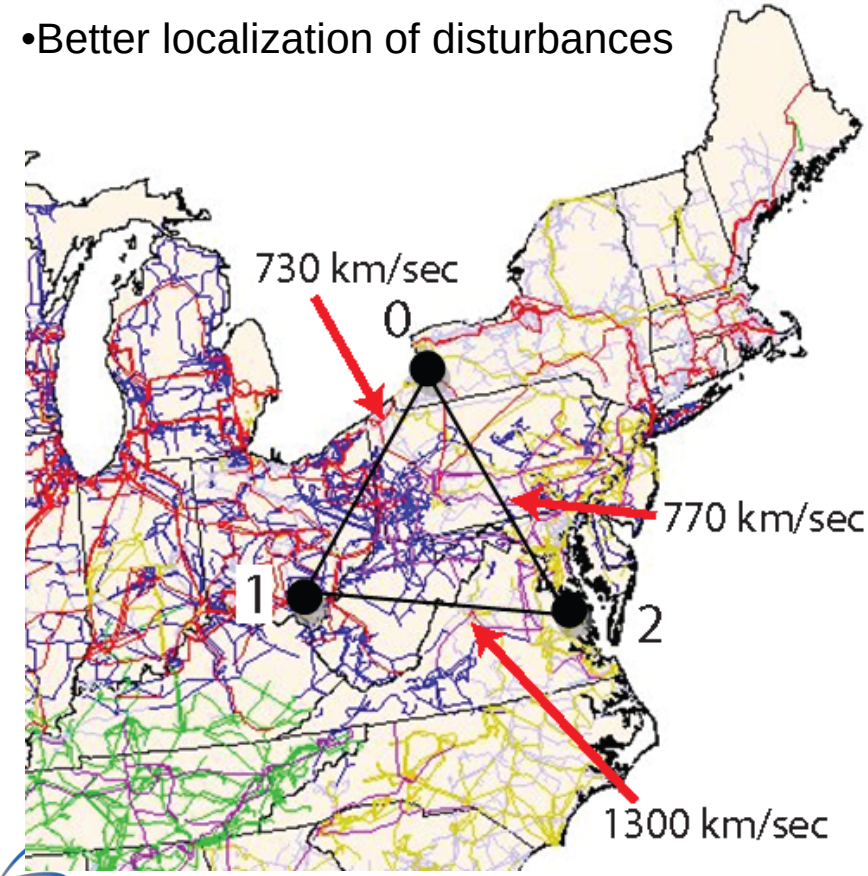
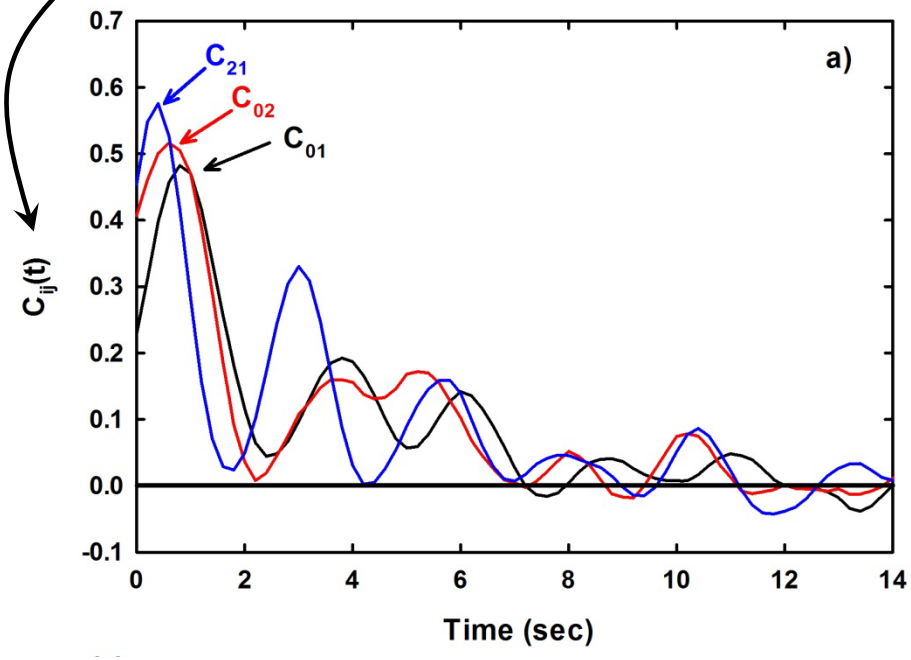
Extraction of EM-Wave Green's Functions From Grid Noise

- Wave “arrival” defined as the maximum value of *df/dt*
- Real-time, on-line, data-driven determination of EM-wave speeds
- Better localization of disturbances



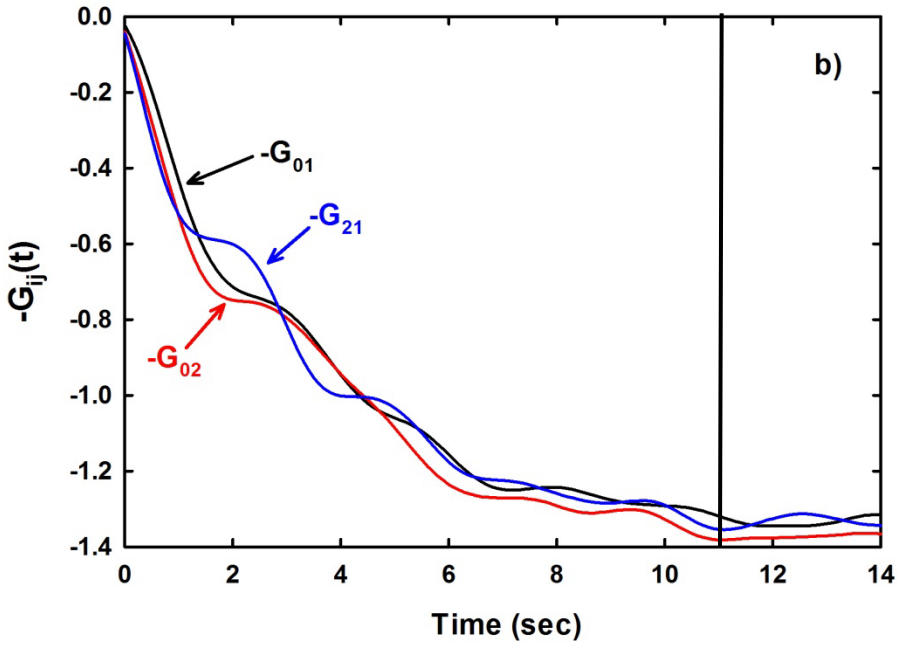
Green’s function for *df/dt*



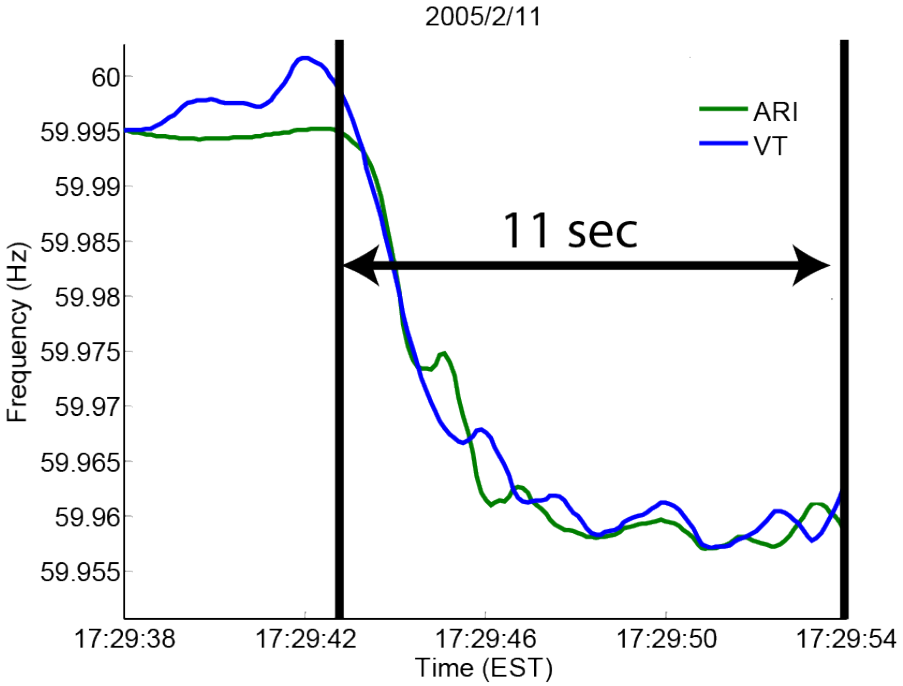
Using 1.5 sec filtering and 4 minute averaging

Extraction of EM-Wave Green's Functions From Grid Noise

Predictive—extracted from ambient noise



Post-event analysis



Using 1.5 sec filtering and 4 minute averaging

S. Tsai, Z. Zhong; J. Zuo; Y. Liu; *Power Engineering Society General Meeting, 2006. IEEE* doi: 10.1109/PES.2006.1708904

Extraction of EM-Wave Green's Functions From Grid Noise

Conclusions

- **Pre-disturbance, ambient grid noise can be used as a predictor of electric grid dynamic response to contingencies**

Future work

- **Normalization of the predicted response**
- **Extend to PMU data at the interconnection scale**
- **Direct comparison of pre-event Green's functions and post-event responses**
- **Extract frequency and damping of inter-area modes**
- ***Extend to extraction of generators and aggregate dynamical load models—significant unknown in dynamical grid models***