60 Hz Mains Correlations for the U.S. Power Grids

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LIGO-G020245-00-E

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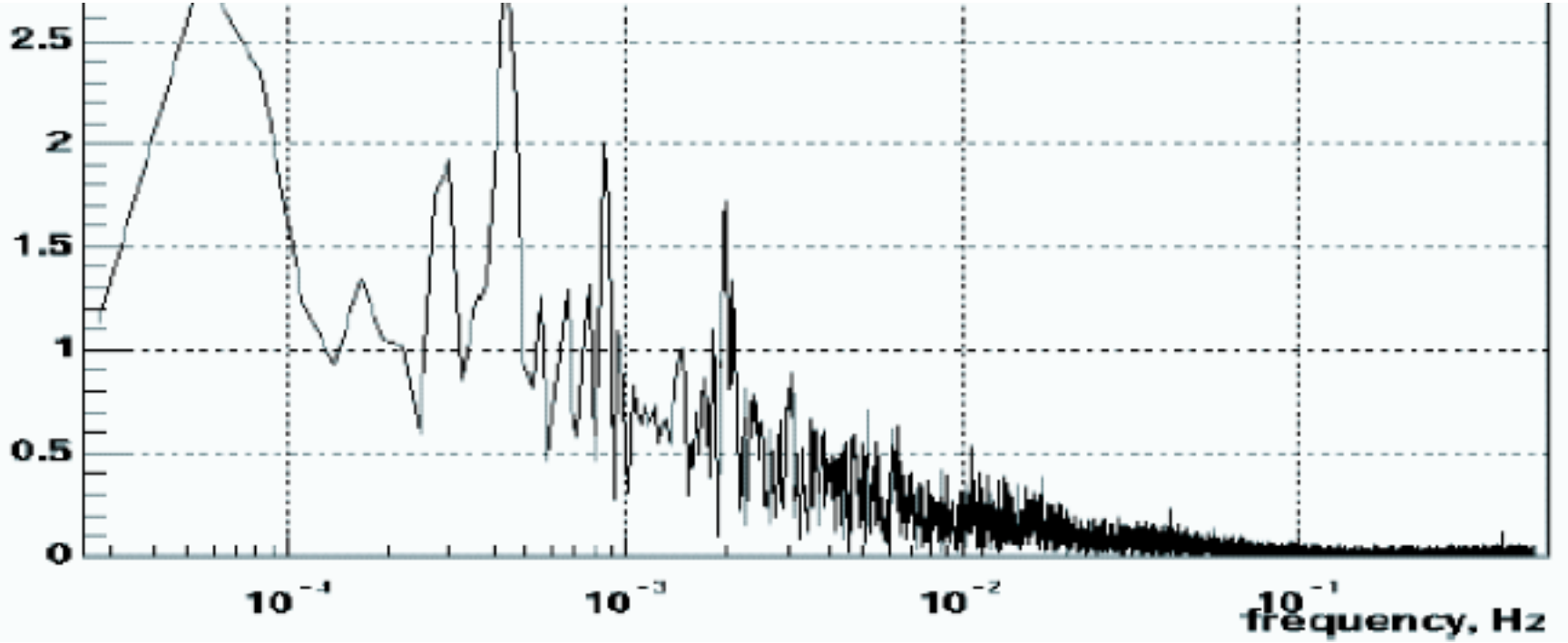
Correlations of 60 Hz Mains Lines

- During E3 & subsequent engineering runs, investigations by S. Klimenko (U.Fl.) uncovered “surprisingly long” correlation times for LA-WA site-to-site correlations of 60 Hz power mains
  - » Looked at 60 Hz mains power conditioning monitors in LIGO physical environment monitors (PEM)
  - » Correlations also present (to a lesser degree) in differential dark port signals
  - » Poses a potential concern for measureements requiring long integration times:
    - – CW sources
    - – Stocahstic background

Mains Correlations Observed Using LIGO PEM Monitors
Klimenko et al.



- Cross spectral density of phase noise at 60 Hz reported for the E3 engineering run by Klimenko et al.
  - » Graph from LSC internal E3 report

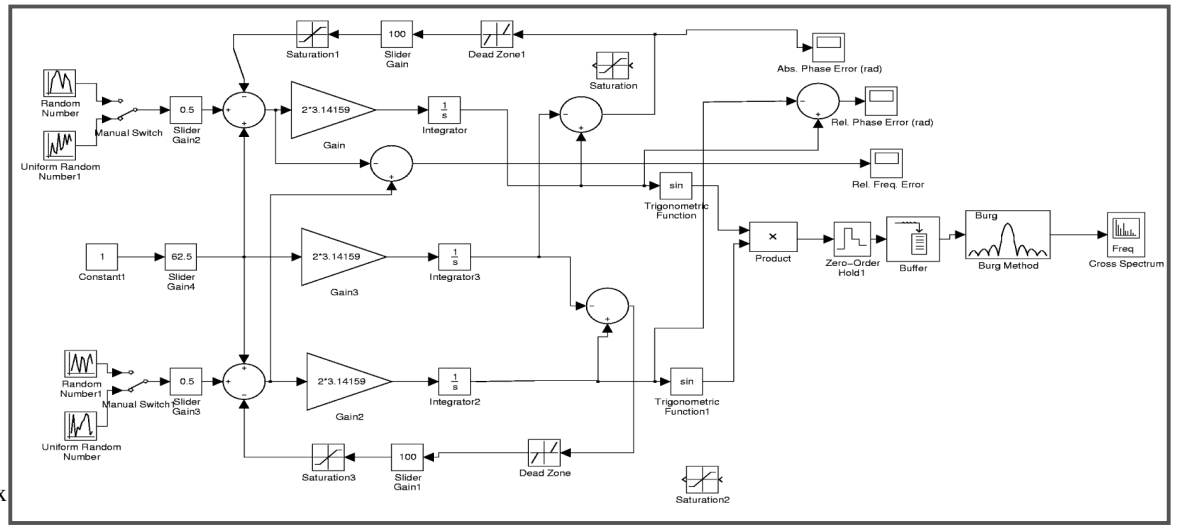
Simple Matlab model demonstrated that effects could arise from synchronously imposed frequency corrections by power grid operators

- Phase corrections are imposed according to several constraints:
  - **Instantaneous frequency error**

$$|\Delta f(t) - \Delta f_0| \le \Delta f_{\max} = 0.02 Hz$$

  - **Maximum phase error over a period T ~ O[1day]**

$$\left| \int_{t_0}^{t_0+T} \Delta f(t)\,dt - \Delta f_0 T \right| \le \frac{\Delta f_{\max}}{2\pi}; \Delta f_{\max} = 2\pi f_0 t_{\max}$$

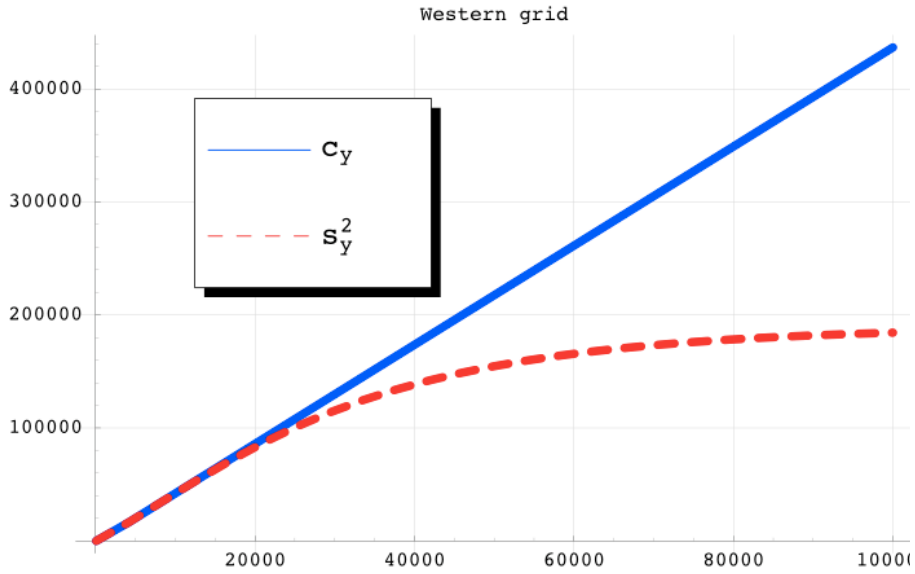


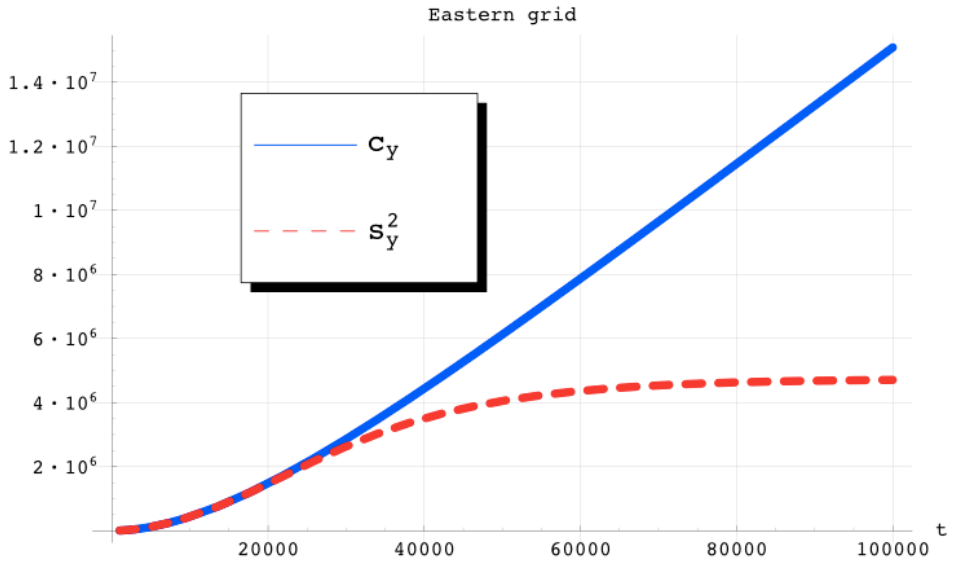
Δt_{max} = 2s (West)
8s (East)

- Phase corrections have become synchronized with GPS

Phase Errors

- Frequency errors -> stochastic forcing function, determined by power load fluctuationson the grid
- Phase (integral of frequency errors) -> diffusion process bounded by constraint





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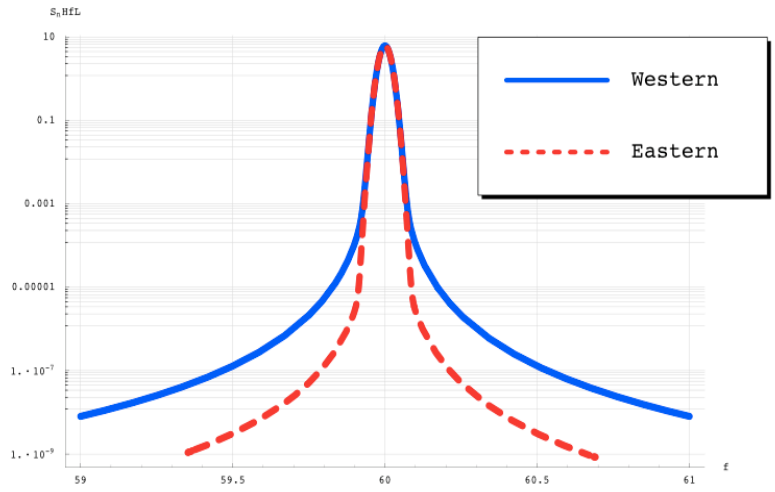
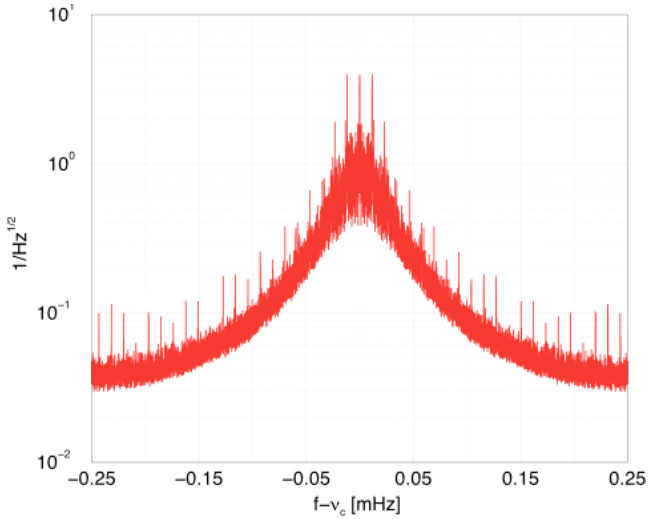
Line shapes

Calculated & Deduced from Western US Grid □□(t) data

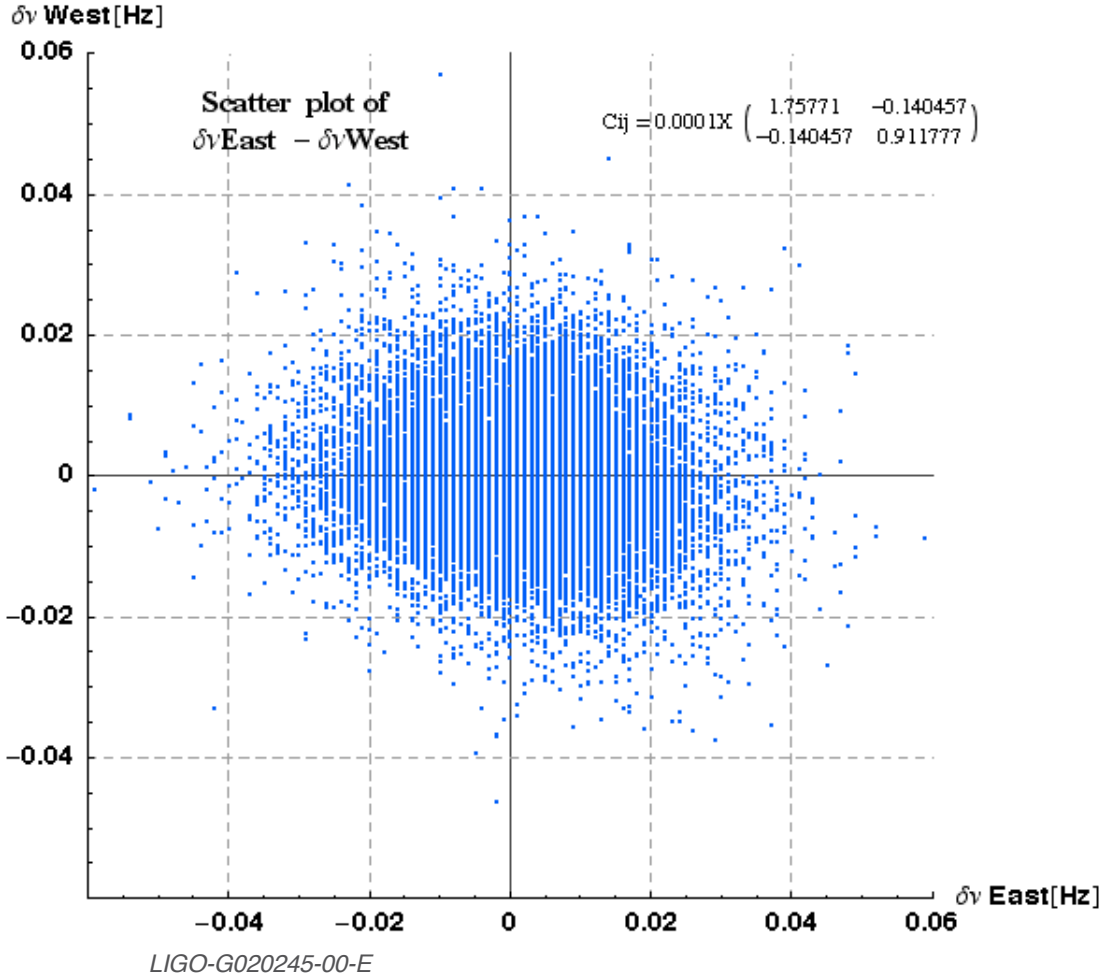


Frequency line shape modeled from simple control laws (matlab & analytical)



Frequency line shape deduced from Western grid phase error data

Details of □□(t) for East & West



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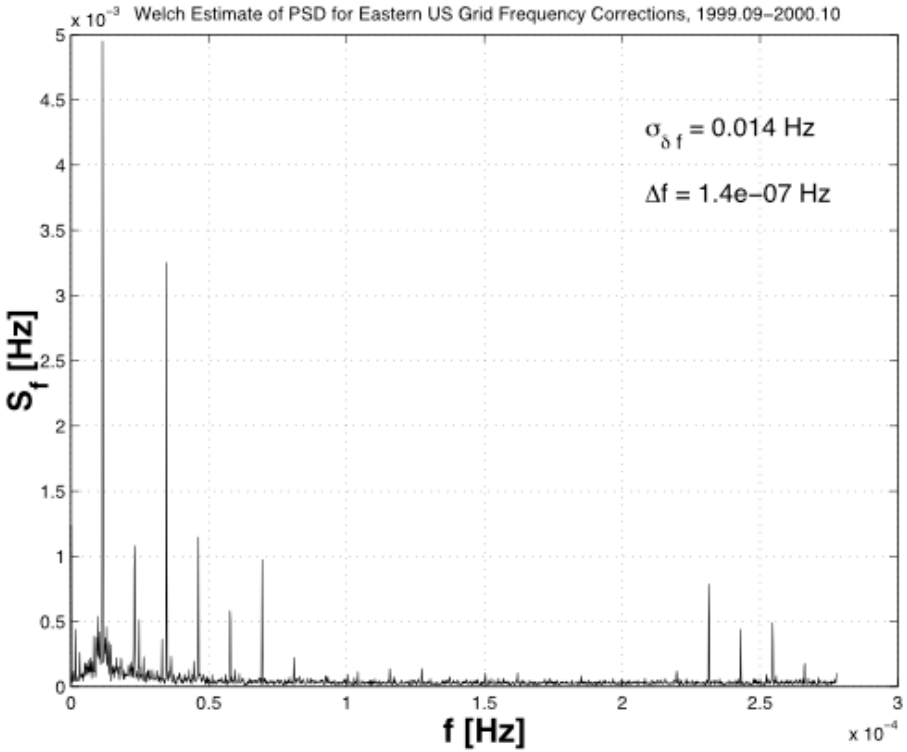
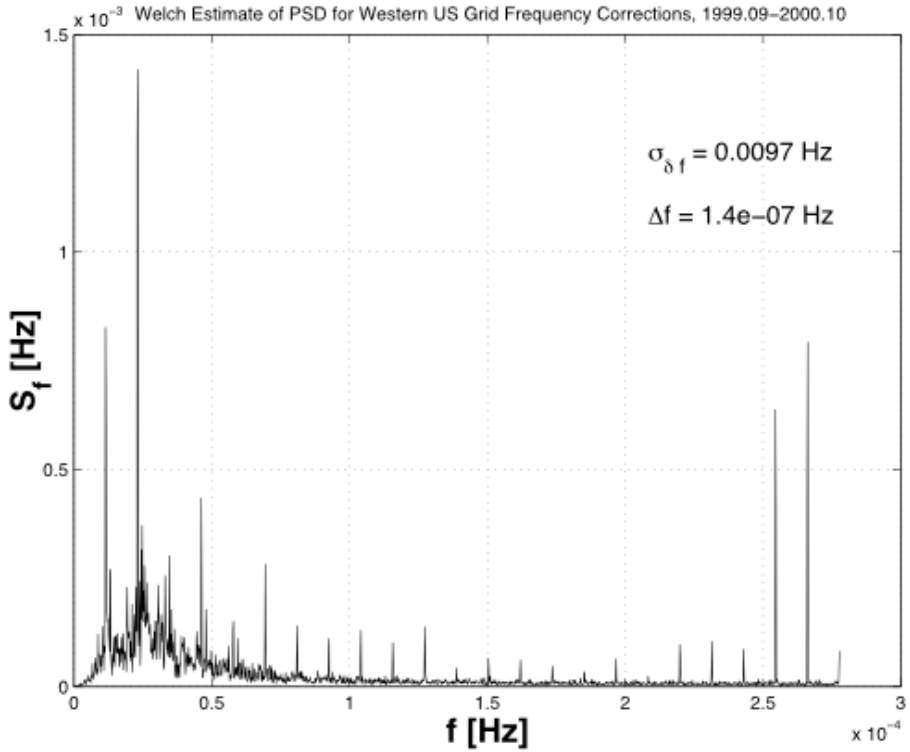
- 17520 points
  - » every 1/2 hour 1999.09.30 - 2002.10.01
- □□$_E$ - □□$_W$ scatter plot shows -11% correlation (power):
  - □$_{EW}$=-0.14/Sqrt[1.76 * 0.91]

PSDs of East, West frequency errors

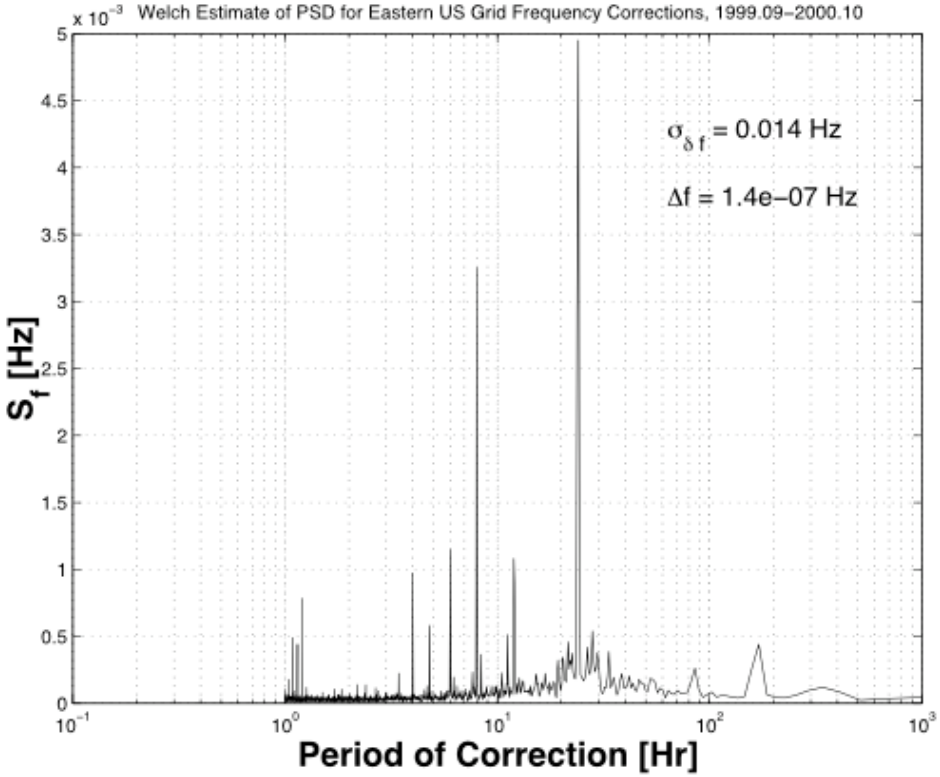


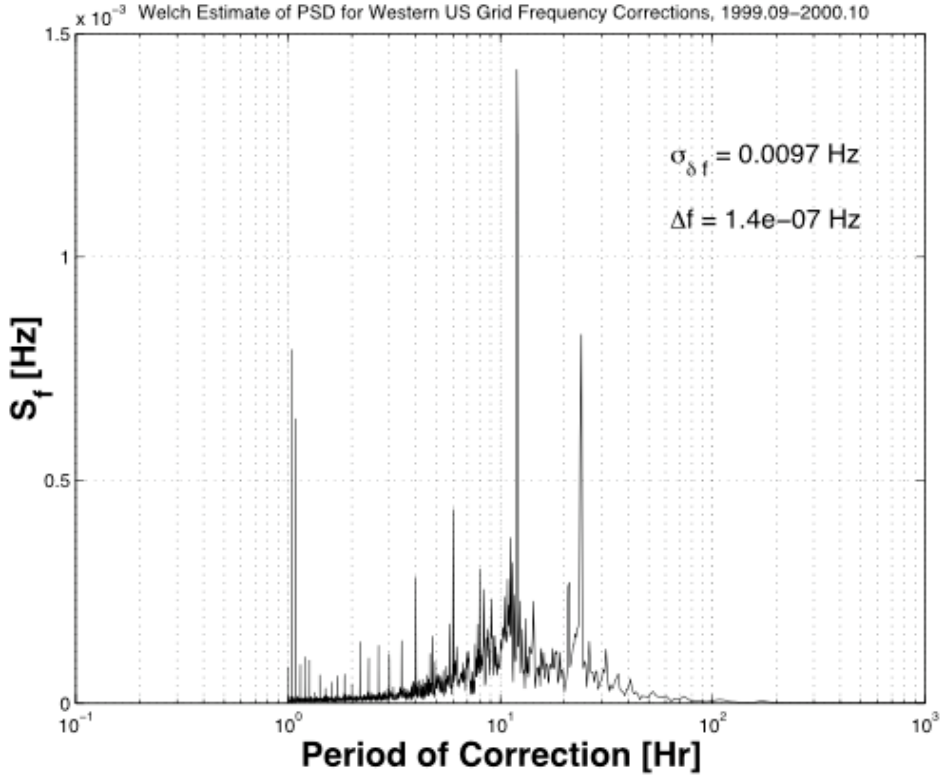
Eastern Grid



Western Grid

PSDs of East, West frequency errors vs. period

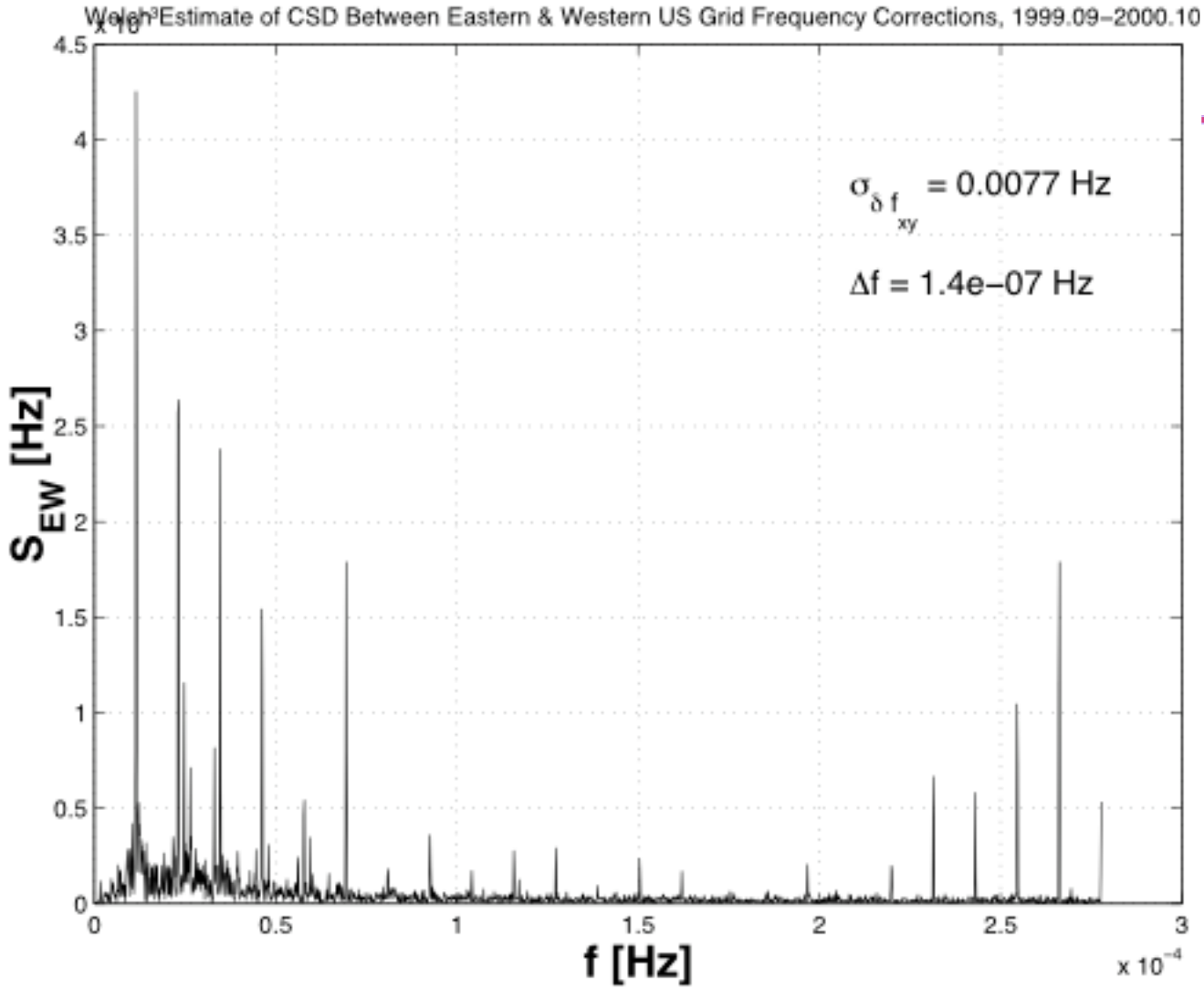




Eastern Grid

Western Grid

LIGO PSDs of East, West Cross Spectral Density



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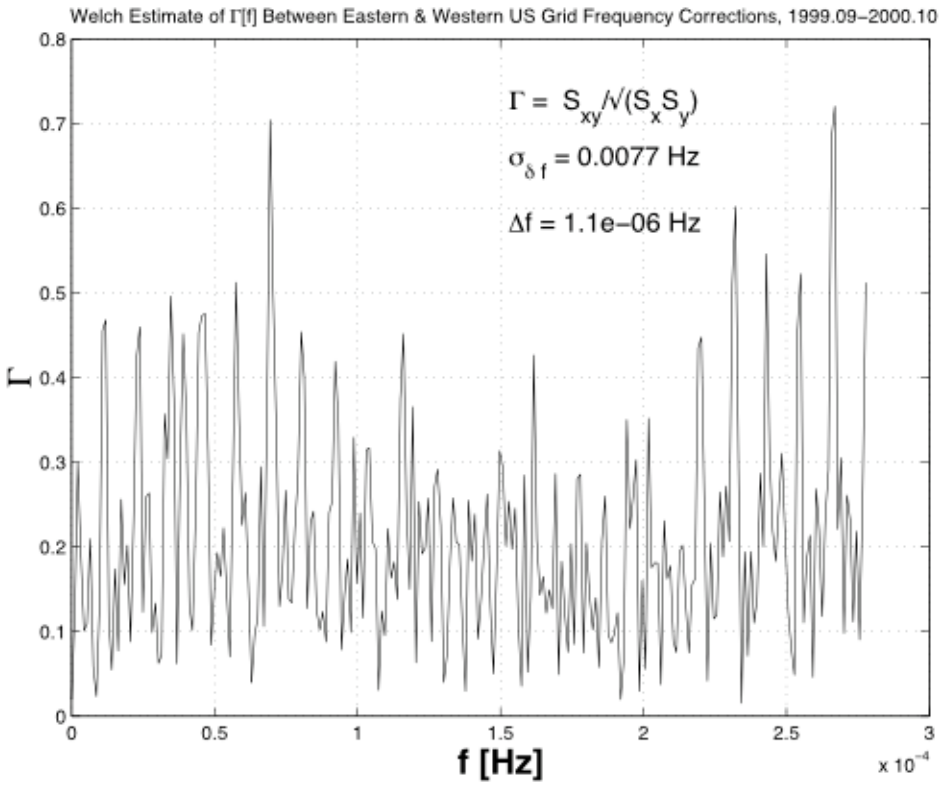
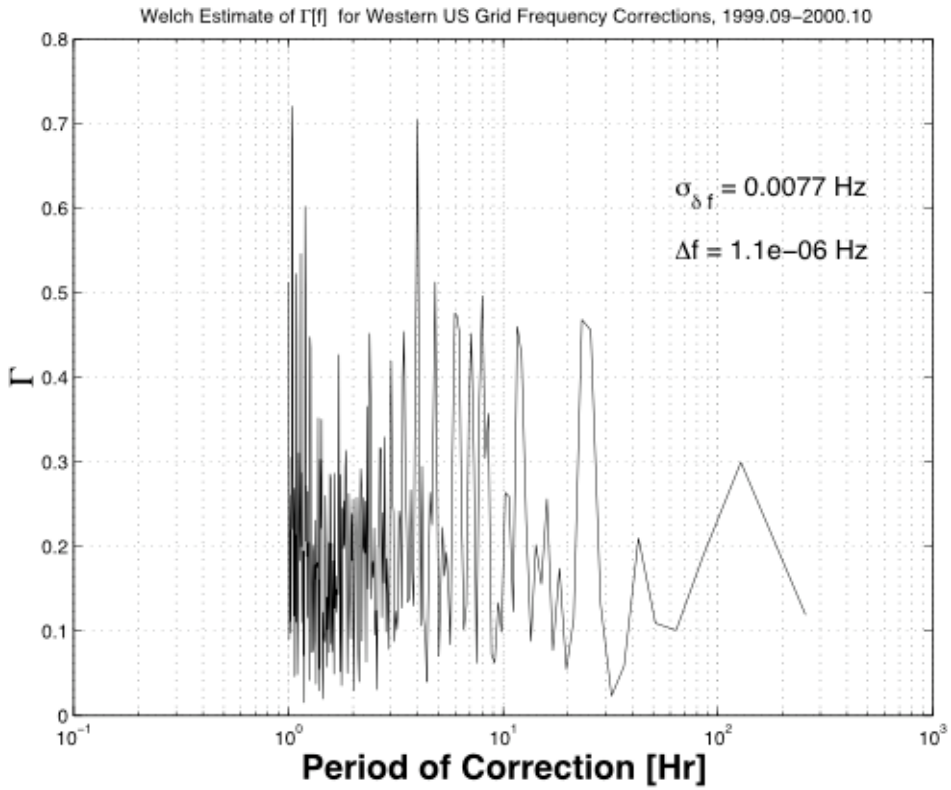
PSDs of East, West Cross Spectral Density vs. Period





Conclusions

- GPS-derived U.S. grid frequency corrections are coherent over T~10^7 s
  - » This can explain observed PEM power mains correlations
  - » Data available have very low bandwidth => $f_{Nyquist}$ =1 Hr
    - – Finer details not available at this time
    - – Suggests heterodyning local PEM measurements with stable[r] 60 Hz oscillator to provide long term resampled trend data of mains line (stabilize LO, e.g., with GPS)
    - – Transfer function to AS_Q (h[f]) channel expected to attenuate correlations greatly (but they may remain if 60 Hz mains are visible)
- Line features contained within $\pm$1 mHz band near mains frequencies
- Windowing of spectra containing coherences could disperse power across spectrum
  - » Possible concern for stochastic background measurement (T_{int}~2 min)
  - » Algebraic (coherent) line removal in time (or frequency) domain before cross-correlation will be explored
- LIGO Technical document: LIGO-T010101-01.pdf