Removal of Power Line Noise in LIGO Data

Sumer Moudgill

BACKGROUND

- Gravitational waves are **ripples in space-time**
- They increase and decrease lengths as they travel
- They are difficult to detect from Earth due to distance and the weakness of the gravitational force
- The gravitational wave detectors that see them are the most accurate scientific instruments in the world
- Most detected events come from black hole and/or neutron star collisions
- They provide insights into stellar evolution and the structures of compact objects

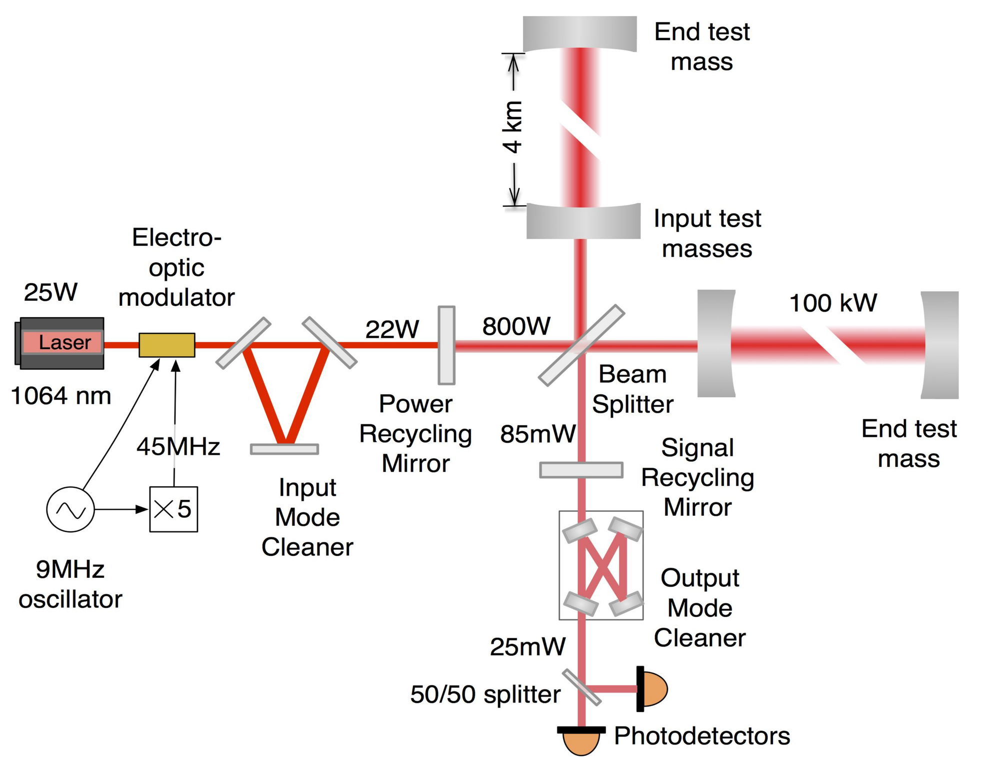


Fig 1

THE PROBLEM: LINE NOISE

- Noise is any data that interferes with signal

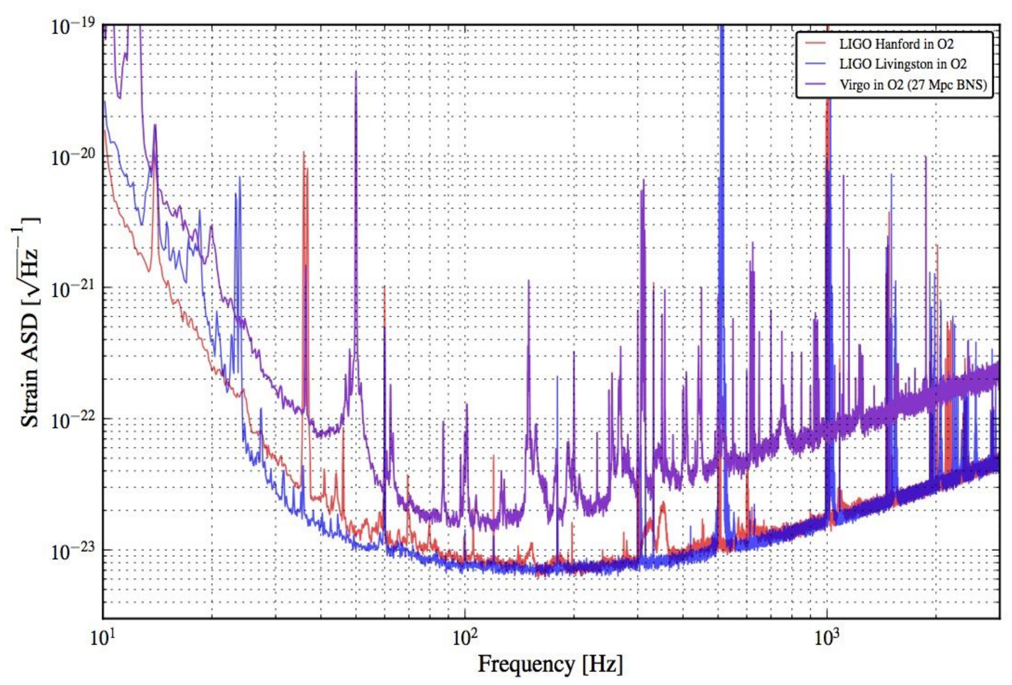


Fig 2

Two kinds of noise:

1. Broad-band noise
   a. Occurs over a range of frequencies
   b. Removed using band-pass filters
2. Line noise
   a. Caused by power lines, calibration & vibrating strings
   b. Occur over one or a small number of frequency bins
   c. Generally removed by notch filters

Problem:

Notch filters remove all data at notch frequency, including signal.
Filters can change the phases of signals.

STATEMENT OF PURPOSE

- Remove power lines noise at 60Hz, 120Hz, 180Hz without removing transient signals at those frequencies or changing phase

DATA

- The only publicly available unprocessed data is the 4096 seconds of 16kHz raw data around the first 7 events
- ~16 hours of data from the first two observational runs
- Data is preprocessed by:
  - band-pass filter at 45-300 Hz
  - notch filtering at 331 Hz to remove calibration noise leakage

THE ALGORITHM

The algorithm functions as follows :

1. Select a section of time-domain data (32 sec)
2. Zero pad the data to improve the accuracy of frequency (16x)
3. Perform FFT
4. Search frequency bins around the notch frequency for the maximum magnitude
5. Return frequency, magnitude and angle
6. Use those parameters to create a cancellation wave
7. Add the cancelation wave to the data

The algorithm has to be repeated for each notch frequency to account for frequency spread. Empirically, best results were obtained by running 5, 2, and 3 times, for the 60,120, and 180Hz lines respectively

The algorithm exploits the fact that, over short time periods, power-line noise has constant frequency/phase/magnitude

By the nature of the algorithm, it will minimally perturb data

COMPARISON METRIC

I developed the following metric for measuring excess noise in power lines :

1. Compute the ASD of the input data
2. For power line frequency *f*, sum up the bins corresponding to *f*±0.5 Hz and compute the *near* average per bin, nav
3. Sum up the bins corresponding to *f*±11.5 Hz, excluding bins *f*±1.5 Hz bins, and compute *adjacent* average per bin, aav
4. The comparison metric is M_f=(nav/aav)-1

If all power line noise were removed, M would be 0. A negative value for M means that the algorithm is removing more than just power line noise

RESULTS

- 2 samples of representative O2 data, taken from the region of the event GW170817
- Default filters, padding and cancellation were used
- Blue is ASD before application of my algorithm, and orange is after
- Left is H1 and right is L1
- The M_{60} for H1 is 0.78 and the M_{60} for L1 is 0.42.

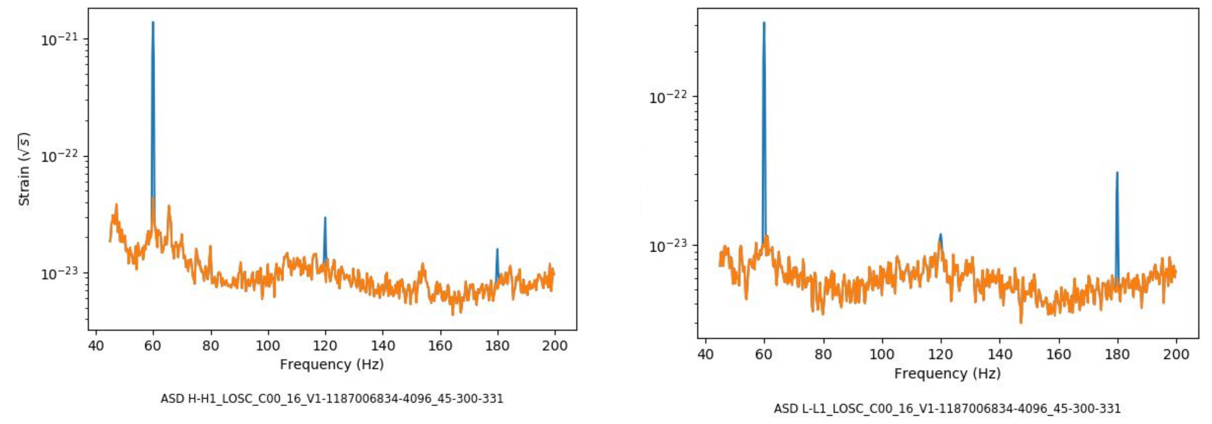


Fig 3

Note that broadband noise was essentially unaffected.

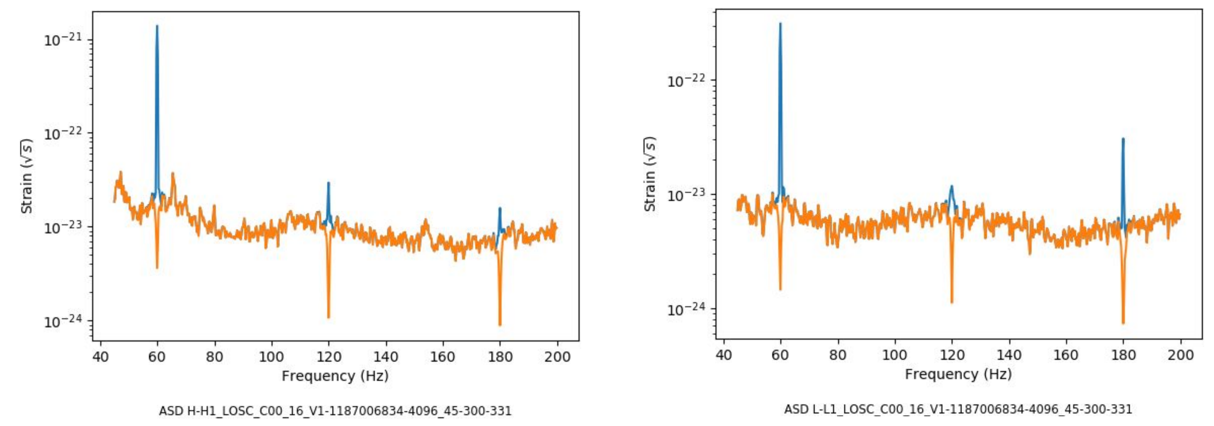
NOTCH FILTER

In order to compare it to gwpy's notch filter, I reverse-engineered gwpy's notch filter

- 6th order IIR elliptic filter
- Pass-band *f*±1 Hz, with a maximum attenuation of 1dB
- Stop-band *f*±0.1 Hz, with a minimum attenuation of 10dB

The results below are the ASDs before and after using this filter at 60Hz, 120Hz and 180Hz

Fig 4



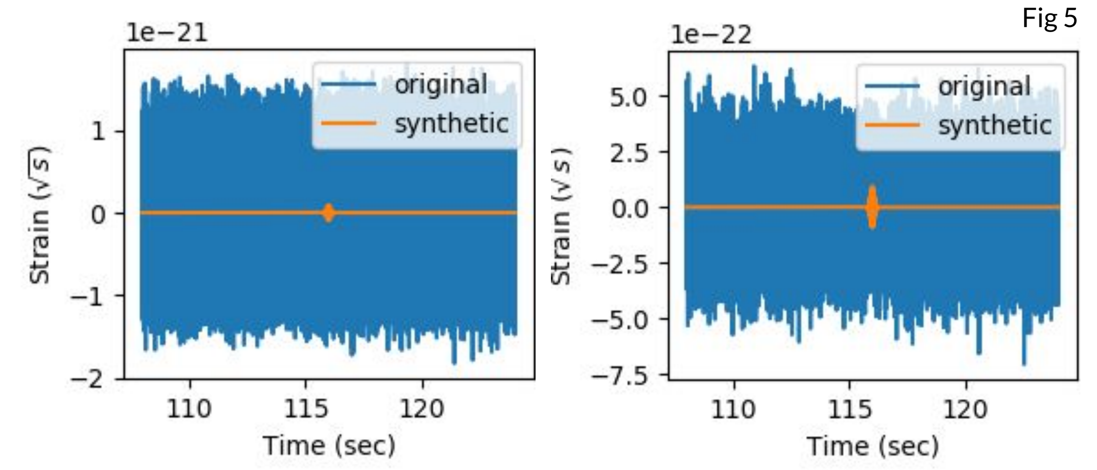
As you can see, the GWPY notch filter overcorrected, and removed more than just the line noise

The M_{60} for H1 is ~-0.8 and the M_{60} for L1 is ~-0.75

EVENT FILTERING

- Add low-power 60Hz sine-gaussian signal to simulate event

Fig 5



- Test by convolving test signal with data
- Blue is correlation with uncancelled data; orange is correlation with data after my algorithm was applied
- After cancellation (orange), slight peak at correct location; stronger than any in H1 data (top left)
- Much more prominent peak in L1 data (top right)

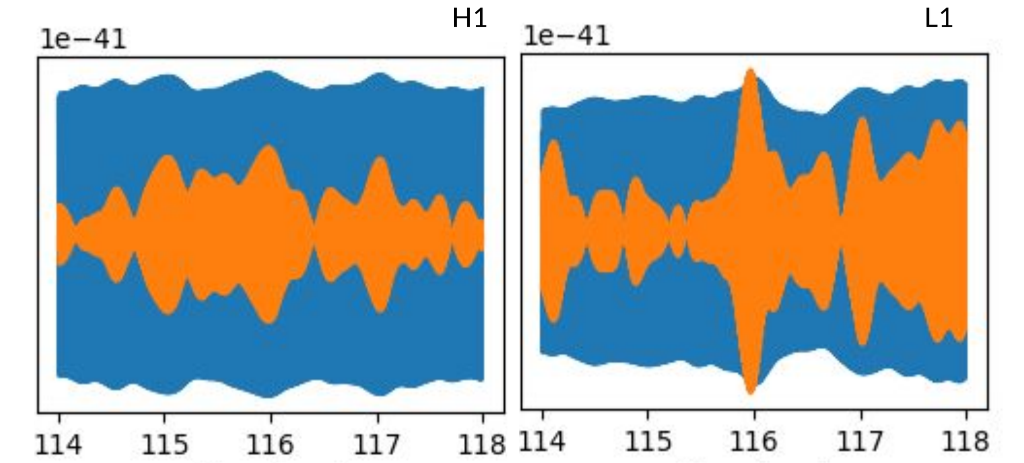


Fig 6

- In the graph below, green is after cancellation with notch filter.
- Correct peaks are more prominent after applying my algorithm than after applying gwpy's notch filter.

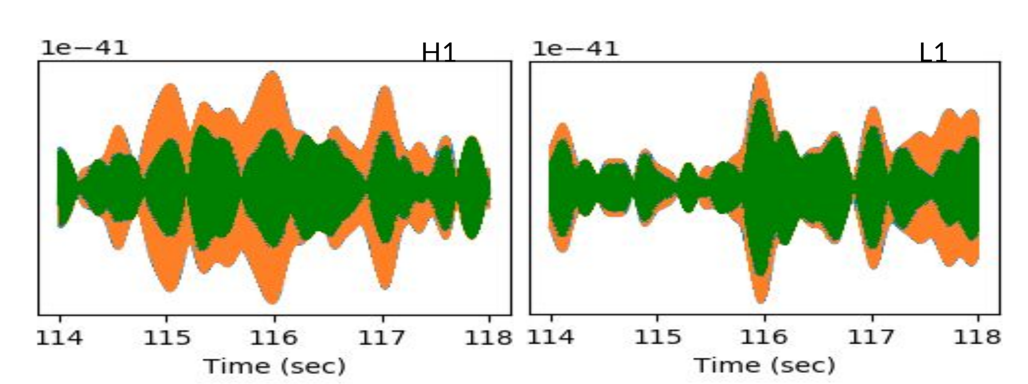
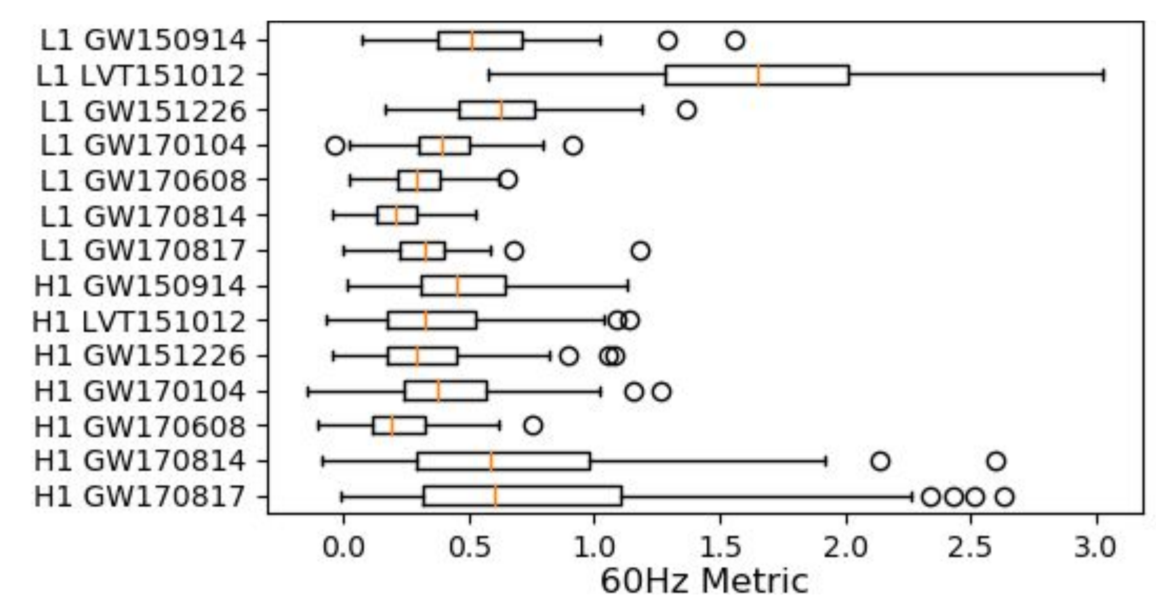


Fig 7

RUNS SUMMARY

- Box and whisker plots for entire data set - 126 32-second sections for each of the 7 events from both detectors
- 60Hz Line noise was mostly reduced to ~ 0.5x background noise
- Since uncancelled power line noise is ~100x background noise, this is a significant reduction
- Most third quartiles are smaller than background noise
- Worst performing data sets never exceeded 3x background noise
- One outlier (L1 LVT141012)

Fig 8



- The algorithm mostly reduced 120Hz line noise to below 0.5x background noise
  - only one outlier exceeded background noise
- For early events (O1 and first event in O2) 180Hz noise is up to 8 times higher than the background (otherwise, the algorithm performs well)

CONCLUSION

- My power line noise removal algorithm removes power line noise without removing transient data
- Line noise removal will aid in detection & parametrization of events peaking at frequencies near the noise line
- Events peaking around 60Hz are especially important as the formation modes of black holes with the required masses to produce such events are unknown
- In the future, we intend to create an algorithm to remove even more line noise using correlation between different noise lines and try to figure out the cause of the outliers

REFERENCES

1. LIGO Scientific Collaboration (2016). GW150914: First results from the search for binary black hole coalescence with Advanced LIGO. *Phys. Rev. D 93, 12203.* doi:10.1103. arxiv : 1602.03839
2. LIGO Scientific Collaboration and Virgo Scientific Collaboration (2019). A guide to LIGO-Virgo detector noise and extraction of transient gravitational-wave signals. *LIGO-VIRGO Collaboration.* arxiv : 1908.11170
3. LIGO Scientific Collaboration and Virgo Scientific Collaboration (2018). GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs. *Phys. Rev. X 9, 031040.* doi:10.1103. arxiv : 1811.12907
4. Gravitational Waves Open Science Center. (n.d.). O1 Instrumental Lines. Retrieved from https://www.gw-openscience.org/o1speclines/.
5. Gravitational Waves Open Science Center. (n.d.). O2 Instrumental Lines. Retrieved from https://www.gw-openscience.org/o2speclines.
6. J. C. Driggers et al (2018). Improving astrophysical parameter estimation via offline noise subtraction for Advanced LIGO. *Phys. Rev. D 99, 042001 (2019).* doi: 10.1103. arxiv : 1806.00532
7. Albert Lazzarini, Andrea Vicerè, and Robert Schofield (2002). Analysis of the effects of long term correlations over long baselines over narrowband features in cross-correlation measurements. URL : https://dcc.ligo.org/public/0026/T010101/000/T010101-01.pdf

Fig 1 : www.pnas.org/content/114/12/3017

Fig 2 : www.epsnews.eu/2017/08/virgo-and-ligo-together-in-quest-of-gravitational-waves

Figs 3-8 : My visualizations

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