A Cross-Persistence Measure to Guide Recourse Actions

ARPA-E Open Program DE-AR0001032

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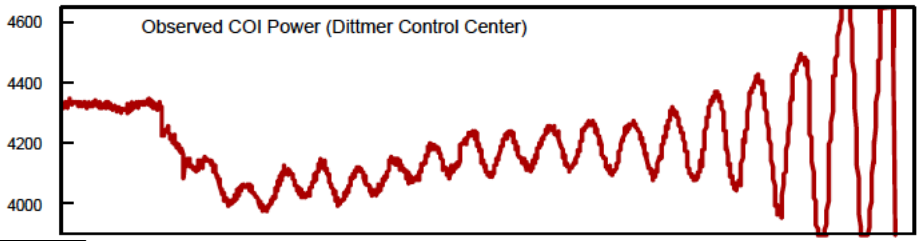
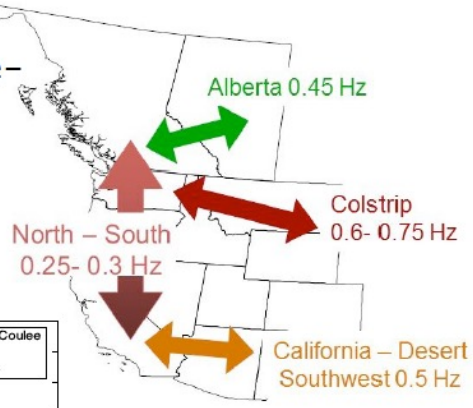
Background: Monitoring Damping

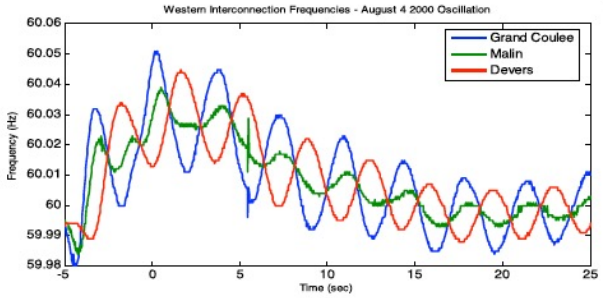
Sustained oscillations show lack of control in the grid, and can lead to blackouts.



Wide-Area View of Oscillations with Synchrophasors

Synchro-phasors provide wide-area geographic visibility of power oscillations:
- Is it a local or inter-area oscillation?





It would be useful to monitor system damping from ambient data, prior to a disturbance.

D. Kosterev, J. Undrill, "Oscillations in Power Systems," NASPI Jun. 3, 2011

Introduce a Persistence Measure

$$\Upsilon = \left\| \frac{R(\tau)}{R(0)} \right\|_2$$

System Persistence Measure

$$\Upsilon = \frac{\int_{w=-\infty}^{\infty} S(w)^2 dw}{\left(\int_{w=-\infty}^{\infty} S(w) dw \right)^2}$$

Important Properties:

- **Scales linearly with "stretching" of impulse response, regardless of shape.**
- For exponentials, doubling the time constant, doubles the measure.
  - For single mode, non-oscillatory exponentially-decaying impulse response, **it equals the time constant**;
  - For single mode, oscillatory exponentially-decaying impulse response **it is half the time constant**.

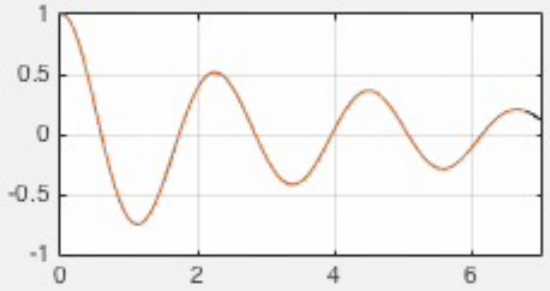
Calculable from the autocorrelation!

03/14/2017
06:02:00

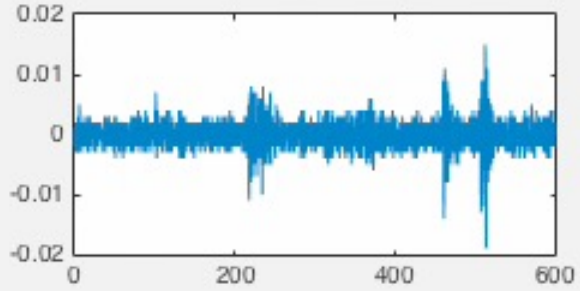
Get New Data

Pause

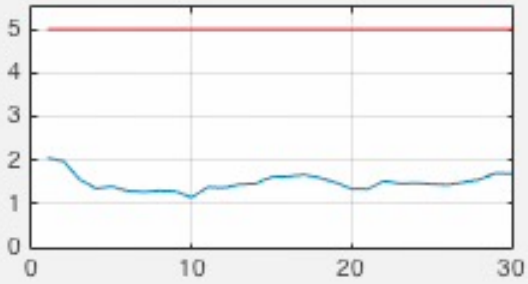
Autocorrelation and Fit



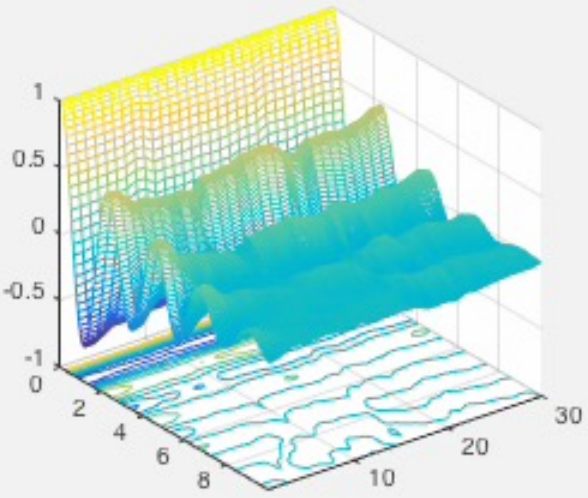
Signal



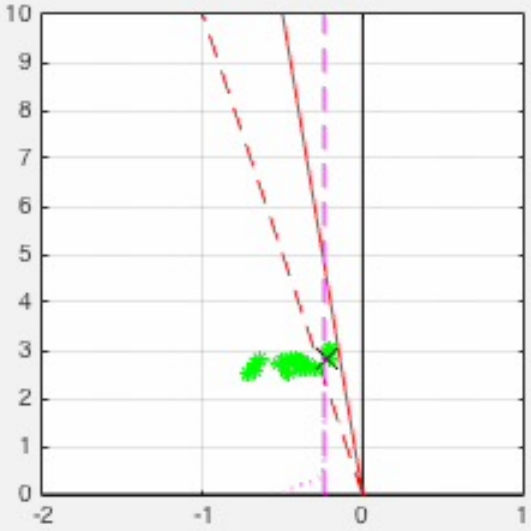
Persistence Measure



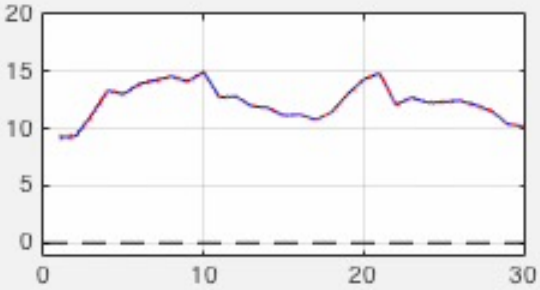
Autocorrelation History



S-Plane

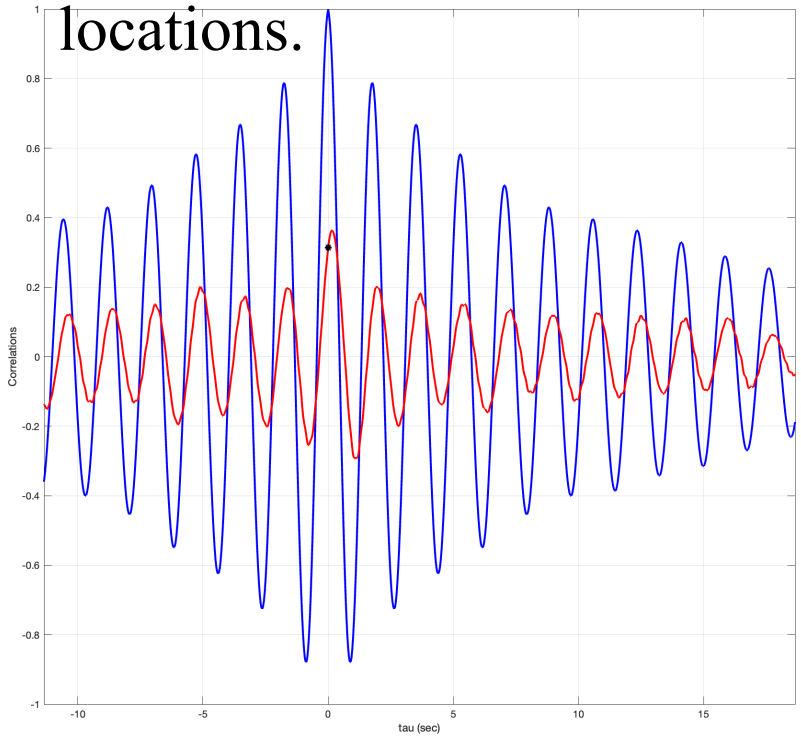


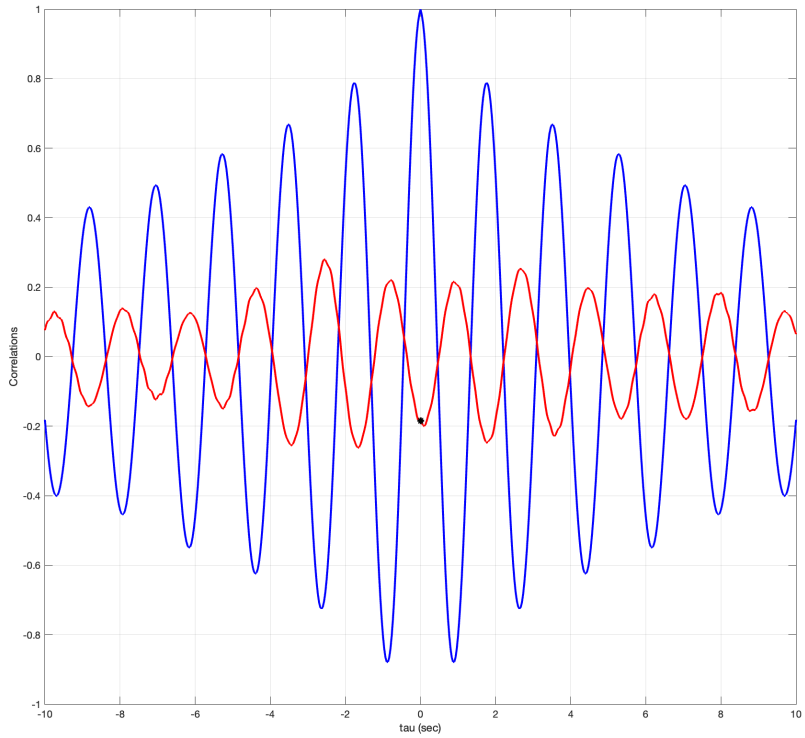
First-Turn Percent Damping



The Idea of Cross Persistence

The autocorrelation and cross correlation of signals can be out of phase. When they are moving against each other in an important mode, their locations need to be brought into sync, or become better damped – by modulating flows between the locations.





A Cross Persistence Metric

- Normalize data sequences *x* and *y*.
- Persistence: $\Upsilon_{xx} = \int_{-\infty}^{\infty} R_{xx}(\tau) R_{xx}(\tau) d\tau$
- Define Cross-Persistence

$$\begin{aligned} \Upsilon_{xy} &= \int_{-\infty}^{\infty} R_{xx}(\tau) C_{xy}(\tau) d\tau \\ &= \int_{-\infty}^{\infty} R_{yy}(\tau) C_{yx}(\tau) d\tau \\ &= \Upsilon_{yx} \end{aligned}$$

- Equals the persistence metric when *x* = *y*

Test on synthetic impulse responses

Consider: $x(t) = A_x e^{\sigma t} \cos(\omega t + \phi_x) u(t)$

$y(t) = A_y e^{\sigma t} \cos(\omega t + \phi_y) u(t)$

The high-frequency limit ($\omega >> \sigma$) is

$$\Upsilon_{xy} = \Upsilon_x \cos(\phi_x - \phi_y)$$
$$= \left(\frac{-1}{2\sigma}\right) \cos(\phi_x - \phi_y)$$

The low frequency limit($\omega \to 0$) is

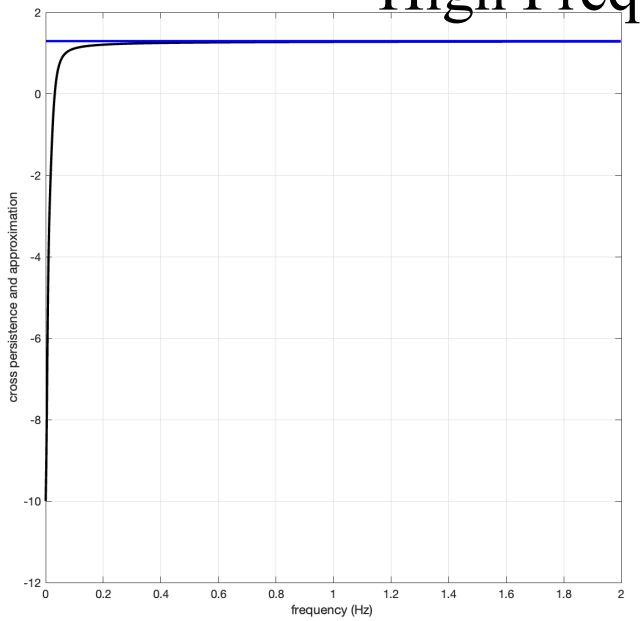
$$\Upsilon_{xy} = \Upsilon_x \ \ \text{sign}\left(\cos(\phi_x - \phi_y)\right)$$
$$= \left(\frac{-1}{\sigma}\right) \text{sign}\left(\cos(\phi_x - \phi_y)\right)$$

Test on Synthetic Impulse Responses

- Set $\sigma = -0.1$
  $\phi_x = \frac{\pi}{4}$
  $\phi_y = \frac{2\pi}{3}$

Vary frequency from 0 to 2 Hz.
Plot Cross-persistence

High Frequency Limit



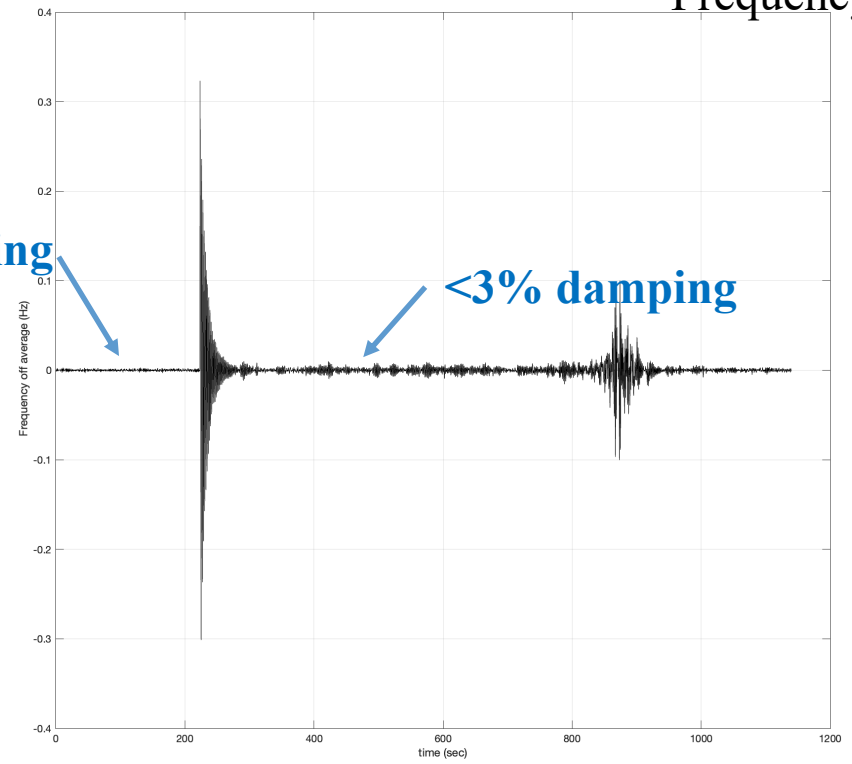
Low Frequency Limit

Event Example

Frequency difference from average

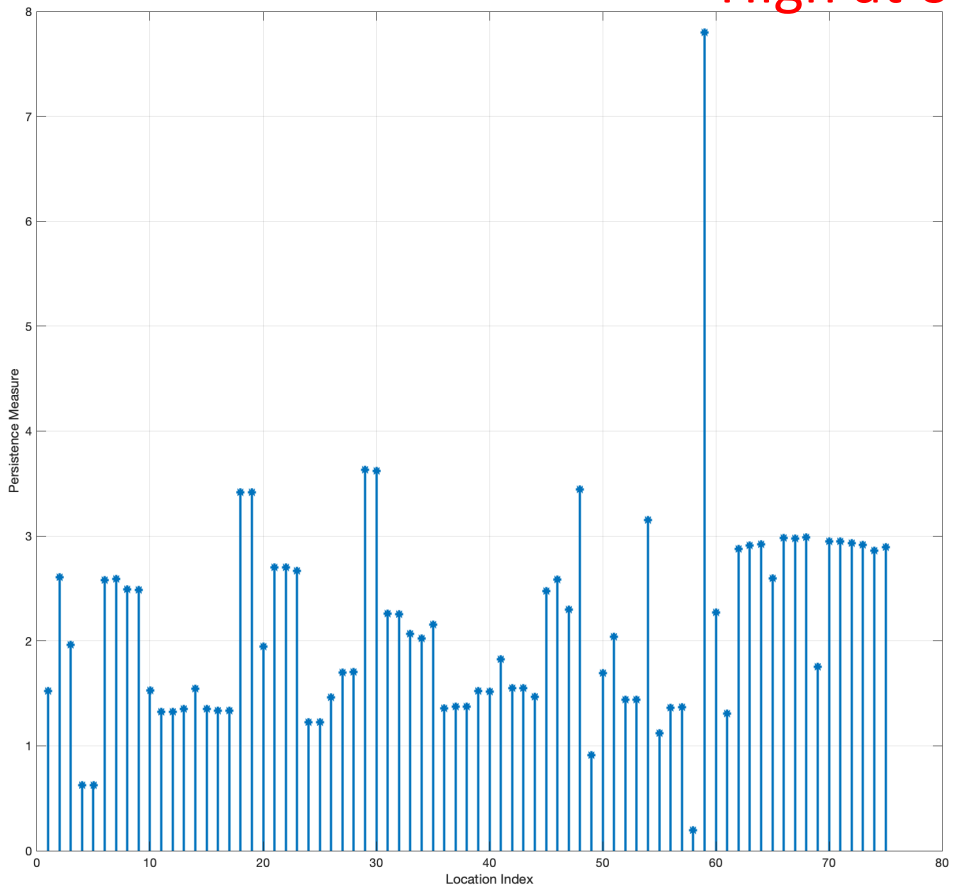
~14% damping

<3% damping

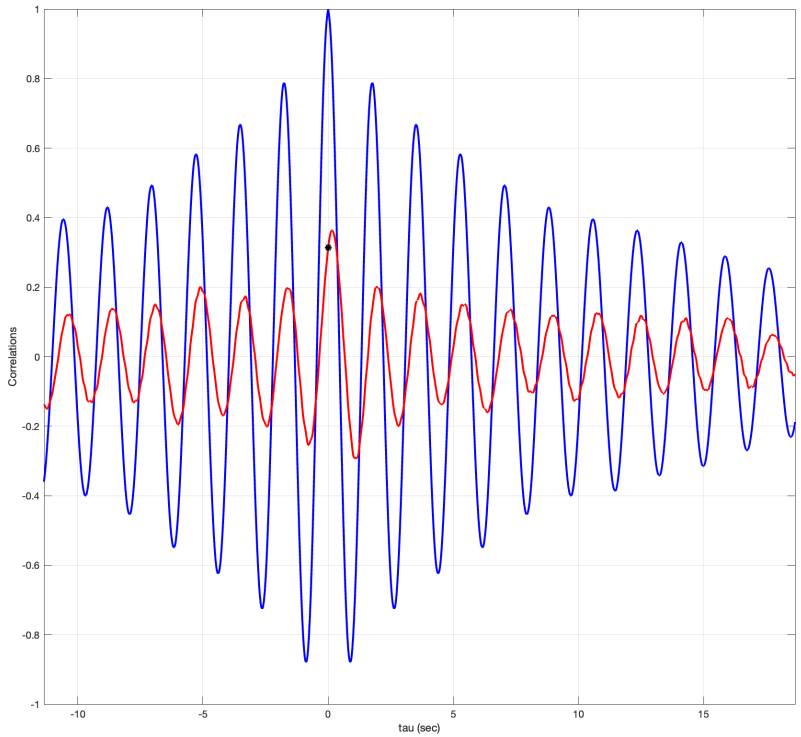


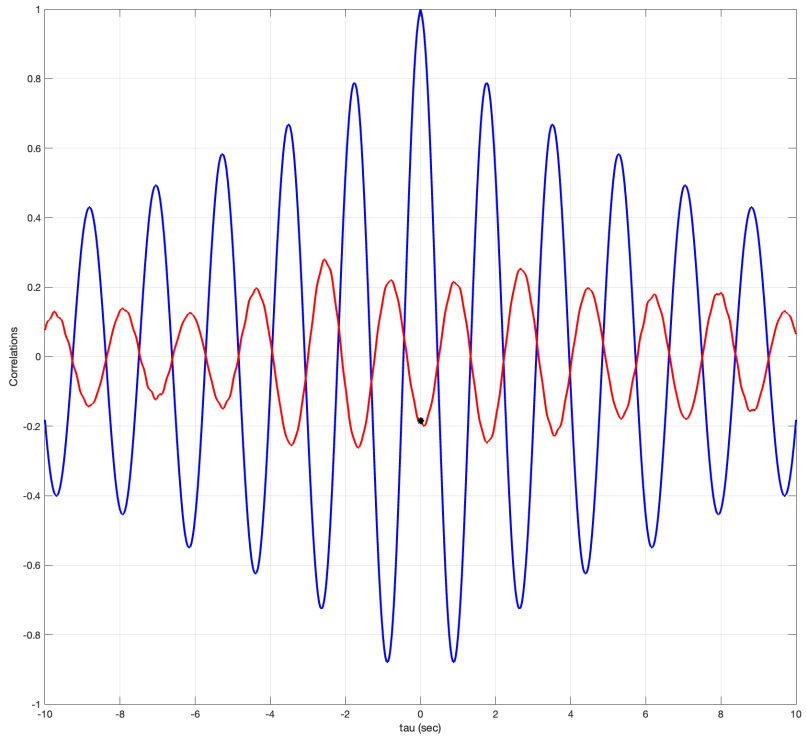
Persistence

High at one measurement location

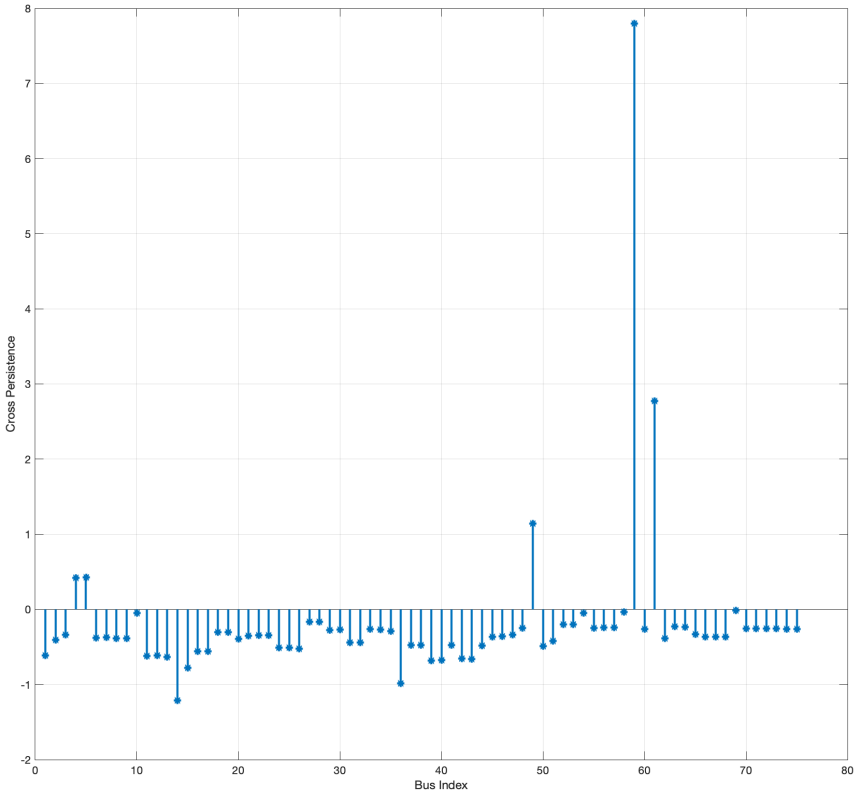


Compare Auto- and Cross-Correlations

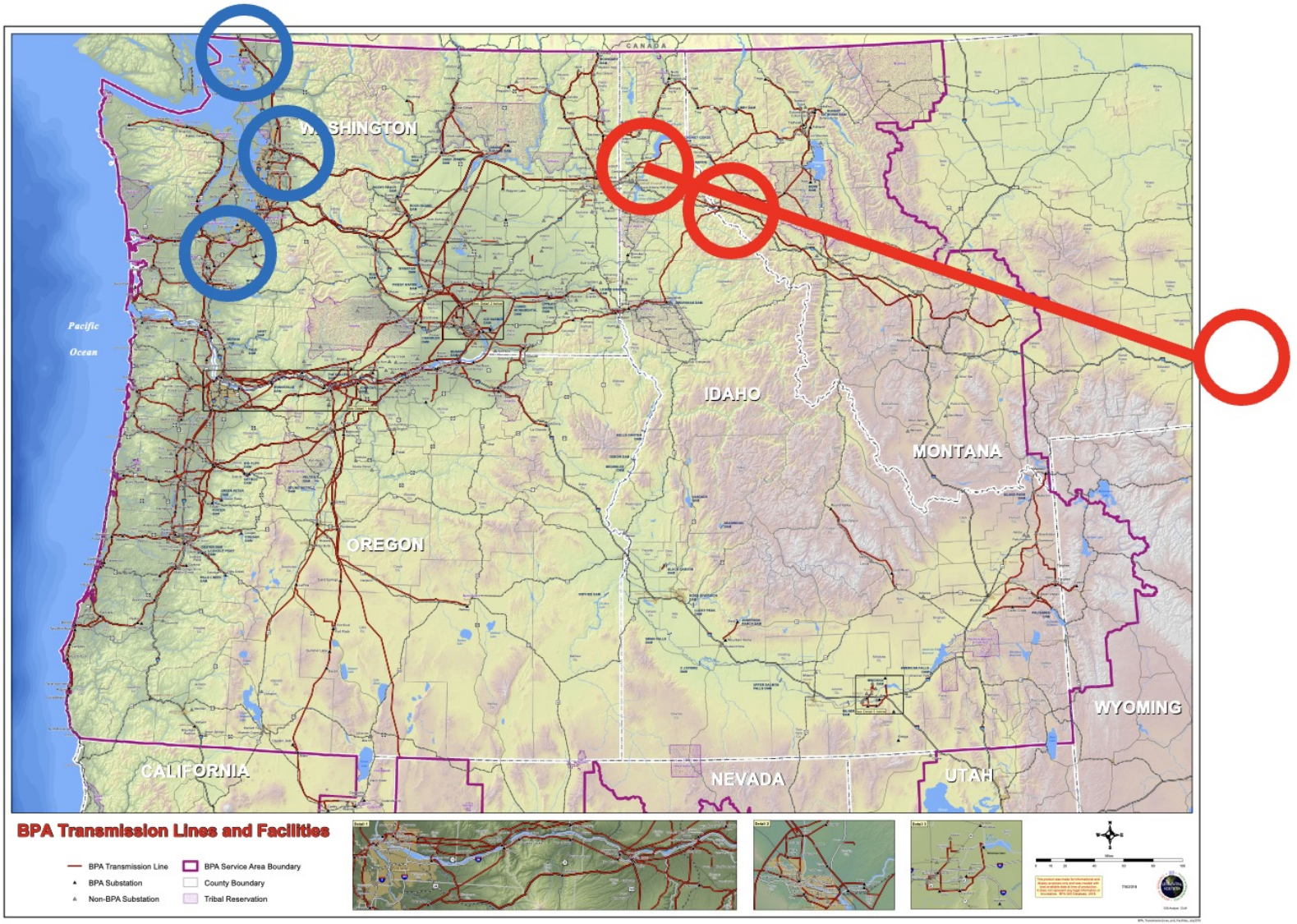




Cross Persistences



Locations


CANADA
WASHINGTON
Pacific
Ocean
IDAHO
MONTANA
OREGON
WYOMING
CALIFORNIA
NEVADA
UTAH
BPA Transmission Lines and Facilities
BPA Transmission Line
BPA Substation
Non-BPA Substation
BPA Service Area Boundary
County Boundary
Tribal Reservation

Recourse Actions

- The calculations suggest some action at the location with highest persistence, or along the high voltage path from east to the west.
- Reduce Flow Along this Path