A Time Domain Simulator for Einstein Telescope

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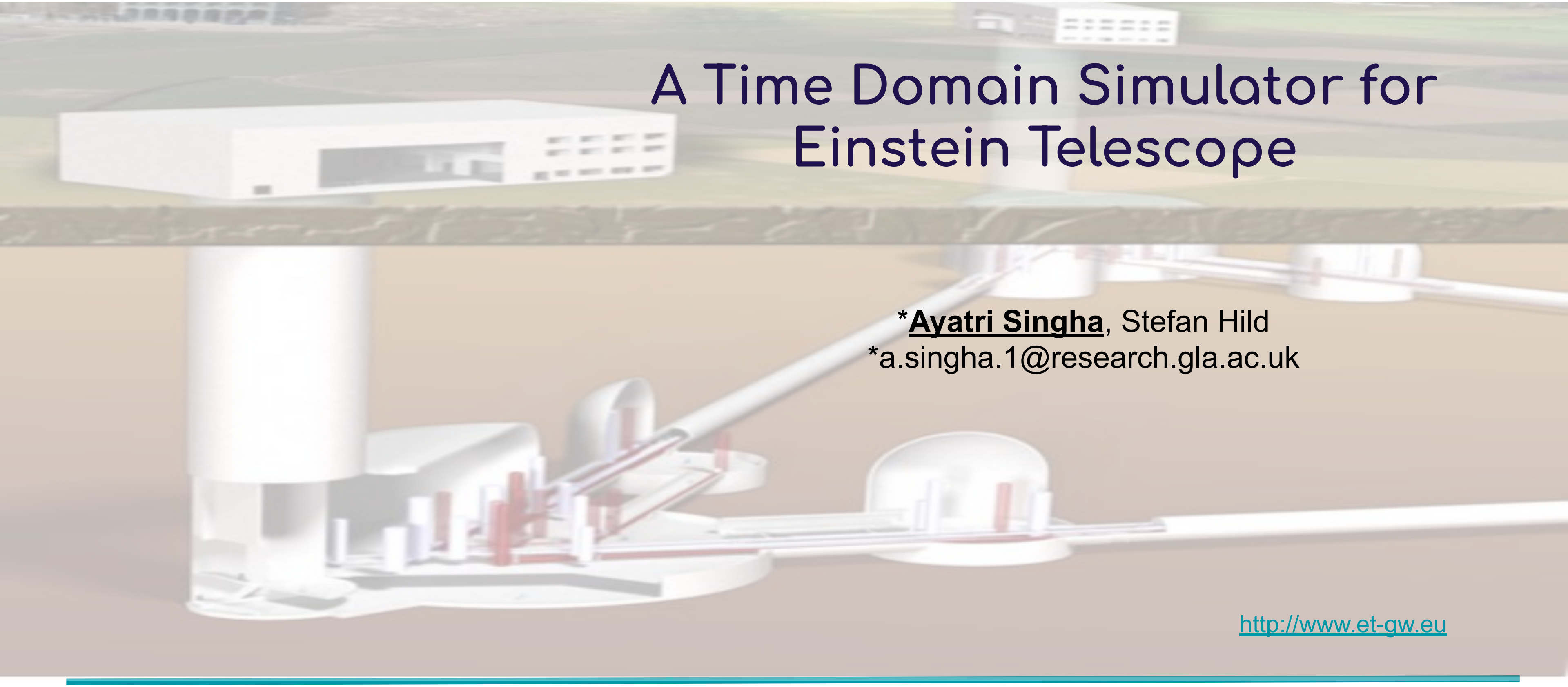
http://www.et-gw.eu



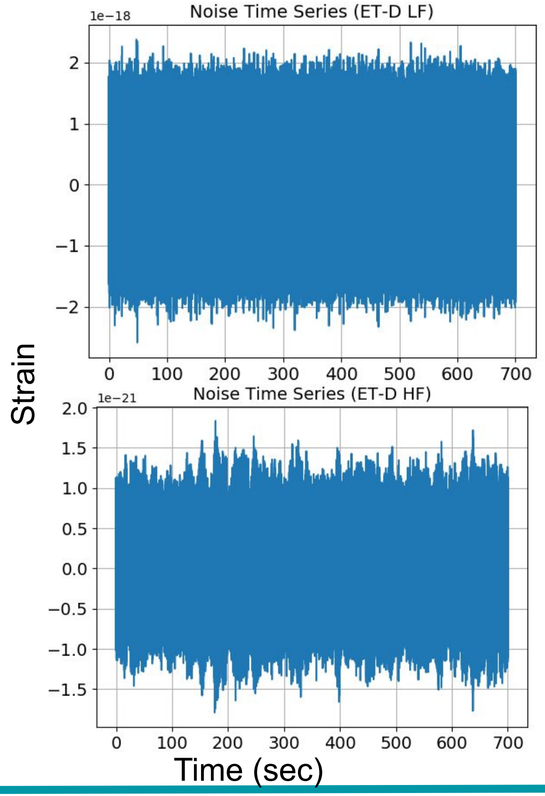
Motivation

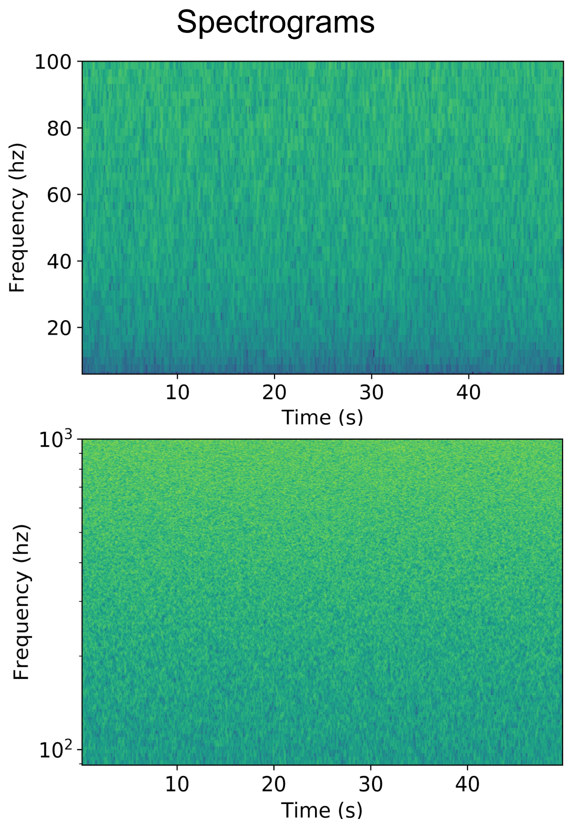
- Why to develop a time domain simulator for ET?
- Might be useful in various aspects:
  - Can test data analysis techniques (see ET Mock data challenge) …
  - Evaluate what influence have calibration errors between LF and HF?
  - How do calibration errors influence null stream?
  - Provide input some detailed design decisions, i.e. how close to put ETMs of one detector to the ITMs of another (is there any optimum in terms coherent or non-coherent Newtonian noise coupling?)
  - Any questions you have that could be answered with time domain simulator?

Contents

- Creation of coloured noise data streams
- Combining the LF and HF data streams into single data stream, i.e construction of optimal filter.
- Simulation for generating null stream.
- Effect of calibration error on null stream time.
- Future steps

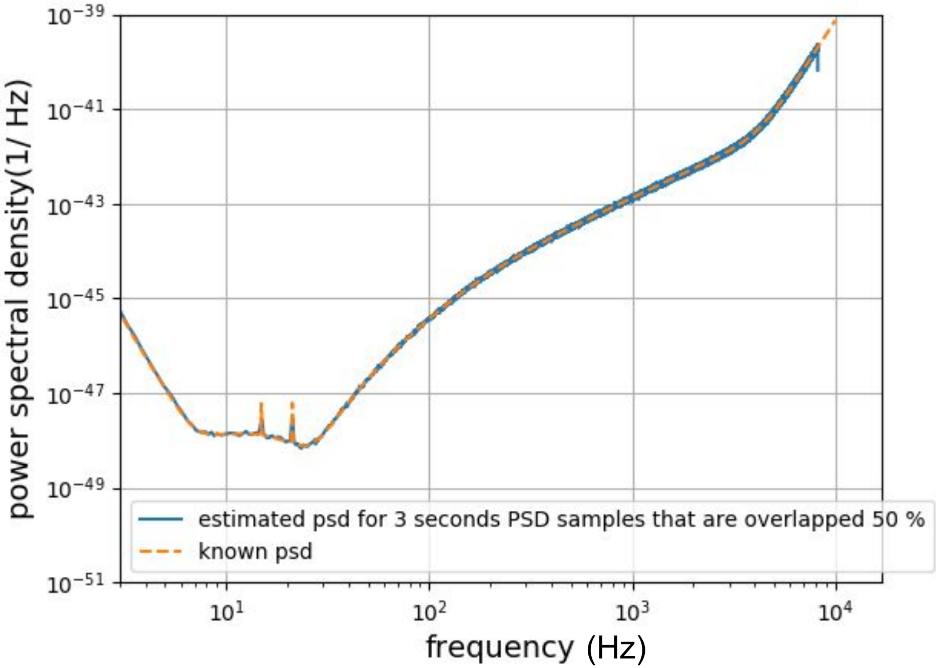
STEP 1: Colour noise generation



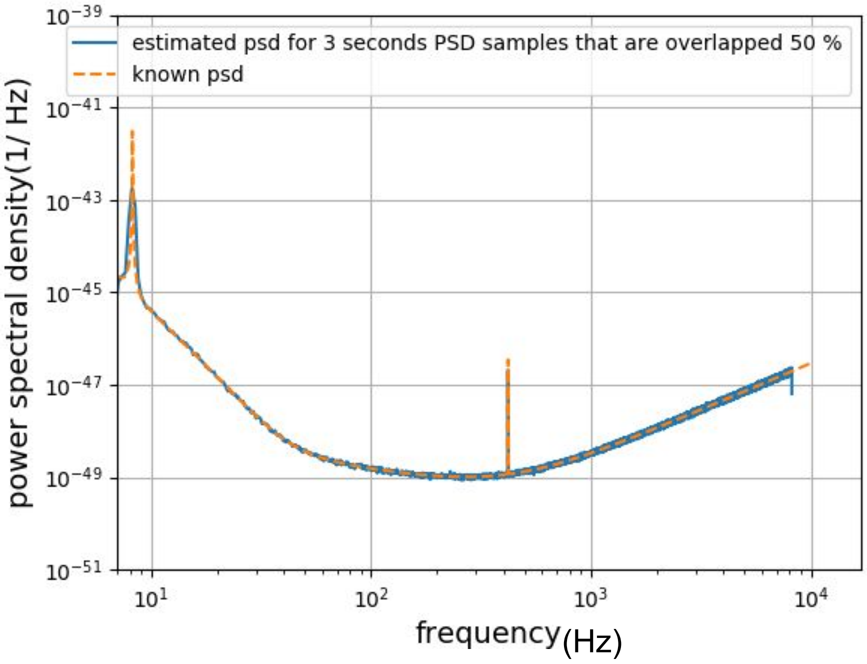


Power spectral density evaluated from generated coloured noise time series

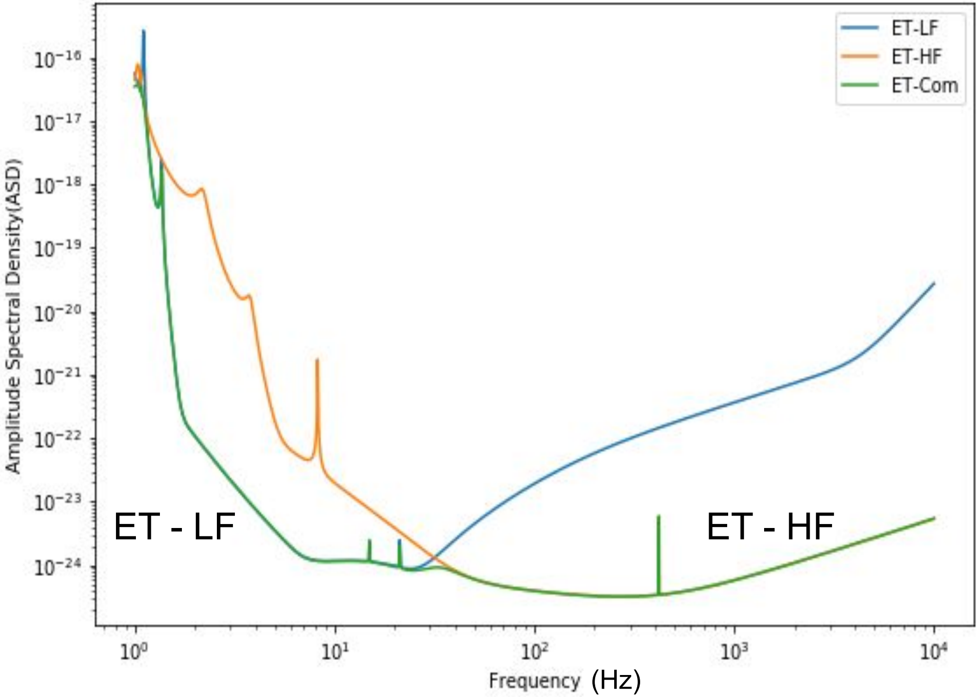
ET-LF



ET-HF



Combining data streams in frequency domain



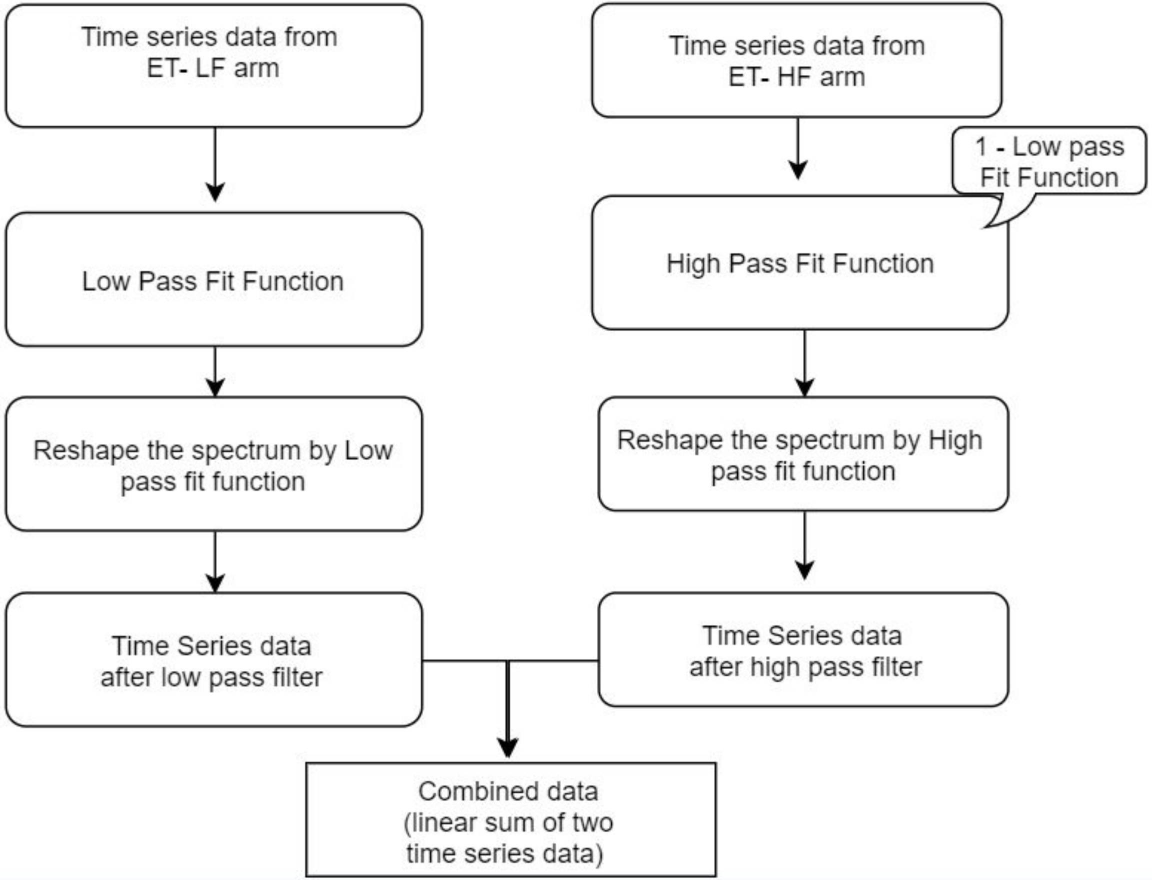
$$n_{Com}(f) = \frac{n_{LF}(f) * n_{HF}(f)}{\sqrt{n_{LF}^2(f) + n_{HF}^2(f)}}$$

- Data can be combined in frequency domain.
- The overall sensitivity will be minimised for both low and high frequency.

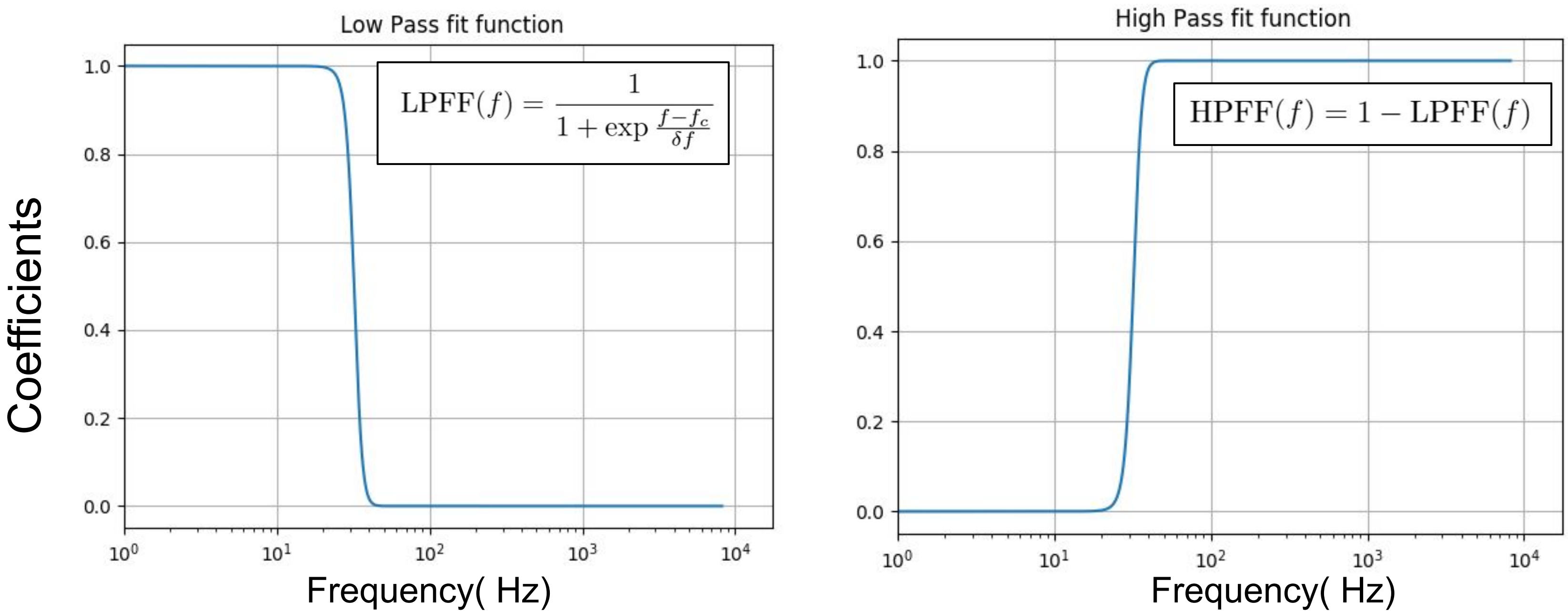
How to combine data in time series?

- It cannot be combined directly as in frequency domain.
- Need to construct filter by which one can combine the time series data linearly.
- Need to choose optimal filter.

Flow chart for combining two time series data from ET low and high frequency arm.



STEP 2: Time domain combination into a single data stream
High pass and low pass fit function

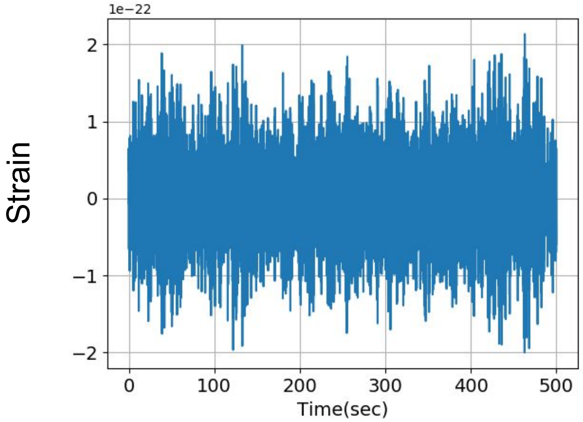


STEP 3: Reshaping the noise time series by low and high pass filter

Time series data from ET-HF and ET-LF

STEP 4: Combining two noise time series

Noise time series from ET- LF after applying low pass filter



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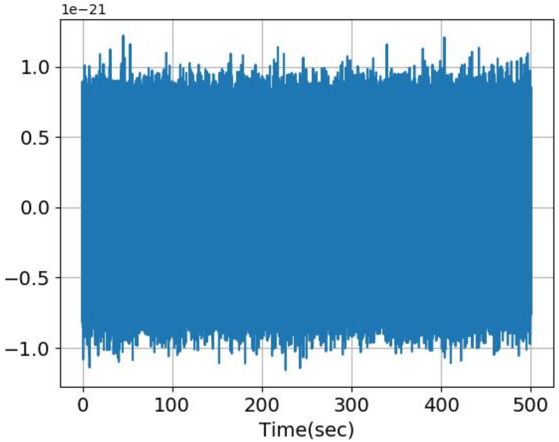
Noise time series from ET- HF after applying high pass filter



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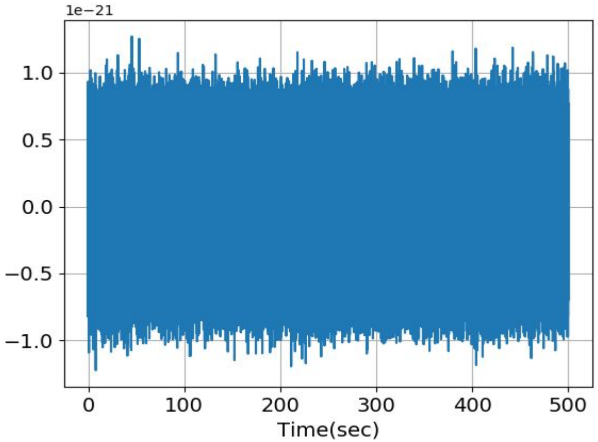
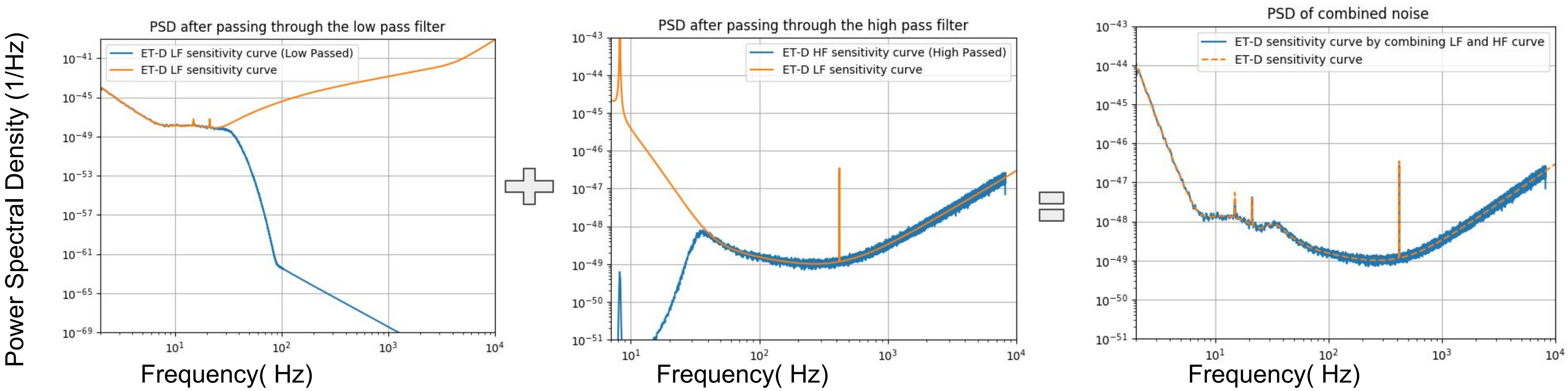
Noise time series after combining

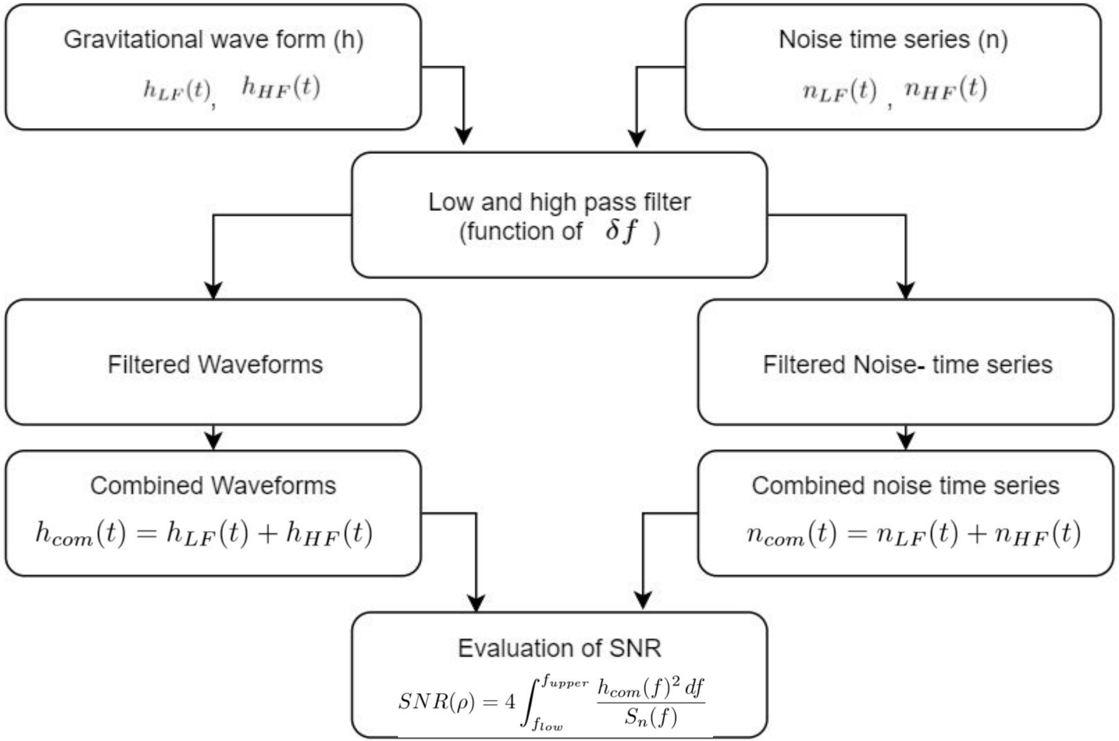


Power spectral density of time series data after passing through high and low pass filter



Power spectral density has been evaluated by Welch method (considering 7 seconds of samples with overlapping of 50%).

Flowchart to fix optimal choice for the low and high pass filter



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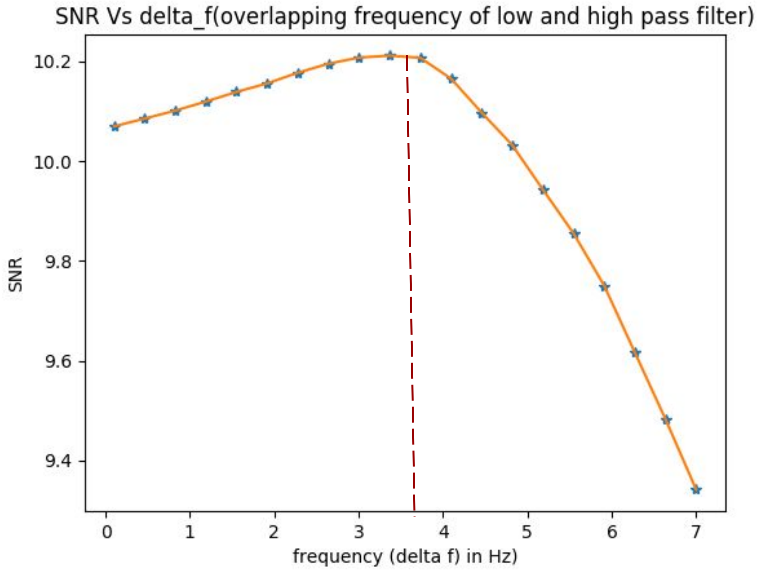
Optimal choice for the low and high pass filter



- Gravitational waveform has been generated from following parameters using TaylorF2 model-
- Mass1 = 1.4
- Mass2 = 1.4,
- distance = 5000,
- delta_f=1.0/1000,
- lower cut off frequency = 2 Hz

$$SNR(\rho) = 4 \int_{f_{low}}^{f_{upper}} \frac{h_{com}(f)^2 \, df}{S_n(f)}$$

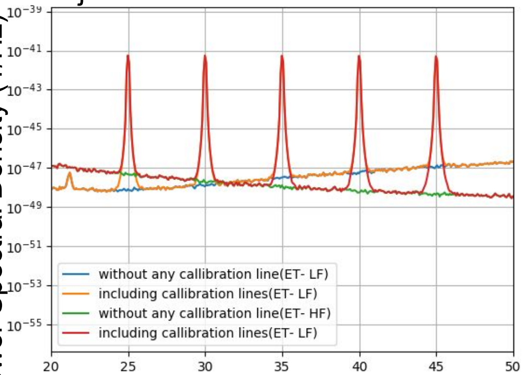
$\boldsymbol{\delta}$f = 3.6 Hz is our optimal choice for this filter

Demonstration the effect on Calibration lines for using Optimal Filters

Equi-spaced calibration lines are injected between frequency range 25 to 45 Hz

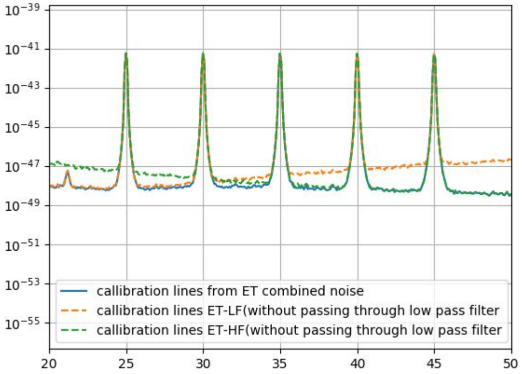
Injected Calibration lines

Power Spectral Density (1/Hz)



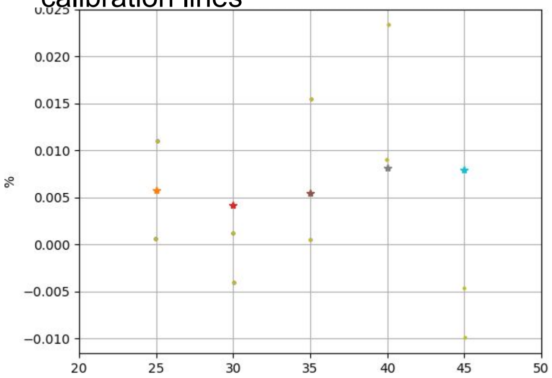
frequency (Hz)

Reconstructed Calibration lines

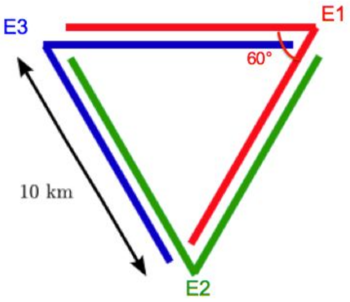


frequency (Hz)

Ratio of Reconstructed to injected calibration lines



frequency (Hz)



Null Stream Analysis

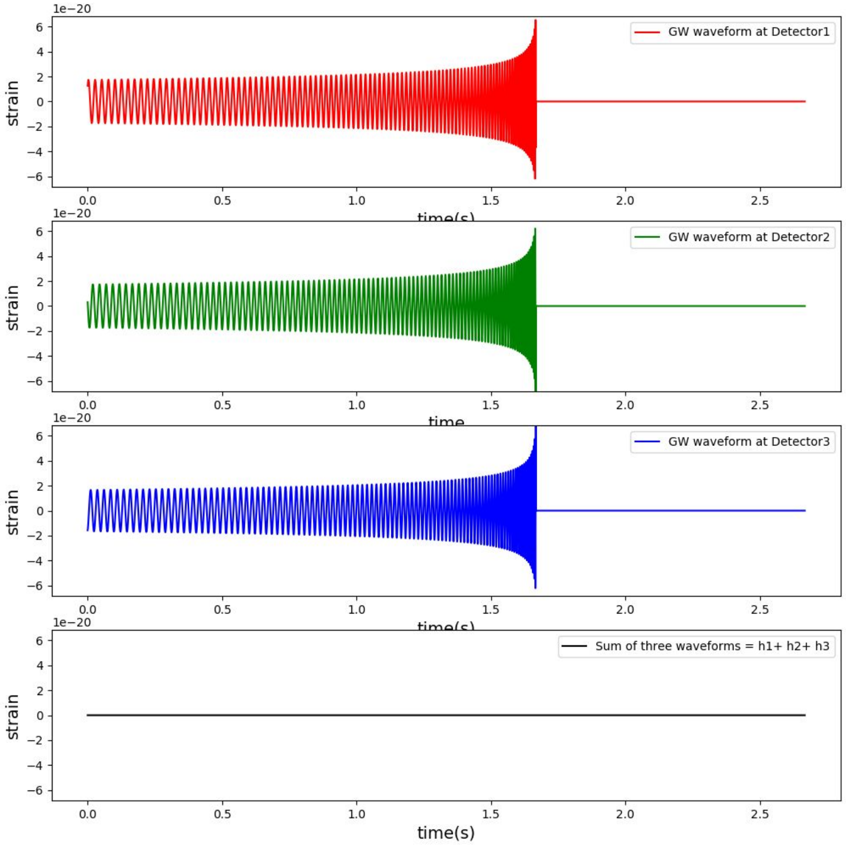
Data strain at each arm can be expressed as

$$x^A(t) = n^A(t) + d^A_{ij} h^{ij}(t)$$

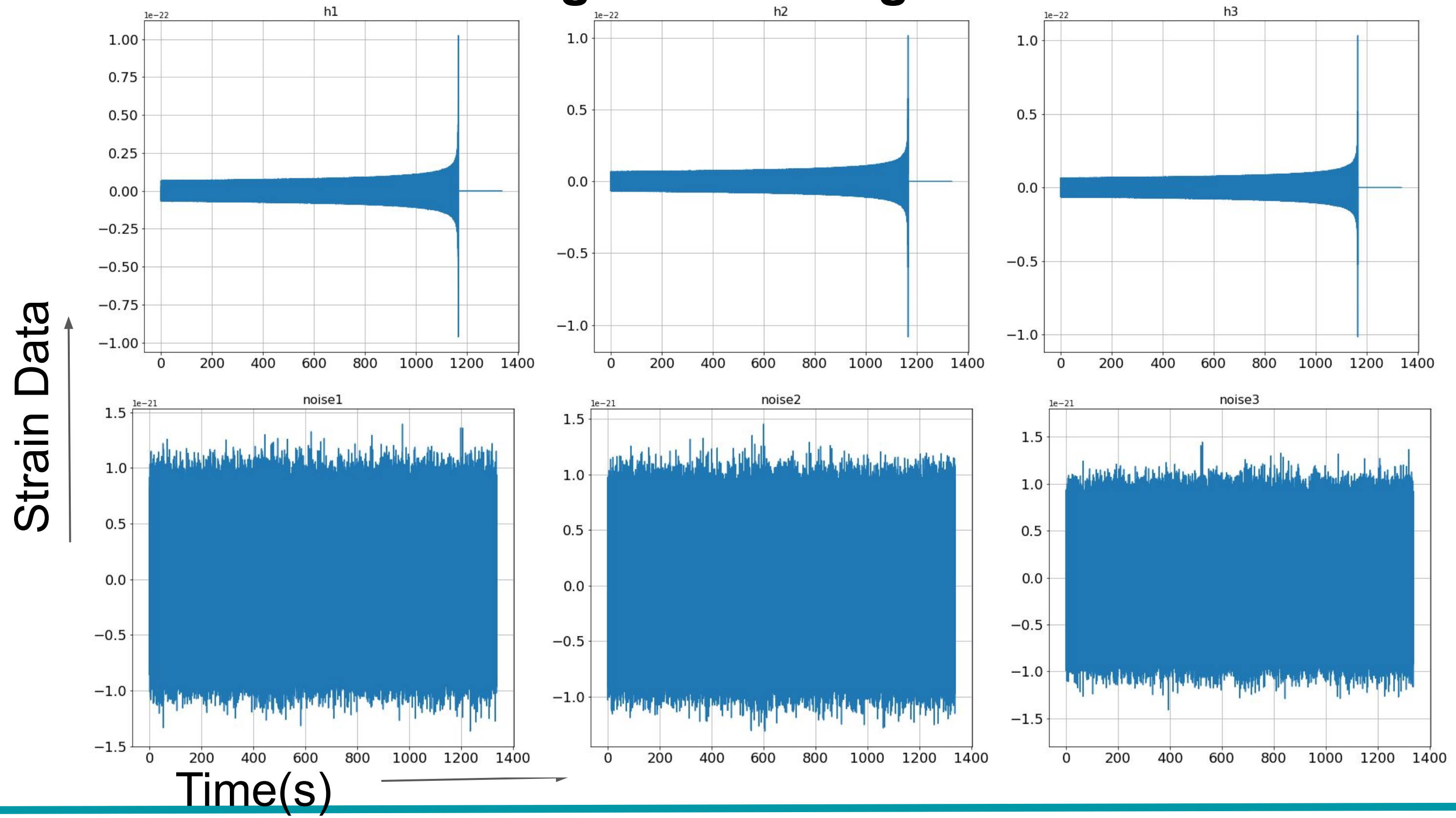
- Null stream can be written as

$$X_{null}(t) = \sum_{A=1}^{3} x^A(t) = \sum_{A=1}^{3} n^A(t) + \sum_{A=1}^{3} d^A_{ij} h^{ij}(t)$$

$$= \sum_{A=1}^{3} n^A(t)$$



Null steam using mock data generation

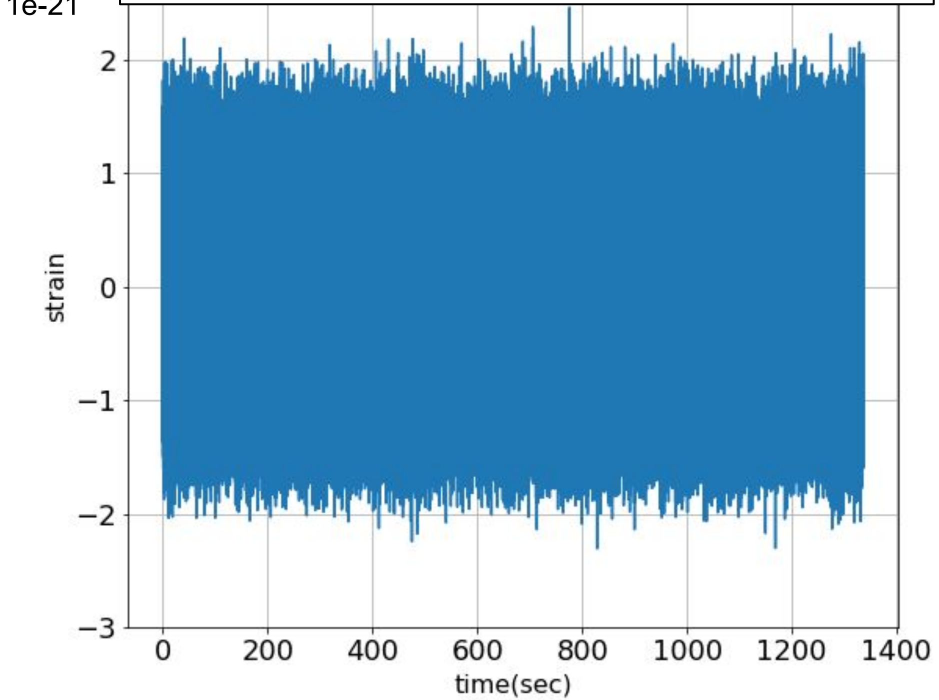


Null stream using mock data generation

Null stream = sum of all the Waveforms and noise generated for three arms of ET.

As we know , the sum of three waveforms = 0, hence we are left with pure noise.

Null Stream = Data Stream1 + Data Stream2 + Data Stream3

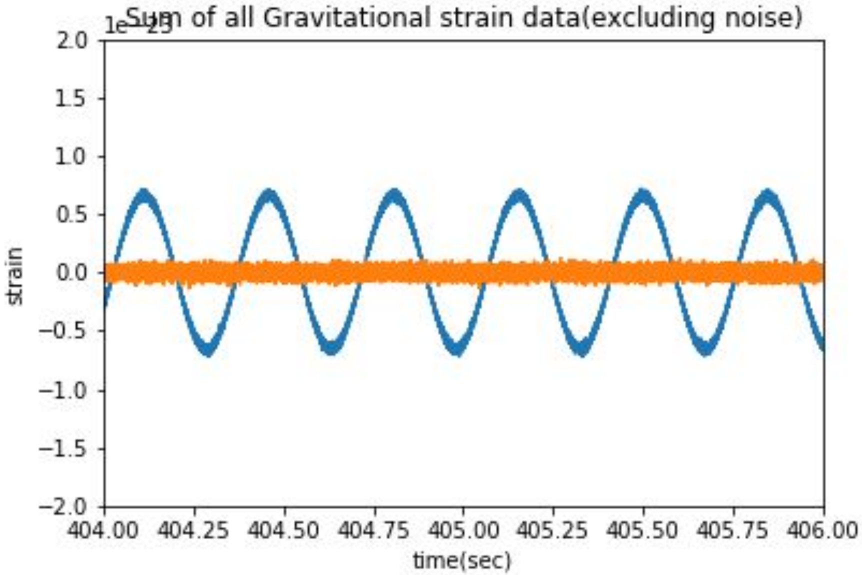


Effect of amplitude calibration error on null stream

- The fraction of signal present in null stream due to calibration error

$$\delta h(t) = NS(t) - n^1(t) + n^2(t) + n^3(t)$$

The background blue curve is representing the gravitational waveform including 4% amplitude calibration error. As a result of this calibration error we are getting orange plot, which is simply sum of the tree waveforms(ideally should be zero)

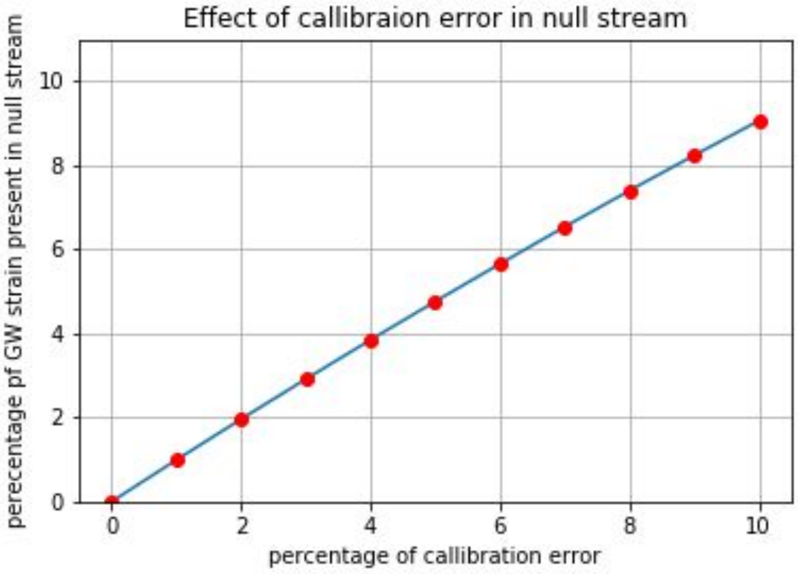


Effect of amplitude calibration error on null stream

- The average fractional energy that is being present on null stream can be computed by

$$\%(\frac{\delta h}{h}) = \frac{1}{3}(\frac{\sqrt{\sum \delta h^2(t)}}{\sqrt{\sum h_1^2(t)}} + \frac{\sqrt{\sum \delta h^2(t)}}{\sqrt{\sum h_2^2(t)}} + \frac{\sqrt{\sum \delta h^2(t)}}{\sqrt{\sum h_3^2(t)}})$$

$$\%(\frac{\delta h}{h}) \approx Calibration\ Error$$



Summary:

- Developed framework for a basic ET Time Domain simulator.
- Checked that it delivers required noise characteristics
- Developed combining filters to create a single data stream per xylophone detector.
- Showed that nullstream can only be as good as the calibration of individual detectors.

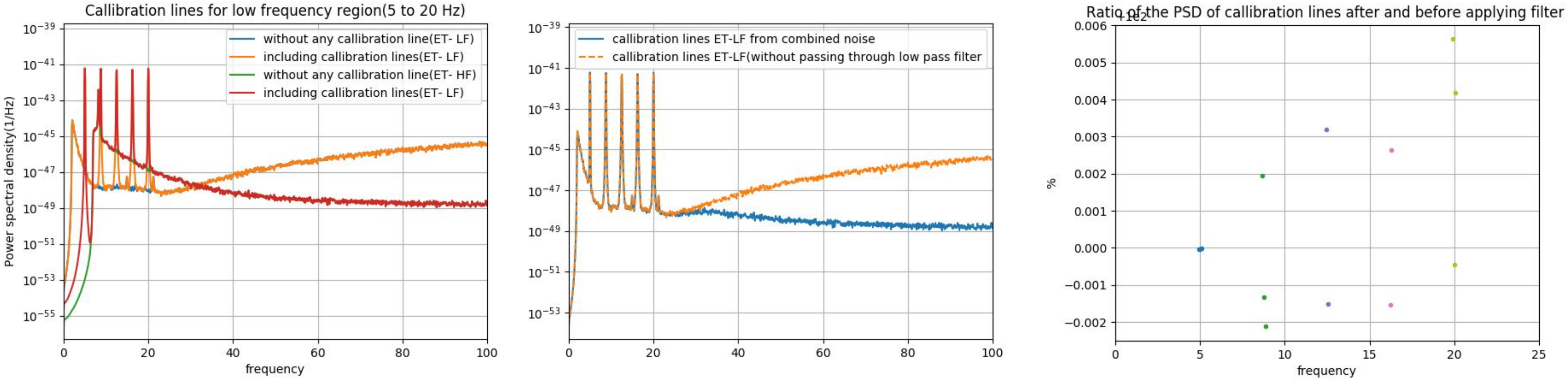
Future Steps:

- Next simulate realistic movement of all mirrors caused by newtonian noise and explore coherence and subtraction effects.
- Happy to hear any ideas **you** have for other applications or questions that could be looked into with time domain simulator.

Thank You!

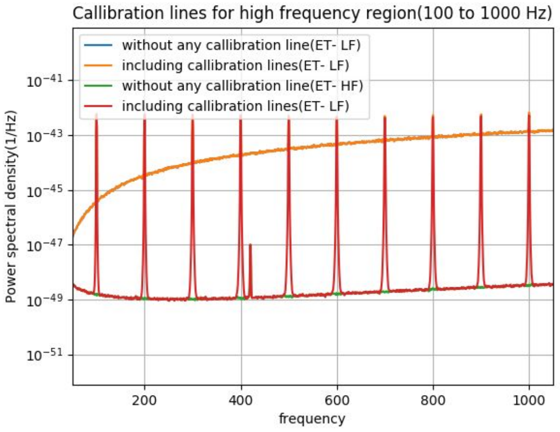
Demonstration the effect on Calibration lines for using Optimal Filters

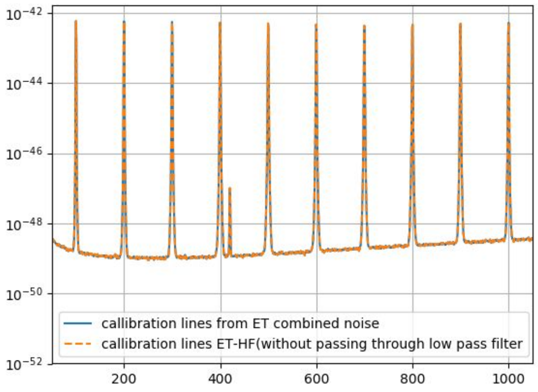
Equi-spaced calibration lines are injected between frequency range 5 to 20 Hz

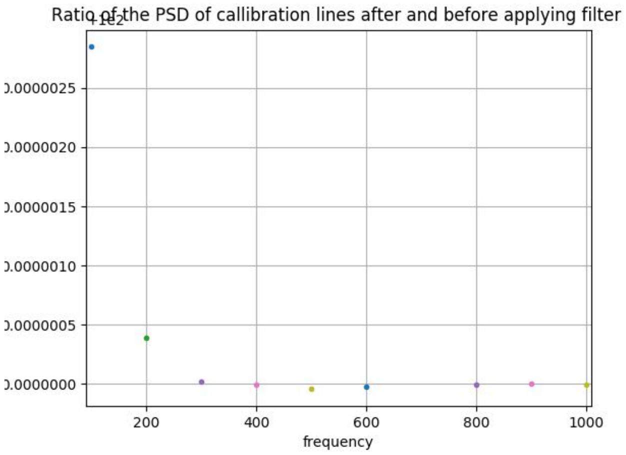


Demonstration the effect on Calibration lines for using Optimal Filters

Equi-spaced calibration lines are injected between frequency range 100 to 1000Hz

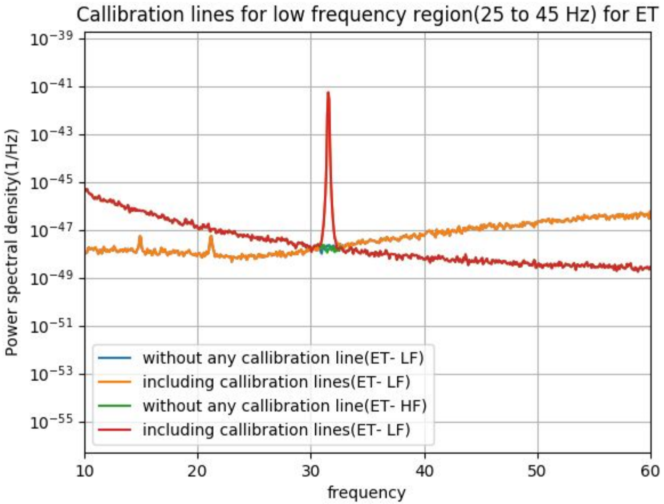


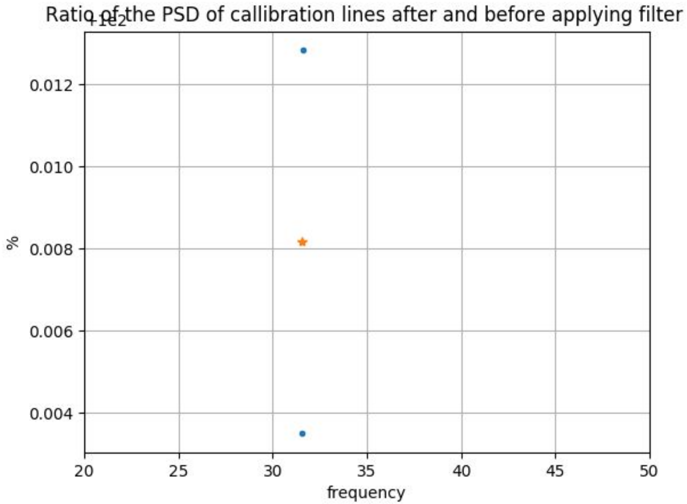




Demonstration the effect on Calibration lines for using Optimal Filters

Calibration lines are injected at 31.56 Hz





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