Application for the release of a set of auxiliary channels from the O3 observing run

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Improving the low-frequency sensitivity of interferometric detectors is crucial for gravitational wave (GW) astrophysics and multi messenger astronomy. This is due to a few key reasons:

- Gravitational wave signals from coalescing compact binary sources (CBCs) are brighter at low frequencies, and thus, we can disproportionately increase the overall detection range by improving the sensitivity in this region [1].
- Improvements at low frequencies particularly impact the sensitivity toward the most massive binary black holes, such as GW190521, which are some of the most interesting astrophysical classes of sources.
- For detectors with current noise curves, waveforms for high-mass and Intermediate-Mass Black Hole (IMBH) binaries closely resemble short-duration transients (glitches) of terrestrial origin. Sensitivity to these signals is mainly limited by the detector's limited resolving power in the relevant frequency range. Pushing the lower frequency limit further down would enable us to detect more cycles in the signals, and distinguish them from glitches more easily.
- Cleaning up this frequency range will also impact the scientific yield from the louder detections, due to the improvement in the precision of parameter estimation. For instance, if we can accurately determine the phase of the signals at 10Hz (vs the $\sim$ 24Hz we can do with current performance), it would allow us to measure the masses and effective spin more precisely by roughly a factor of 10. It will also aid efforts to issue early warnings to observers for CBC mergers that are accompanied by electromagnetic transients [2].

At design sensitivity, the primary sources of noise at low frequencies (say $f \simeq 10 - 20$ Hz) are seismic and thermal in nature. In today's detectors, the noise is dominated by other effects, such as non-linear coupling of noise from the control system to the main interferometer (See Figure 1). These noise sources are expected to be dominant also in future detectors, and identifying and removing them from data (live or in post-processing) is key to achieving the sensitivity goals of future runs and third-generation GW interferometers.

Linear coupling of environmental noise to the detector strain is a well-known phenomenon [8]; it results in extra additive noise that is reducible if the environmental noise is independently sensed. Previous work in the area has developed tools to optimally subtract the extra noise, and their application has significantly enhanced the sensitivity of the detectors after the O2 observing run [9]. Once all the linear couplings have been accounted for, we can have multiple primary environmental sources of noise that together couple to the strain - one of the most interesting cases is when "fast" sources of environmental noise (here, "fast" is used for frequencies that are within the detector's nominal sensitivity band) couple to "slow" processes associated with degrees of freedom like the beam position (Rana Adhikari, Private Communication). This phenomenon can also make the noise in the detector band appear non-stationary as it is modulated by a time-varying function; this effect has already been observed in previous analyses [3, 4, 5]. For more motivation and past efforts at identifying and addressing this issue, see Refs. [1, 6]).

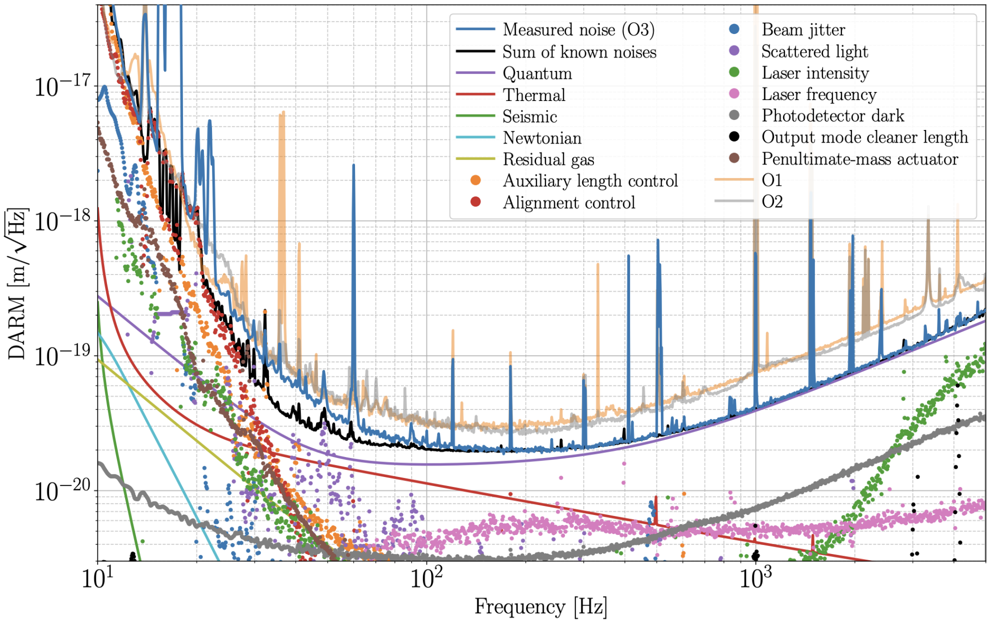


Figure 1: Hanford noise budget, O3, taken from [7]. As clearly seen, the fundamental noise sources (Quantum + Thermal) at low frequencies ($\leq 30\,\mathrm{Hz}$ are orders of magnitude smaller than the actual noise level in GW detectors. Below 30Hz, the dominant noise sources are alignment control and auxiliary length control. According to [7], they couple bilineraly to the data.

We can write down the general form of the couplings as follows. Suppose the 'DARM' data is $d(t)$, and the fast and slow auxiliary channels are a_{fast} and a_{slow}, respectively. The model for the measured strain is:

$$d(t) = \left[\left((a_{\mathrm{fast}} * T_{\mathrm{fast}})(a_{\mathrm{slow}} * T_{\mathrm{slow}}) \right) * T_{\mathrm{combined}} \right](t) + n_d(t) \tag{0.1}$$

Here, T_{fast}, T_{slow} are unknown transfer functions between the observed channels and their physical mixing, and $*$ denotes convolution.

If we knew which channels were relevant and could individually sense them, we could estimate the transfer functions, and then subtract the contribution of the first term in Eq. (0.1) to get down to the fundamental noise floor. We are instead in the regime in which we have a large set of 'fast' channels that have been sensed, no handle on the 'slow' channels, and do not know *a-priori* which 'fast' channel(s) is/are responsible for the extra noise. In such a case, we need to (a) find the relevant 'fast' channel, (b) estimate the 'slow' channel from the data itself, and (c) estimate the transfer functions.

We recently made some progress in this direction, i.e., developed an approach to estimate the 'slow' channel and the transfer functions given a candidate 'fast' channel. We have tested the approach on simulated data with encouraging results, but we are at a point where we really need to apply it to a reasonable length of measured data to understand whether the reality departs from the simple model outlined above.

We did some preliminary investigations with the three-hour auxiliary channel data release from the O2 run of advanced LIGO. As a first step, we looked for *linear* correlations between the strain data (the 'darm' channel) and the auxiliary channels, of the form

$$d(t) = (a_{\mathrm{fast}} * T_{\mathrm{fast}})(t) + n_d(t), \text{ or equivalently,} \tag{0.2}$$

$$\tilde{d}(f) = \tilde{T}(f)\tilde{a}_{\mathrm{fast}}(f) + \tilde{n}(f) \tag{0.3}$$

We can measure and account for such correlations, and then estimate the first term in Eq. (0.2); in the past, this approach has been applied with success and improved the sensitivity of the detectors in the O2 observing run [9].

We picked the following subset of channels in the auxiliary data release as being likely to have linear correlations with the strain, based on a mixture of physical arguments and exploration:

- `L1:ASC-CHARD_Y_OUT_DQ`
- `L1:ASC-CHARD_P_OUT_DQ`
- `L1:ASC-DHARD_Y_OUT_DQ`
- `L1:ASC-DHARD_P_OUT_DQ`
- `L1:LSC-SRCL_IN1_DQ`
- `L1:LSC-MICH_IN1_DQ`
- `L1:SUS-BS_M1_DAMP_V_IN1_DQ`
- `L1:HPI-HAM1_BLND_L4C_RX_IN1_DQ`
- `L1:LSC-PRCL_IN1_DQ`
- `L1:ASC-INP1_P_IN1_DQ`
- `L1:ASC-PRC1_P_IN1_DQ`

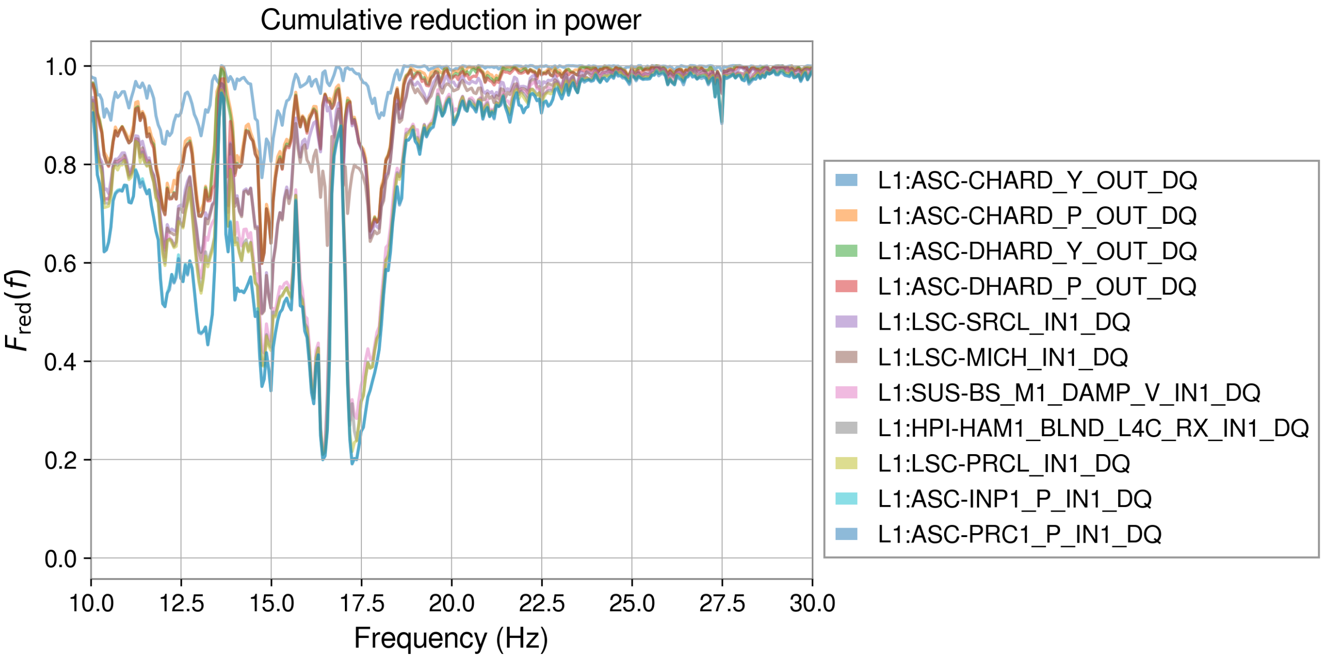
These channels were not included in the set used for broadband noise subtraction in O2, which focused on beam jitter, power mains, and calibration lines [9]. Figure 2a shows the reduction in power by the cumulative removal of noise in the `GWOSC` data that is linearly correlated with the auxiliary channels listed above. The reduction in power at higher frequencies ($f \gtrsim 25$ Hz) is consistent with over-fitting, but that at lower frequencies is physical. Figure 2b shows the resulting power spectrum, $\langle \tilde{d}'(f)\tilde{d}'^{*}(f)\rangle$, after each stage of linear noise subtraction. These same channels are expected to be the main channels that couple non-linearly to the data in the 10–30Hz range according to Figure 1.

We measured the correlations and checked the subtraction on the three-hour data release from O2. We are writing this document in order to request for the auxiliary data for the above channels over a longer period of time. There are two reasons behind this request:

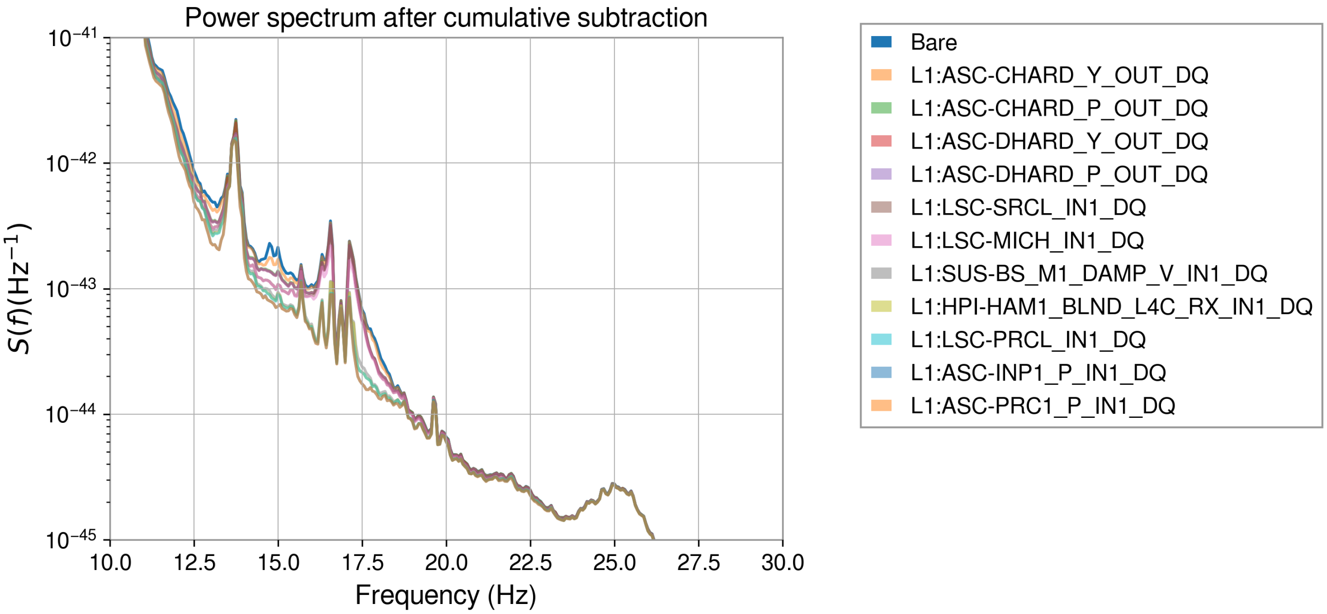
- **Blind detection of non-linear couplings:** The $\sim 10^4$ seconds of data from O2 were very instrumental for us to understand which channels were important and how to use them, but it was also very limited in allowing us to remove effects contributing less than 10% of the noise variance since there are many channels that could couple nonlinearly to the data. In addition, this coupling could be very limited in spectral range (or with rapidly changing coherence phase). To overcome the "look-elsewhere effect" of having many channels, we need more data to detect the couplings.

  More quantitatively, the amount of data needed to detect a coherence of $\epsilon = \frac{<a(f)d(f)>}{\sqrt{<|a(f)|^2><|d(f)|^2>}}$ is $k^2\frac{\epsilon^2}{\Delta f}$ where Δf is the required spectral resolution for the transfer function, and $k \approx 5$ is the required significance (we do not know which channels are the ones that couple to the data, so we demand a $\approx 5\sigma$ detection significance).

  For $\epsilon = 1\%$, $\Delta f = 1$ Hz and $k = 5$, we require $2.5 \cdot 10^5$ s of data. This calculation is valid (with a twice bigger constant) also to the search of non-linear coupling. We therefore estimate that in order to discover and remove all linear couplings in a data driven fashion, and then detect and remove the non-linear ones, at least 10^6 seconds of auxiliary channels data are required. Needless to say, even the regular linear couplings are expected to change with time, and our non-linear coupling removal process is able to reconstruct and smoothly remove such a slowly varying coupling.



(a) Fractional reduction in power



(b) Bare and noise-subtracted power spectrum

Figure 2: *Top panel:* Each line shows the cumulative reduction in noise power (given by Eq. (**??**)) achievable by removing linear correlations with the all channels up-to and including the labeled channel. The reduction at higher frequencies ($f \gtrsim 25\,\mathrm{Hz}$) is consistent with over-fitting. *Bottom panel:* The power spectrum of the noise-subtracted data, $\tilde{d}'(f)$ after each stage of linear noise subtraction.

- **Prospects for discovery:** Investing substantial time in improving the low-frequency is a very high-risk high-gain project. The two risk factors are:

  1) will we succeed in reducing the noise in an amount that will suffice for discovering new events?

  2) Will there be data we can run it on and make these discoveries.

  While the first risk factor is inherent, and we are willing to take it, the second is putting in jeopardy the limited time of junior scientists involved in the project and hence their future career. For this reason, the work that had been done until now on this problem was done by the PIs, and as a result was very erratic in nature.

  Upon the release of the auxiliary channels data, we plan to open a project involving students and postdocs to combat the bilinear noise in the LIGO detector. The presented results and techniques that were used in this note will then be demonstrated on a large (and up to date) data set, published, and help the GW community to advance low-frequency sensitivity in current and future runs.

In summary, we have preliminary work showing potential for future improvement, both in theory (through simulation) and in practice, which provides motivation for releasing the auxiliary channels in the public domain.

In between the O2 and O3 runs, the improvement in low-frequency sensitivity wasn't substantial, and the fundamental noise sources are subdominant to additional noise that could be the result of non-linearly coupled environmental noise sources. Tackling these noise sources is therefore at the forefront of improving the detector sensitivity of both current and future interferometers.

Opening up the low-frequency window is important both for improving the overall sensitivity of GW detectors to CBC mergers, and for opening up the higher redshift and heavier mass parameter spaces. In addition, it could dramatically improve the precision of parameter estimation for known events. This is important to resolve the outstanding questions of BBH formation via better spin measurements, and even for more high-risk/high-reward science cases such as identifying lensed pairs of events.

Finally, our team's past successes and reputation in improving upon the state-of-the-art LVK analyses by utilizing public data makes our application for this release appealing, with large potential benefits for the scientific community at large and the advancement of GW detectors in particular.

References

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