Evaluating Environmental Noise at LIGO

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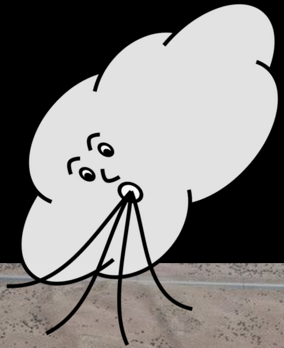
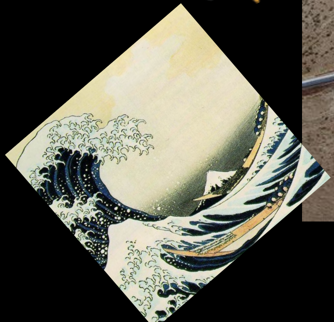
Environmental Noise

- Spacetime is stiff
  - GW amplitudes are small
- LIGO requires extreme precision
  - Extreme sensitivity to environment

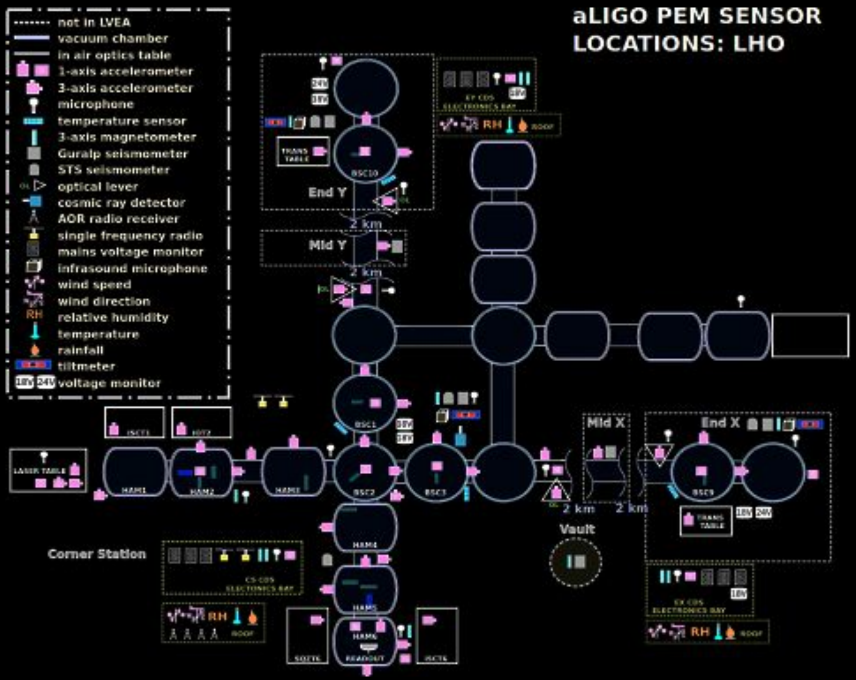




Aerial view of LIGO Hanford beset by environmental noise sources. Credit MIT/Caltech/LIGO LAB, J. Kissel.

LIGO’s PEM Sensors

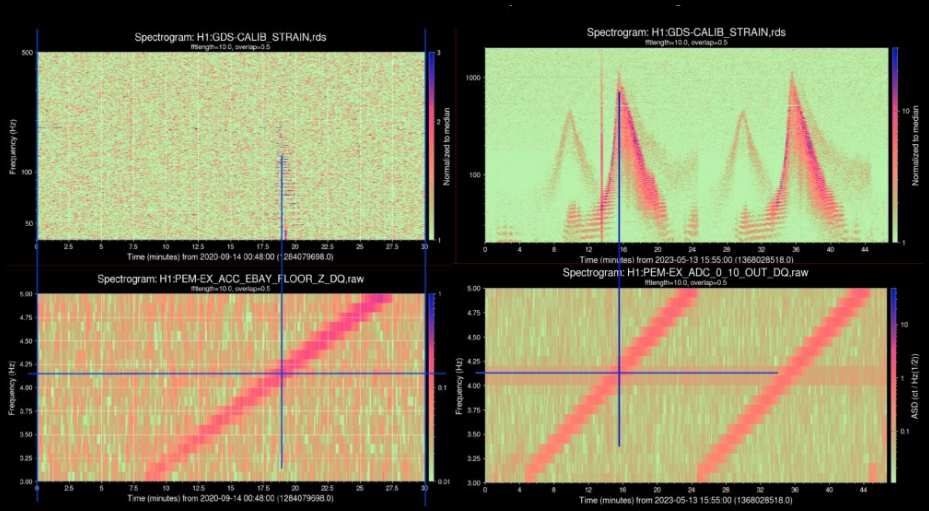
- Observe the environment around each LIGO detector with a network of physical environment monitoring (PEM) sensors
    - Magnetometers
    - Seismometers
    - Radio antennas
    - Cosmic ray detectors
    - More…



Cartoon depicting PEM sensor types and locations at LIGO Hanford. From pem.ligo.org.

Demystifying Mystery Noise

- Identify new sources of noise that we're sensitive to
- Recommend commissioning improvements



4 Hz harmonic response of GW channel (above) to EX big shaker sweeps (accelerometer witness below) in O3 (left) and ER15 (right). From alog 69758 (Schofield *et al.*).

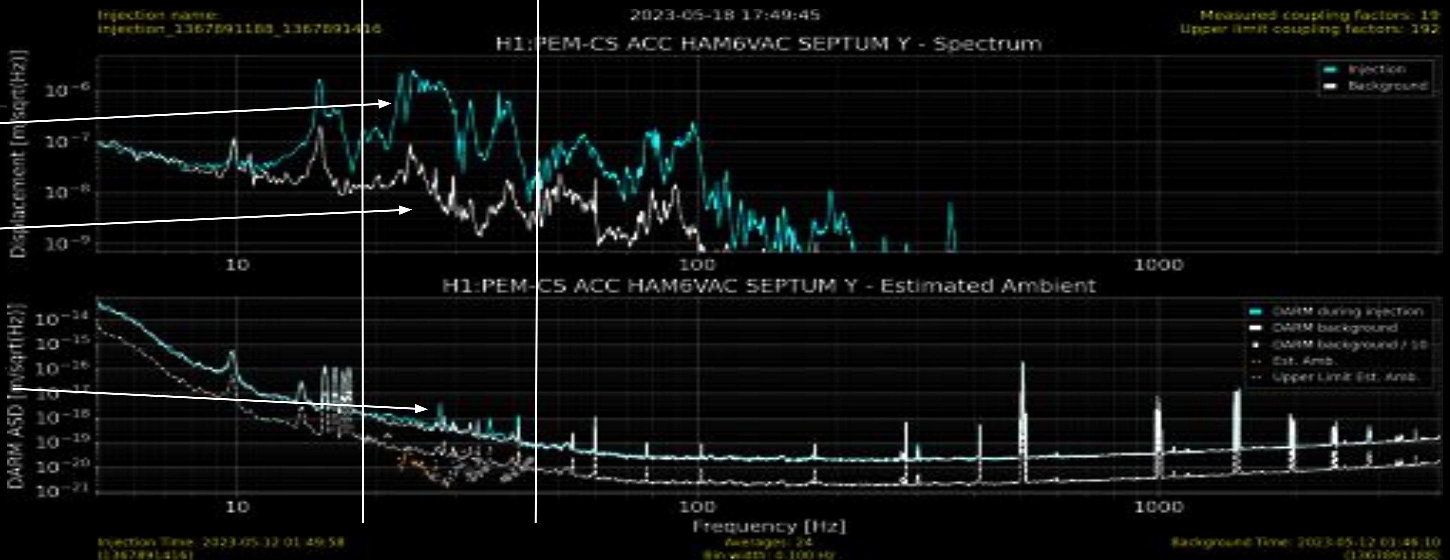
PEM Coupling Functions

- Quantify expected environmental noise in the GW data using coupling functions
- Prior to each observing run, excite the PEM sensors with injections and measure any resulting differential arm length (DARM) recorded by LIGO

Elevated signal in sensor

Reference background

Injection response in GW data



Sensor and DARM response to 20-40 Hz big shaker output optics injection.

PEM Coupling Functions

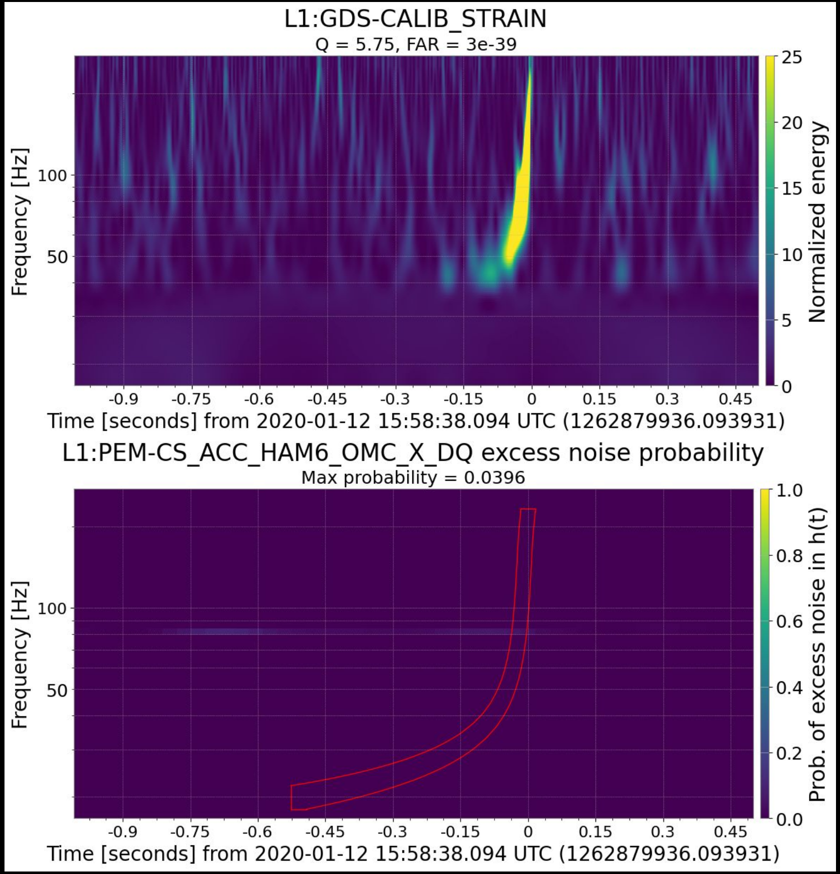
- Use composite injection data to estimate the differential arm length measured due to environmental noise per sensor count
  - Repeat for each PEM sensor at each frequency
- End result: dictionary to convert environmental effects to noise in GW strain measurement

PEM and Event Validation

- For each GW candidate, determine whether environmental noise contaminates the GW signal
  - Do not expect environmental noise to *cause* a detection
- Noise contamination may impact parameter estimation, sky localization
  - Some noise/glitch subtraction tools developed for LIGO data analysis
- Goal: for each GW candidate, rapidly and automatically recommend whether and where noise mitigation is needed
  - Prior to O4, this was done by hand
    - Infeasible for number of expected O4 events

PEM and Event Validation

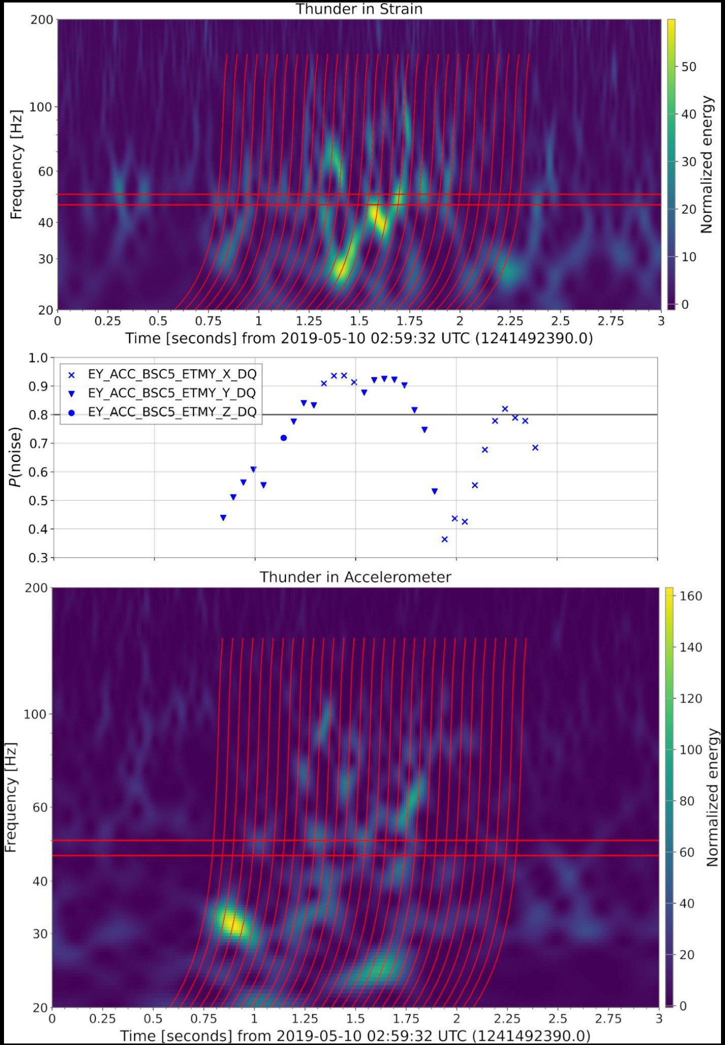
- Solution: **`pemcheck`**
- For each GW candidate:
    - Extract signal time and frequency information
    - Compute spectrograms of GW and PEM sensor data during the event
    - Project PEM data into DARM
    - For each pixel in the GW data spectrogram, compute the probability that the data in that pixel is due to projected PEM noise
    - Discard tiles that do not intersect proposed GW
    - Return the probability of environmental noise contamination as a function of time and frequency for each channel



Top: constant-Q transform of GW data from GW200112_155838.
Bottom: probability of noise contaminating data witnessed by an accelerometer for this event with predicted GW track overlaid.

PEM and Event Validation

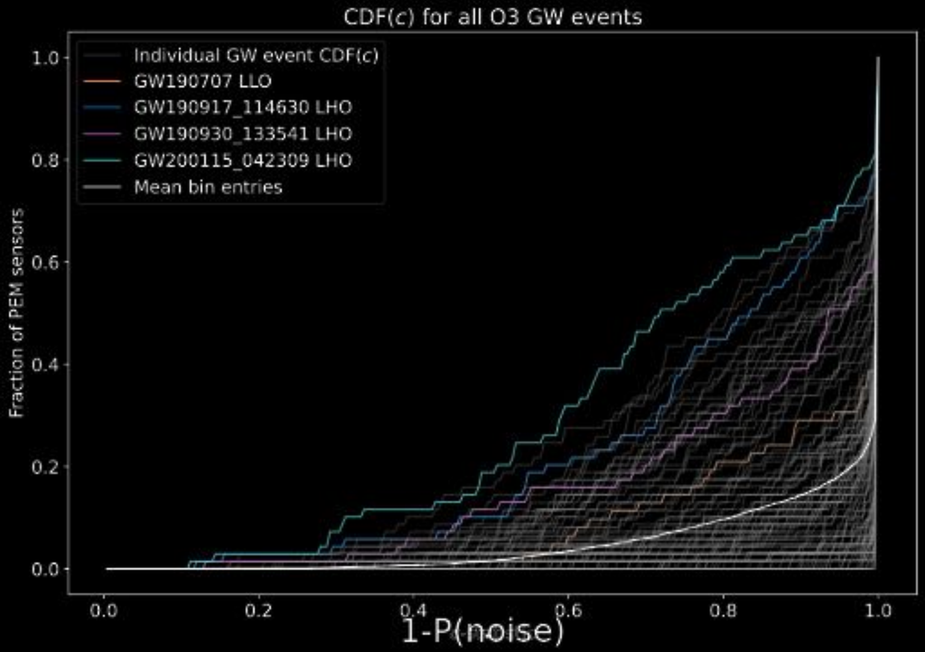
- Noise probability behavior reasonable during known instances of loud environmental disturbances



Top: constant-Q transform of LIGO Livingston GW strain during a thunderclap with simulated GW tracks overlaid. Middle: distribution of worst noise probabilities for simulated GW signals during thunder data. Bottom: constant-Q transform of thunder witness witch tracks overlaid.

PEM and Event Validation

- Apply automated method to O3 GWs
- Report highest P(noise) for each event
- No P(noise) exceeding 90%
- Look at high P(noise) events by hand
  - Some cases of coupling overestimation
  - Some cases show evidence for environmental contamination
- Evaluating just the worst cases by hand saves time



O4 Outlook

- O4 PEM injection campaign complete
  - Preliminary coupling functions released
- This calculation is run automatically for all O4 events below a 2/year false alarm rate threshold
  - 8 GW candidates (15 triggers) as of Friday afternoon…
- Produces webpage report with single-sentence recommendation for rapid response & event validation rota members
  - Minimal support for significant environmental noise
  - Substantial support for environmental noise
    - Contact PEM team for further analysis
    - Recommend times and frequencies for subtraction

Other work

- Watch arXiv for a manuscript about this soon…
- At lunch, ask me about other projects too:
    - Bursts of GWs from cosmic strings
    - Blip glitches
    - Pre-O4 coupling function injection campaign
    - Noise investigations

References

Janssens, K *et al.* 2023 *PRD* **107** 022004 (Preprint 2209.00284)

Berger, B *et al*. 2023 *ApPhL* **122** 184101

Soni, S *et al.* 2020 *CQG* **38** 025016 (Preprint 2007.14876)

Nguyen, P *et al*. 2021 *CQG* **38** 145001 (Preprint 2101.09935)

Davis, D *et al*. 2021 CQG **38** 135014 (Preprint 2101.11673)