Regression of environmental noise in gravitational-wave detectors.

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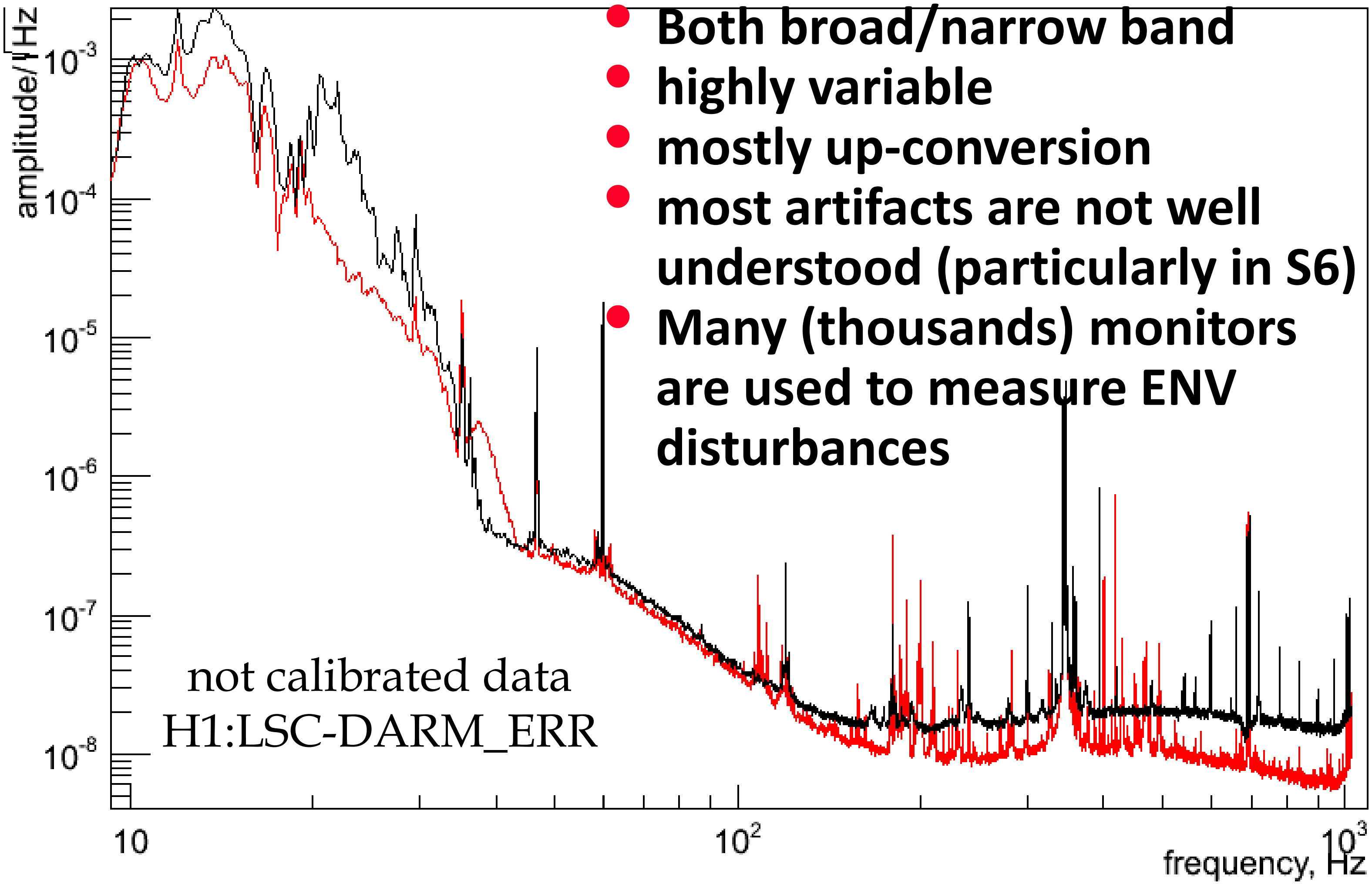
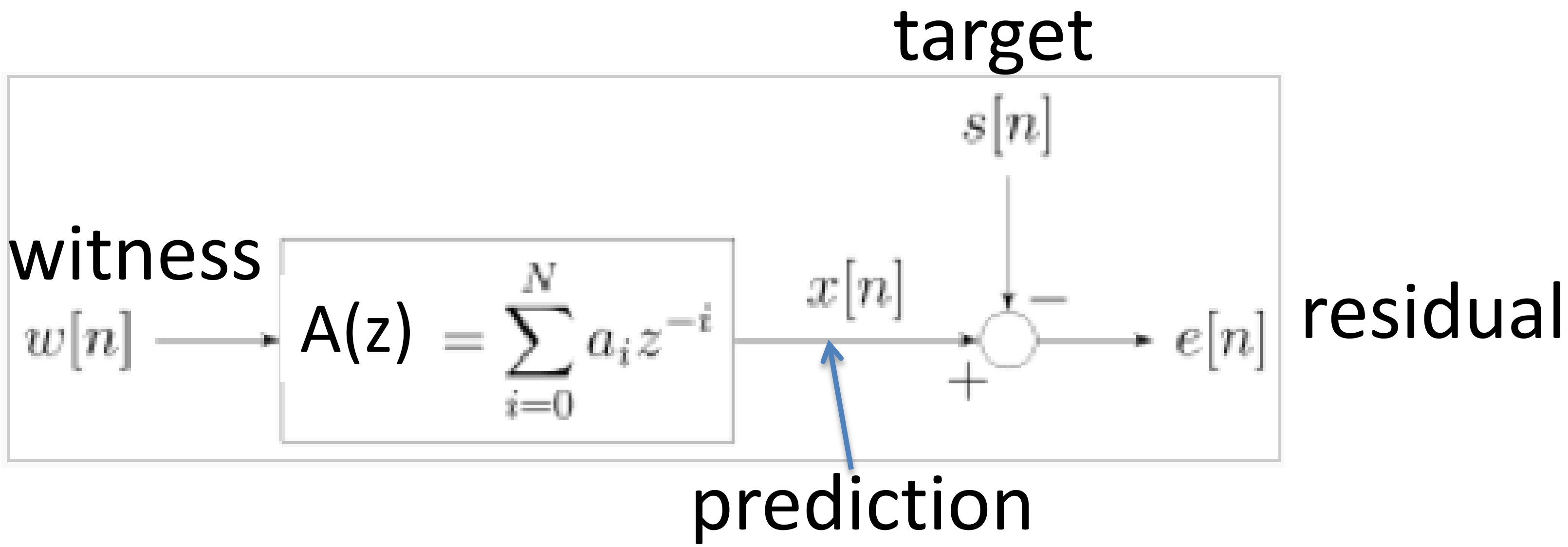
Environmental Noise

Snapshots of H1 data (15 min): black S5(820707090), red S6(942451300)



- **Both broad/narrow band**
- **highly variable**
- **mostly up-conversion**
- **most artifacts are not well understood (particularly in S6)**
- **Many (thousands) monitors are used to measure ENV disturbances**

Basics: FIR Wiener-Kolmogorov Filter



- find A = {a[0],…,a[K]} by minimization of residual

$$\sum_{n=0}^{n=N} e^2[n] = \sum_{n=0}^{n=N} \left| s[n] - \sum_{k=0}^{k=K} a[k] w[i-k] \right|^2$$

- target s[n] can be predicted if there is a linear association with witness channel w[n].
  - N – filter training length, K – filter length

Basics: Wiener-Hopf Equation

$$\begin{bmatrix} r_{ww}[0] & r_{ww}[1] & \dots & r_{ww}[K] \\ \dots & \dots & \dots & \\ r_{ww}[K] & r_{ww}[K-1] & \dots & r_{ww}[0] \end{bmatrix} \begin{bmatrix} a[0] \\ \dots \\ a[K] \end{bmatrix} = \begin{bmatrix} r_{sw}[0] \\ \dots \\ r_{sw}[K] \end{bmatrix}$$

- r is cross-correlation vector between s and w
- R is Toeplitz matrix constructed from autocorrelation of w
  - Solved by using advantage of Levinson-Durbin algorithm

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CQG, 25, 114029 (2008) - application of LPR in burst analysis by cWB & Ω
RSI, 83, 024501 (2012) – active noise cncellation in suspended interferometers

Wavelet Regression

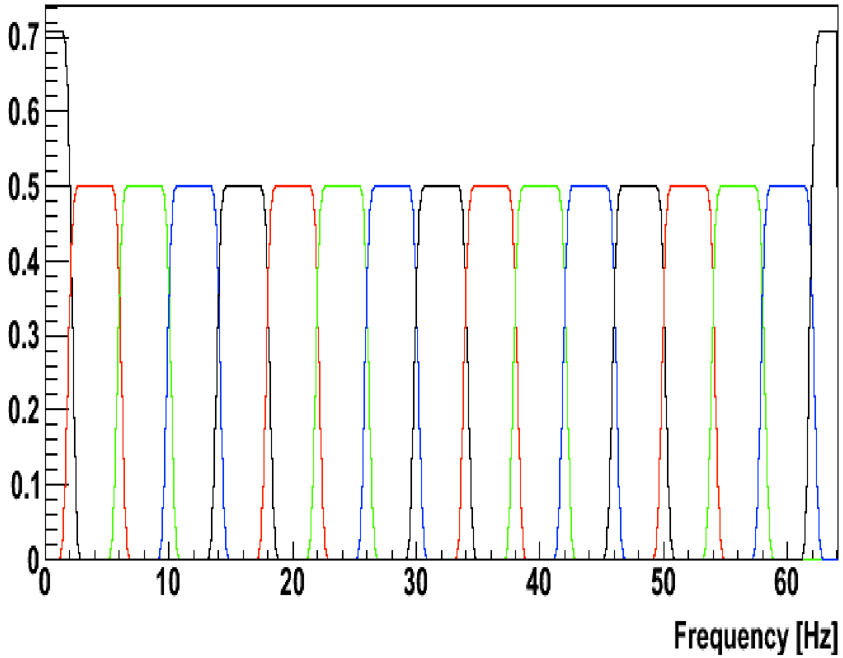
- 3 key components
  - Do analysis in wavelet domain (use WDM – next slide)
    - ✓ Calculate a bank of elementary Wiener filters instead of a BIG filter
    - ✓ pros: split complex problem into a set of simple problems
    - ✓ pros: reduce computational complexity (feasible in real time)
    - ✓ pros: greatly simplify use of regulators
  - Use/construct multiple witness channels
    - ✓ pros: enhance regression
    - ✓ pros: address up-conversion (non-linear coupling)
    - ✓ cons: add noise to prediction
  - Regulators-mitigate fitting problems
    - ✓ reduce excessive noise due to multiple witness channels
    - ✓ obtain stable/robust filter solutions
    - ✓ reduce artifacts

Regression in Wavelet Domain

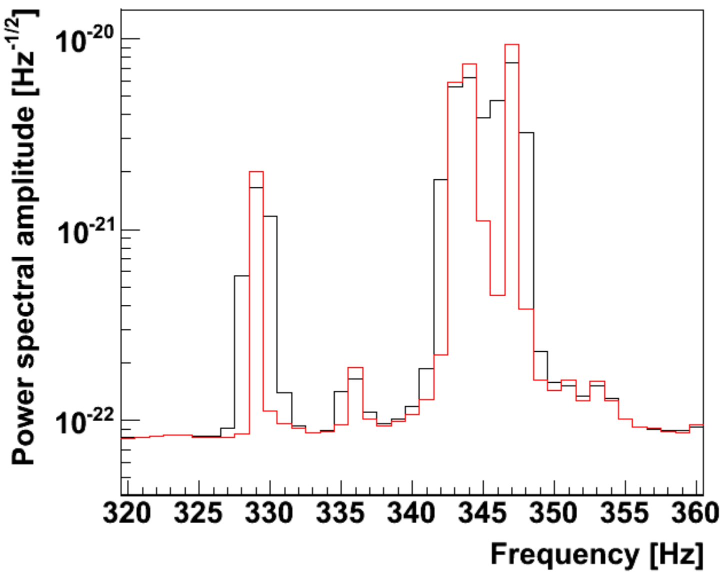
$$s(t) \rightarrow \{s(\omega_n, t)\} \qquad w(t) \rightarrow \{w(\omega_n, t)\}$$

- Wilson-Daubechies-Meyer (& V.Necula) transformation [LIGO-P1100152]
  - ✓ orthonormal, invertible, critically sampled, exceptional control of spectral leakage
  - ✓ each wavelet (frequency ω_n) layer is a time series representing band-limited data.
  - ✓ Filters can be constructed for every target layer and arbitrary set of witness layers
  - ✓ Easily zoom into desired **frequency sub-bands (layers)** in the data

Wavelet (basis) functions in Fourier domain



LIGO data (1Hz resolution):
black – Hann FFT
red - WDM



Multiple Witness Channels

$$\sum_n \left| s[n] - \sum_k a_w[k] w[n-k] - \sum_k a_u[k] u[n-k] - \sum_k a_v[k] v[n-k] \right|^2$$

$$\begin{bmatrix} R_{ww} & C_{wu} & C_{wv} \\ C_{uw} & R_{uu} & C_{uv} \\ C_{vw} & C_{vu} & R_{vv} \end{bmatrix} \begin{bmatrix} A_w \\ A_u \\ A_v \end{bmatrix} = \begin{bmatrix} c_{sw} \\ c_{su} \\ c_{sv} \end{bmatrix}$$

- **Witness channels can be:**
  - **Layers (sub-bands) of multiple witness channels**
  - **Different layers of the same witness channel**
  - **Constructed from other WDM-conditioned witness channels**
    - ✓ **magnetometer x ITM/ETM coils – can remove bi-linear noise**
- **In general, s[n], w[n],u[n],[v[n] and filters A are complex**

Regulators

$-L<k<L$

$$\begin{pmatrix} a_{-L} \\ a_{-L+1} \\ \cdot \\ \cdot \\ a_L \end{pmatrix} = O \begin{pmatrix} 1/\lambda_{-L} & 0 & \cdots & 0 \\ 0 & 1/\lambda_{-L+1} & \cdots & 0 \\ \cdot & \cdot & & \\ \cdot & & \cdot & \\ 0 & & & 1/\lambda_L \end{pmatrix} O^T \begin{pmatrix} C_{yx}(-L) \\ C_{yx}(-L+1) \\ \cdot \\ \cdot \\ C_{yx}(L) \end{pmatrix},$$

hard

$$\begin{pmatrix} a_{-L} \\ a_{-L+1} \\ \cdot \\ \cdot \\ a_L \end{pmatrix} = O \left(\begin{array}{cccc} 1/\lambda_{-L} & 0 & \cdots & 0 \\ 0 & 1/\lambda_{-L+1} & \cdots & 0 \\ \cdot & \cdot & & \\ \hdashline \cdot & & 0 & \\ 0 & & & 0 \end{array}\right) \lambda_\tau \quad O^T \begin{pmatrix} C_{yx}(-L) \\ C_{yx}(-L+1) \\ \cdot \\ \cdot \\ C_{yx}(L) \end{pmatrix},$$

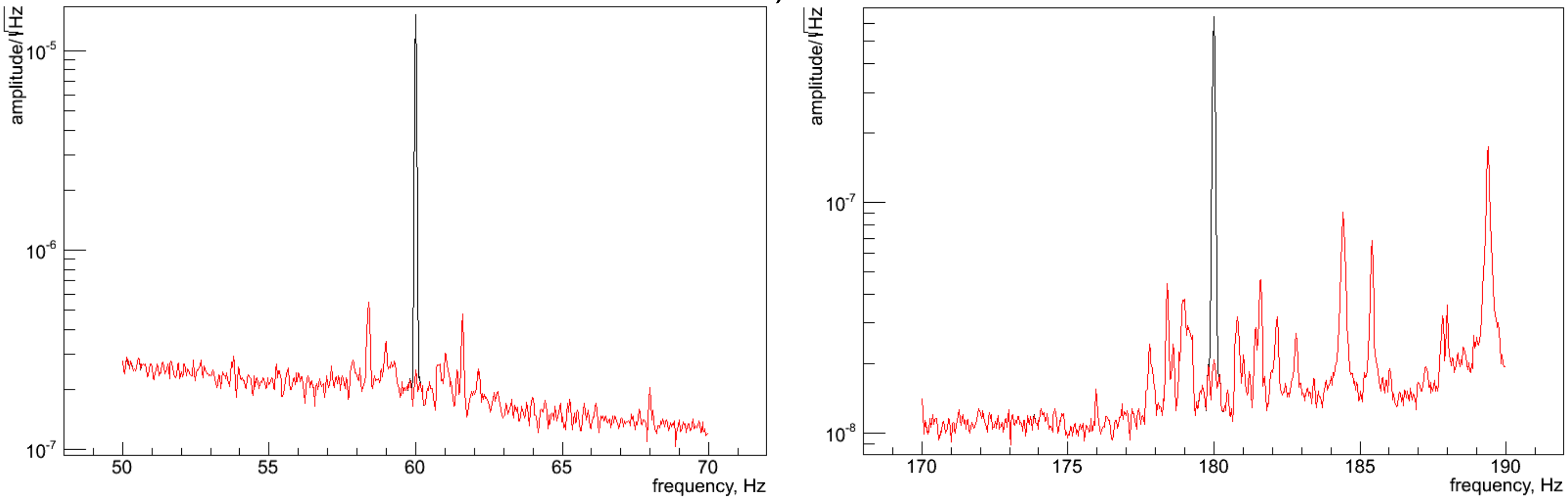
soft

$$\begin{pmatrix} a_{-L} \\ a_{-L+1} \\ \cdot \\ \cdot \\ a_L \end{pmatrix} = O \left(\begin{array}{ccccc} 1/\lambda_{-L} & 0 & \cdots & \cdot & 0 \\ 0 & \cdot & \cdots & \cdot & \cdot \\ \cdot & \cdot & 1/\lambda_l & \cdot & 0 \\ \hdashline \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & \cdot & \cdot & & 1/\lambda_l \end{array}\right) \lambda_\tau \quad O^T \begin{pmatrix} C_{yx}(-L) \\ C_{yx}(-L+1) \\ \cdot \\ \cdot \\ C_{yx}(L) \end{pmatrix},$$

- address rank deficiency of WH matrix
- for each filter (in the set) typically only few λ are significant
- reduce filter noise, suppress irrelevant channels

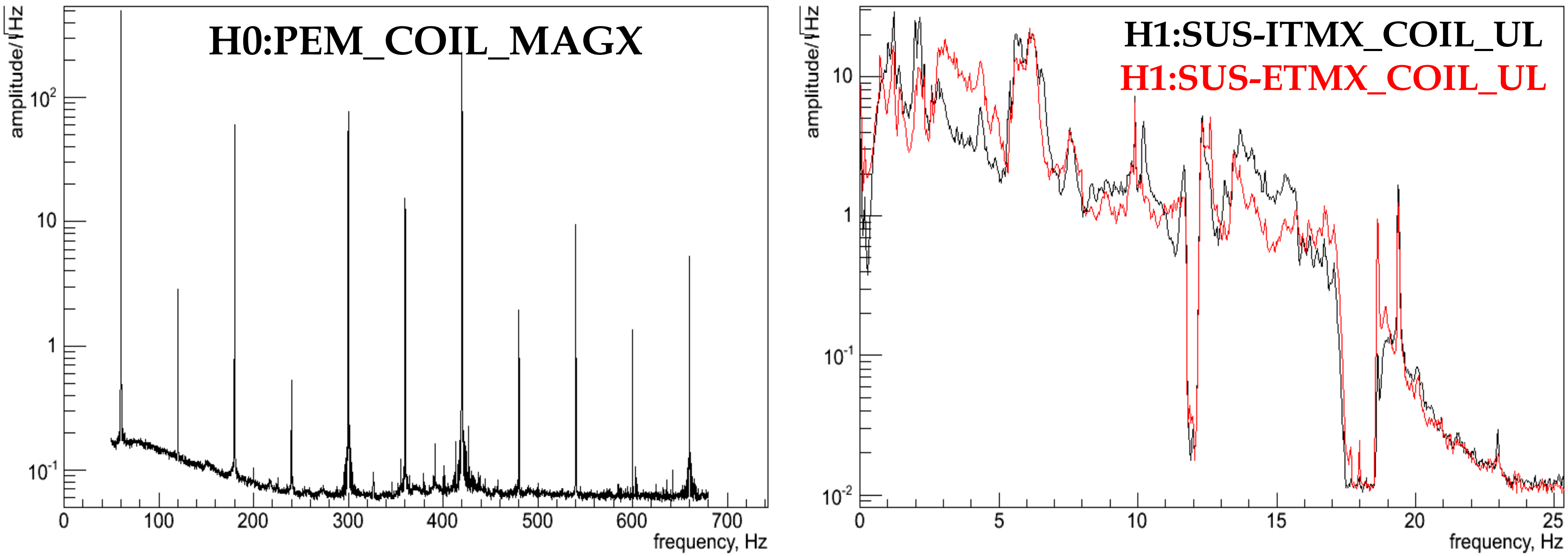
Power Lines

H1:DARM, 15min of S6 data



- most obvious case – power lines – well removed by many methods, including wavelet regression using power monitors or magnetometers (H0:PEM-BSC10_MAGX)
- Are there any other cases of linear coupling, particularly broad-band?
- How to identify and remove non-linear coupling?

Bi-Linear coupling

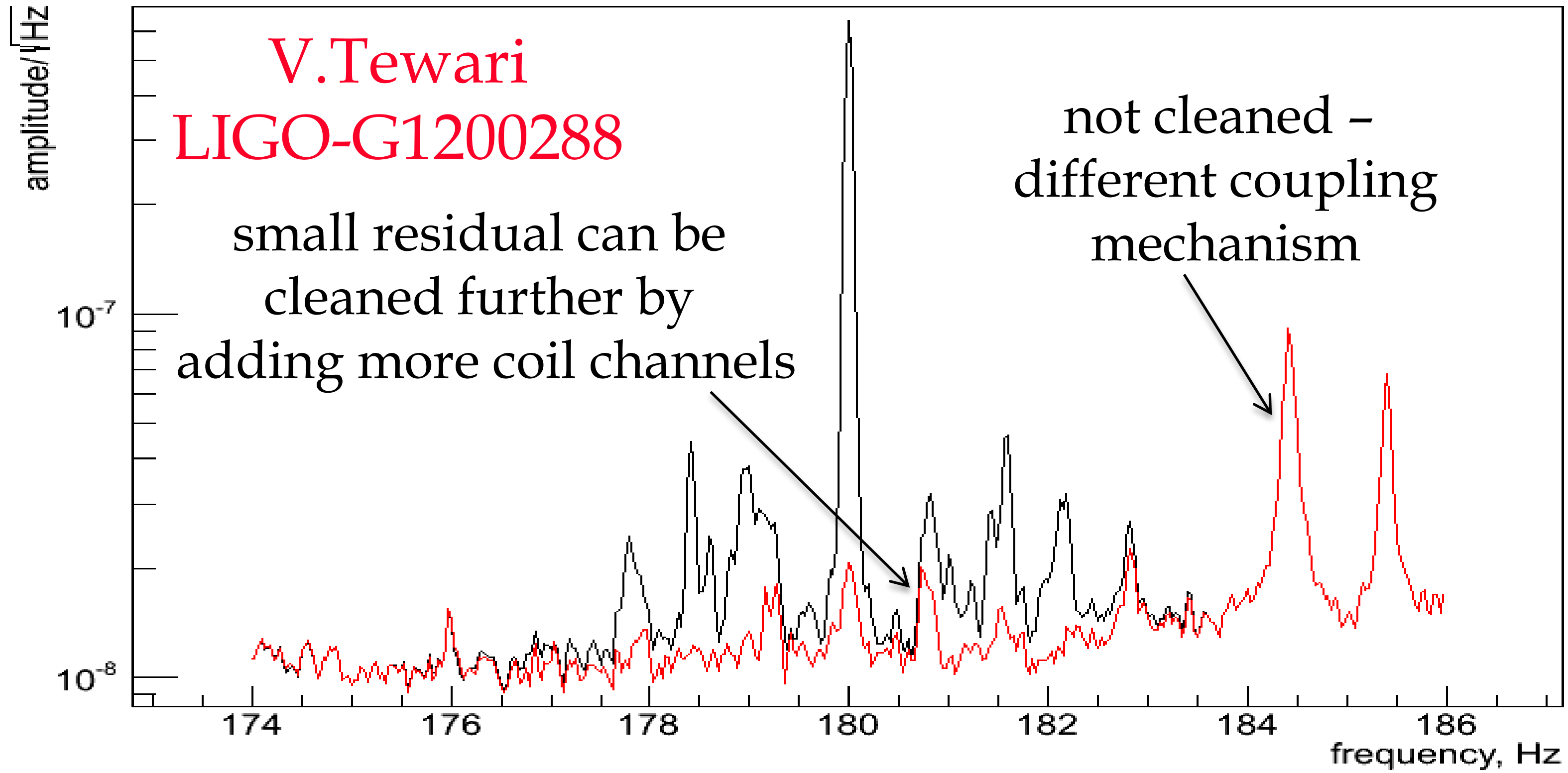


- Interaction of mirror's magnets with ambient magnetic field from power mains and low frequency coil current.
- Construct artificial witness channels

  BICO_XX_YY(t) = H0:PEM_COIL_MAGX(t) X H1:SUS-XX_COIL_YY
- ITMX, ETMX, RM, BS, MMT,...

Regression of PL bi-coherence

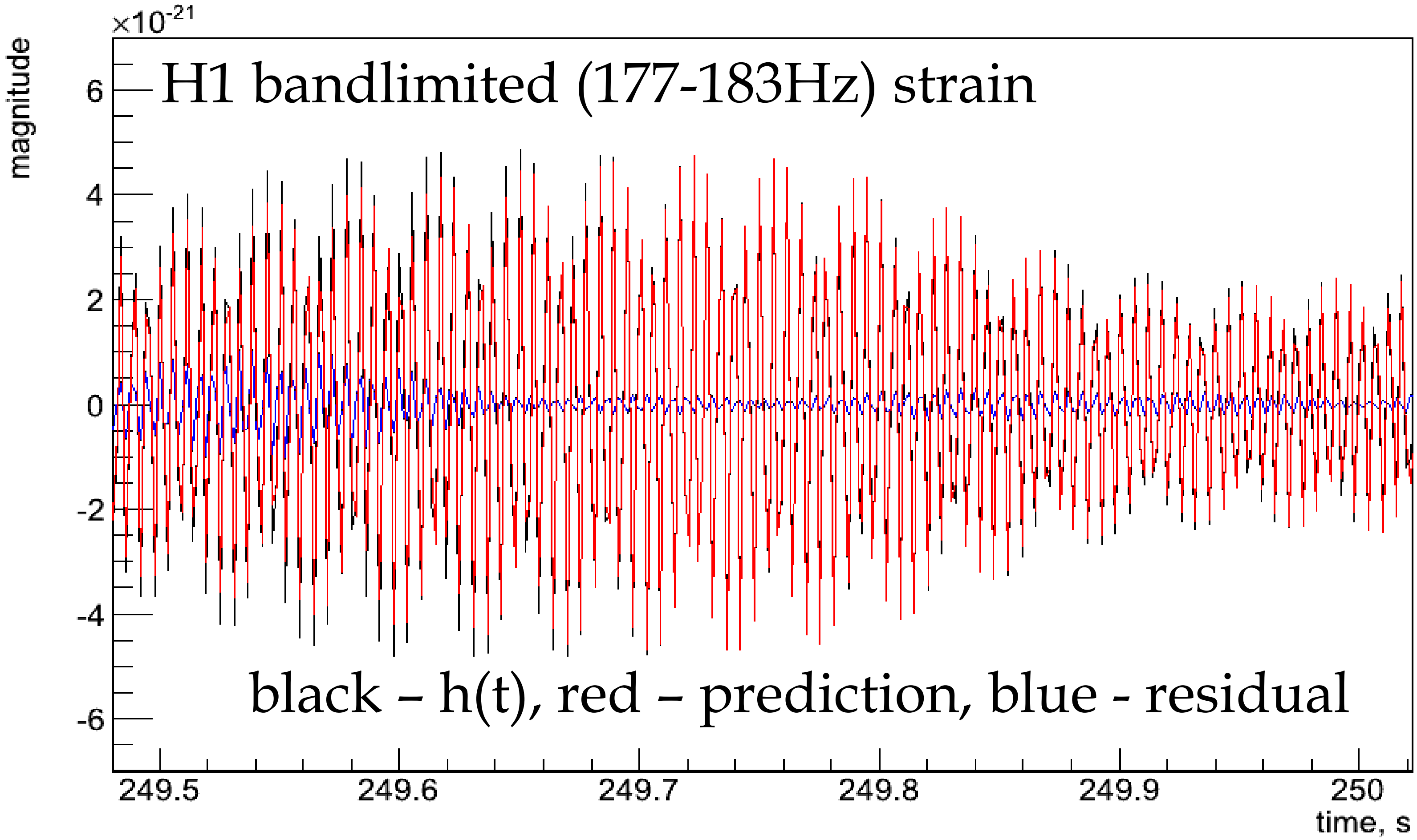
H1:DARM



- first example of up-conversion removal from LIGO data.
- Channels used:
  - H0:PEM-BSC10_MAGX magnetometer
  - 8 BICO(t) witnesses constructed from ITMX and ETMX coil channels.

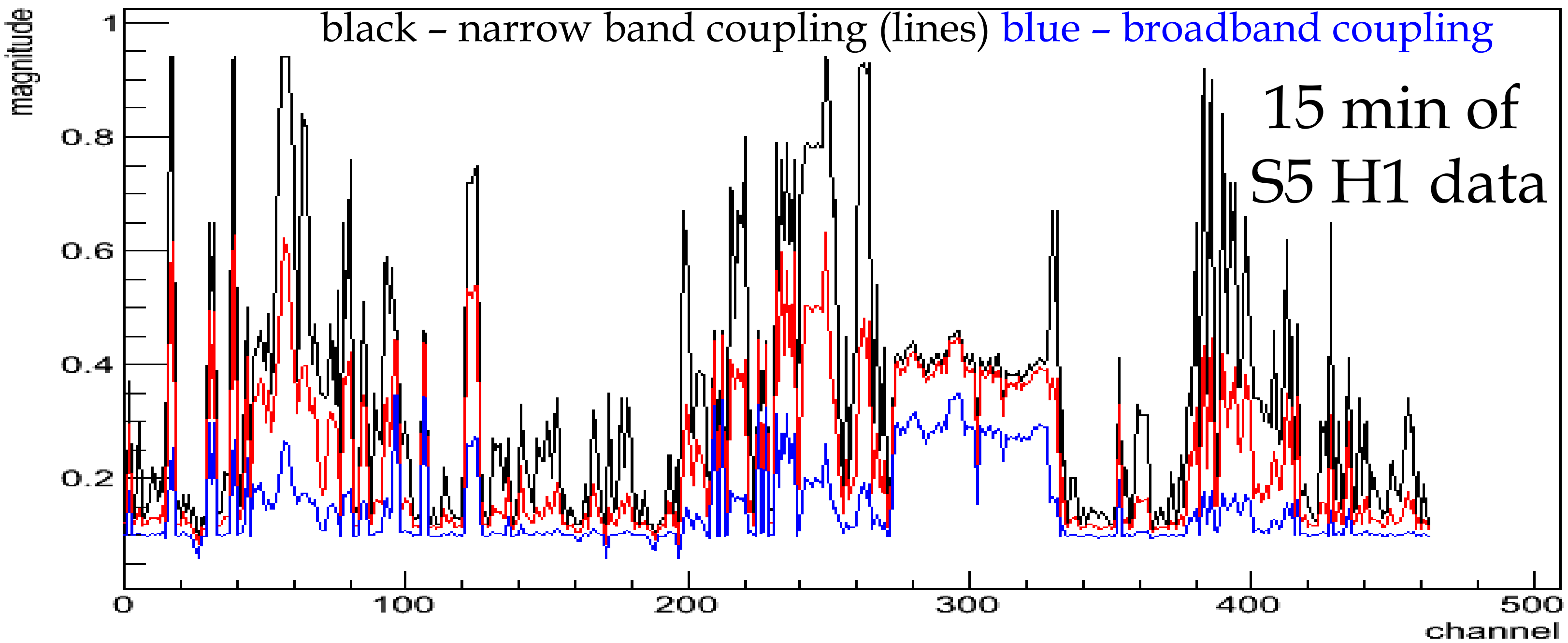
Monitoring environmental coupling

- Significance/strength of environmental coupling can be estimated from the eigenvalue analysis and directly from the prediction (in units of the target channel RMS)



Linear coupling FOM

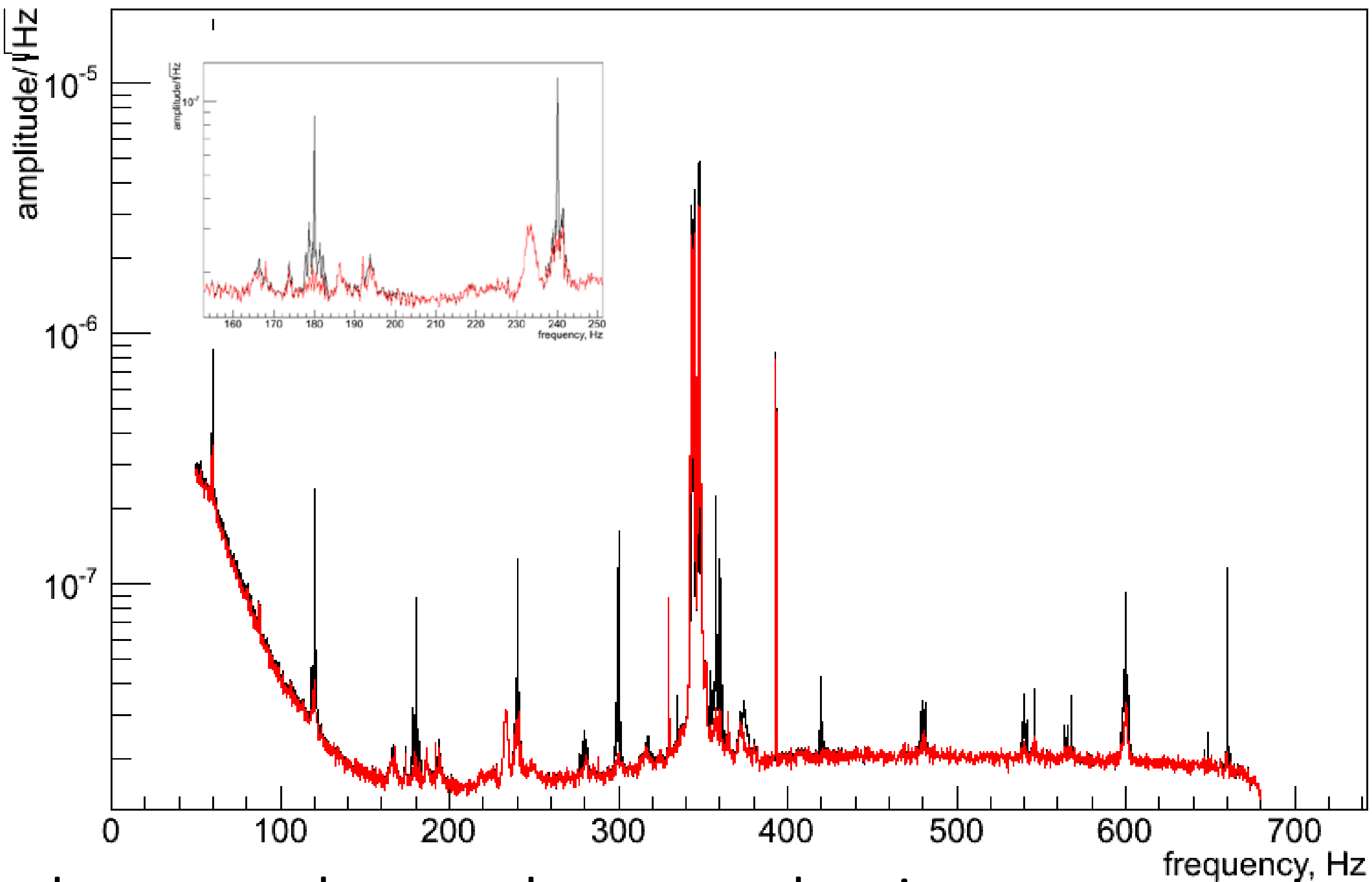
S5 coupling: 50-1024 Hz, 1Hz resolution



- **Witness channel coupling is characterized by RMS of whitened prediction to target channel.**
  - target channel is whitened (RMS=1), power lines are removed
  - black/red/blue – average over 1/10/100 loudest (max RMS) bins
  - coupling is insignificant if RMS<0.5
  - similar FOMS can be produced for different frequency resolutions

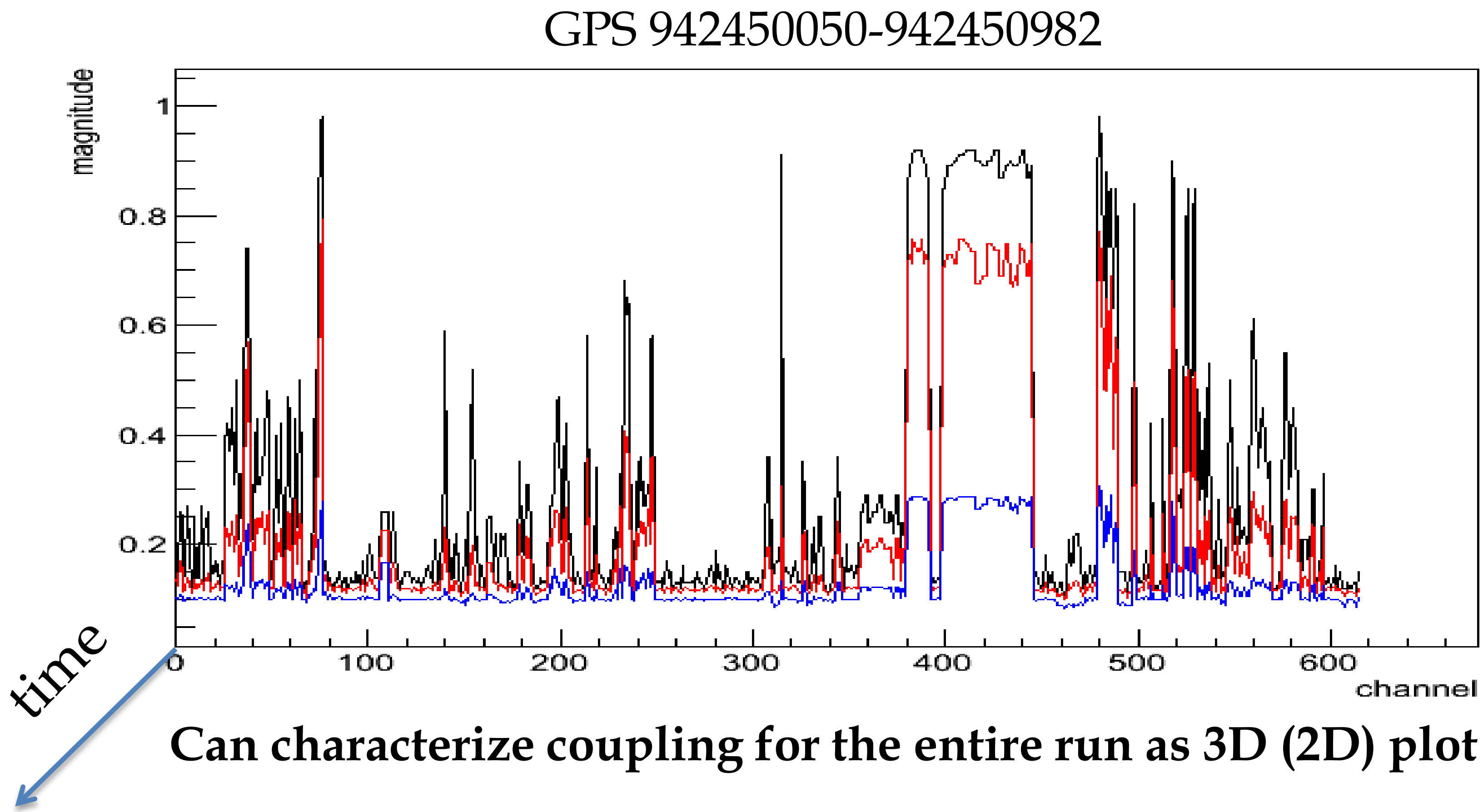
Regression of S5 data

construct 1024 filters for 0-1024Hz band



- Good progress, but need more work to improve regression.
- No obvious correlation of remaining artifacts with aux. channels
  - could be a result of a more complicated non-linear coupling

S6 H1 coupling: 50-1024 Hz

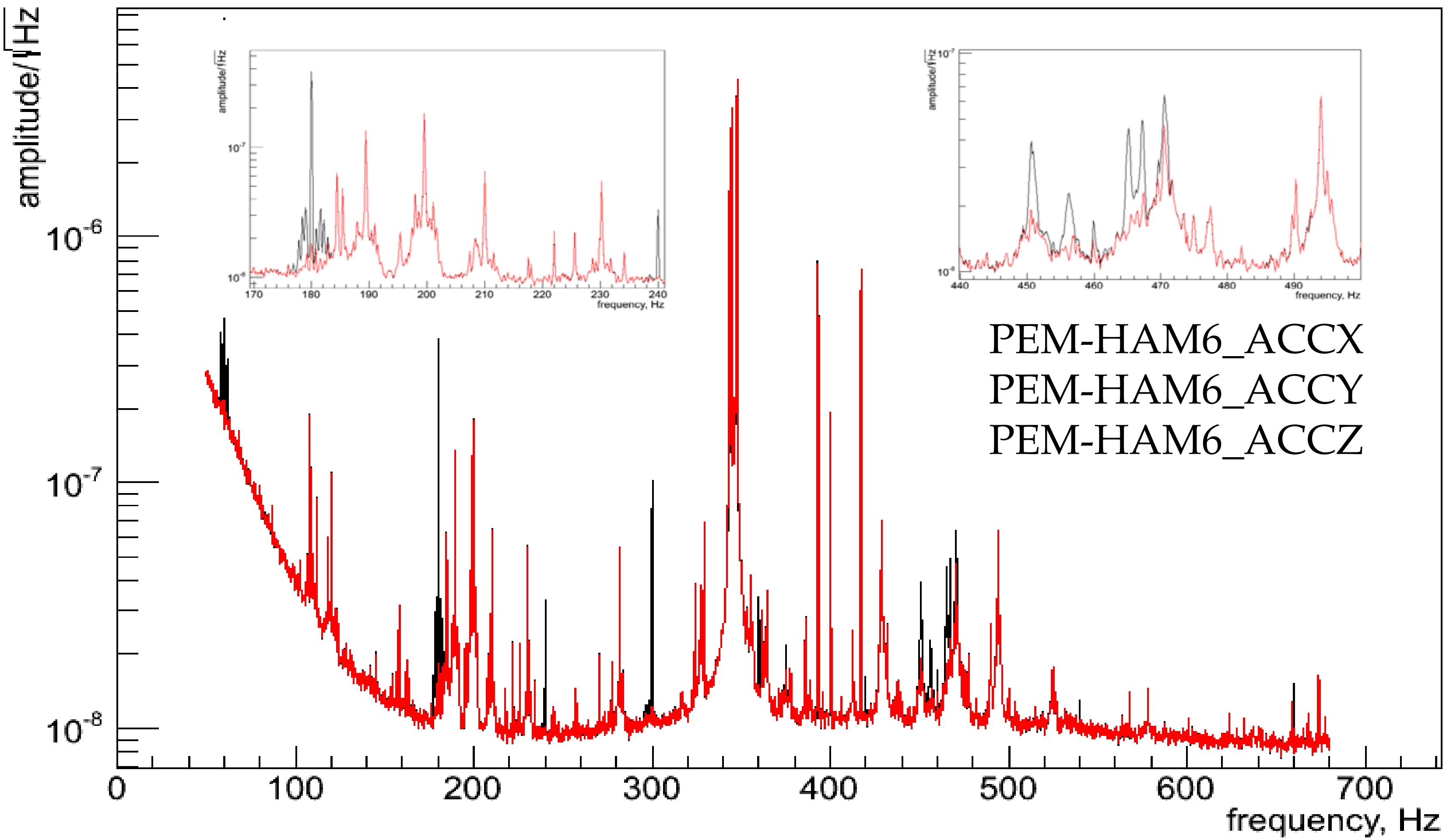


Can characterize coupling for the entire run as 3D (2D) plot

- Despite a large number of environmental monitors, just few show measurable linear coupling with h(t)

Regression of S6 data

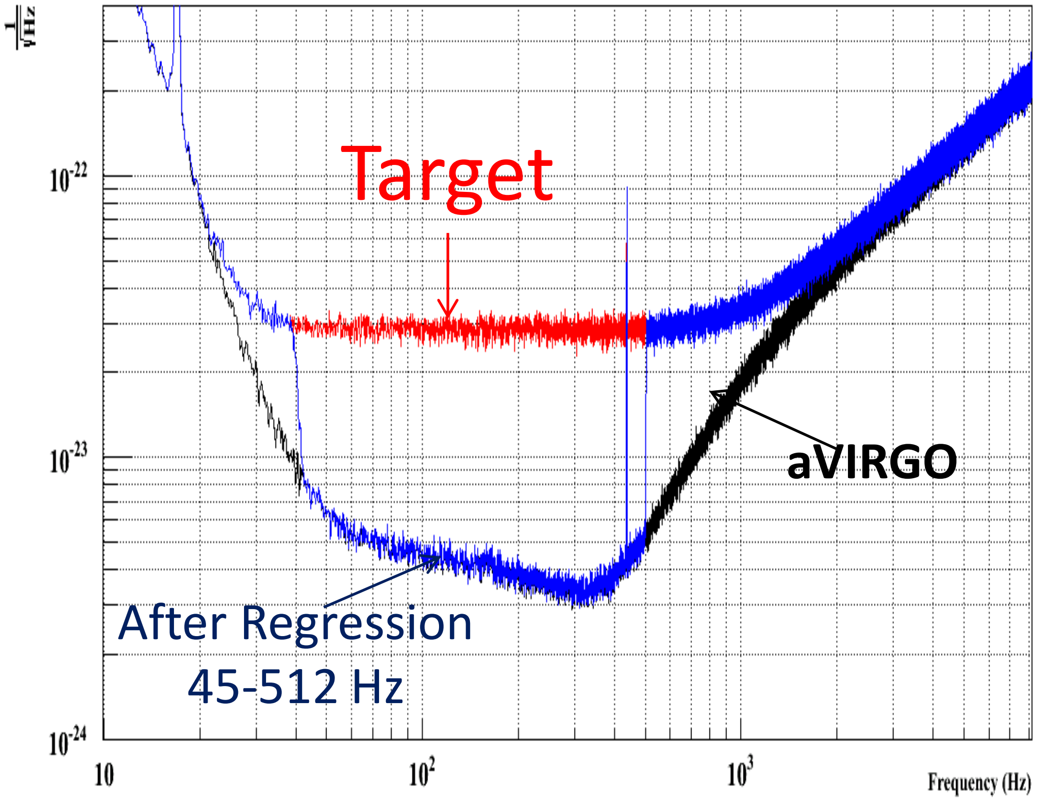
- **S6 has more artifacts, with no obvious association with environment**

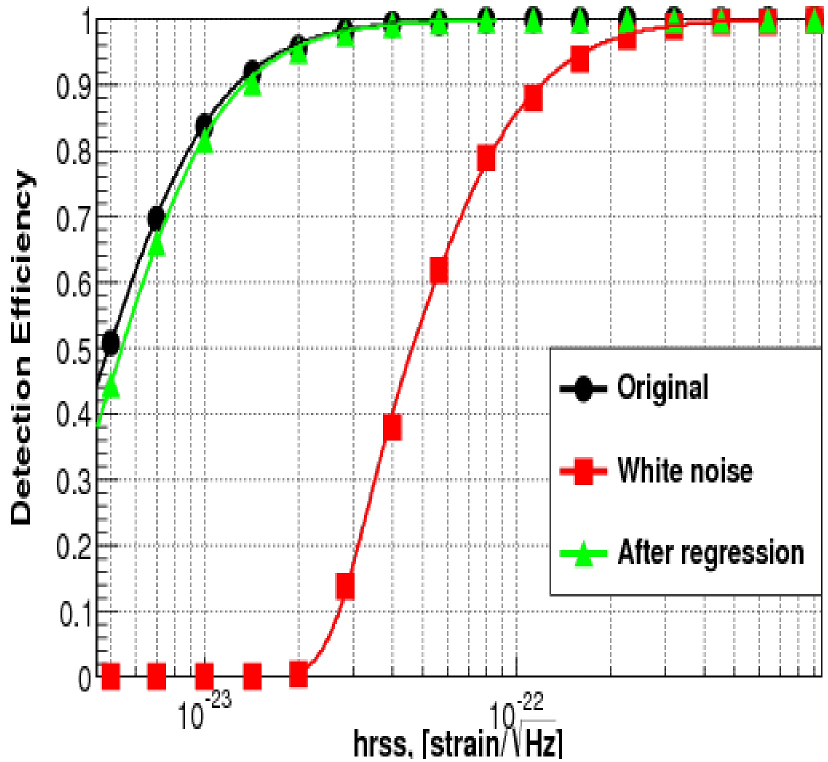


- Environmental noise varies a lot depending on the detector and run configurations.

Simulation test (preliminary)

Network: L1H1V1
Target : aLIGO/aVIRGO noise + White Noise
Witness: White Noise @ $3x10^{-23}$
Efficiency of simulated GW events (SG235HzQ9) is fully recovered after regression





Relevance to aLIGO/aVirgo

- Dream (?): Remove almost any environmental disturbance from the IFO output.
  - We may never isolate instruments from the environment
  - Need to put an effort into the design and improvement of a set of auxiliary channels
- What could we do with the wavelet regression tool?
  - Identify a list of regression problems (already have few)
  - Test runs with S5/S6 data
  - Help systematically design a system of auxiliary channels to address specific regression problems.
  - Monitor environmental couplings starting at early stages of the commissioning.

Summary and Plans

- The wavelet regression tool is working
- Hope to address noise artifacts in 10-1000Hz
  - count on help from commissioners & DC experts
- Run regression on the entire S5/S6
  - condition S5/S6 data for re-run of burst search
  - remove 60Hz up-conversion for Crab analysis
- Work with commissioners on aLIGO applications
  - understand how to design useful auxiliary channels
  - monitoring of early aLIGO data