Calibrating Gravitational Wave Interferometers: A Review with Astrophysical Implications

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I. THE PRESENT

By June 2020, the global network of gravitational wave detectors, run by the LIGO, VIRGO, and KAGRA collaboration, will have just finished their most recent 12 calendar months of data collection at its best sensitivity ever. They will have quintupled the number of detections observed since the last two data collection periods [1]; each detection with typical signal-to-noise ratios of 10 to 20. With that new collection, the detectors cement the field of observational gravitational wave astronomy, *delivering* on its decades-old promise with robust detection of gravitational waves from the collisions of pairs black holes e.g. [2, 3] and of neutron stars, e.g. [4].

At these signal-to-noise ratios, quantitative statements will have been made about the properties of those new events, much like the events found in the first two data collection periods: details about astrophysical progenitors (location, distance, mass, etc.) [5, 6], and the resulting waveforms (polarizations, time-of-arrival compared against Relativity, etc.) [7–10]. With the number of events approaching $\mathcal{O}(100)$, improved quantitative statements can then been made about the population of events, as in [11], and the surrounding cosmology, e.g. Hubble's constant, as in [12, 13].

These exciting conclusions from gravitational wave astronomy would not be possible without an accurate and precise model of the detector's loop-suppressed output – fundamentally, a digitized sum of photo-currents, $d_{\rm err}$, resulting from the interferometric laser power output cast on to a few diodes – and its response to the detectors' differential arm length displacement, $\Delta L_{\rm free}$, caused by incident gravitational waves [14, 28]. That model is then used to estimate a near-real-time data stream that corresponds to the estimated strain on the detector, $h = \Delta L_{free}/L$, where L is the average length of the given detector's arms [15, 17]. Figure 1 shows a simplified diagram of how the model is used to generate h in the LIGO detectors (VIRGO and KAGRA are similar). The creation of this "calibration" model, and the corresponding estimates of uncertainty and systematic error continues to be an exciting challenge in precision engineering as the detectors evolve to achieve better sensitivity.

An example of the network's uncertainty and error during the third observing period is shown in Figure 2. The methods used to create these estimates are described in detail in [16–18]. In the most sensitive regions ($20 \lesssim f \lesssim 500$ Hz), the uncertainty and error estimates of the detectors' calibration are dominated by three components. The first dominant component (frequency-independent): the uncertainty in the detectors' absolute displacement reference system – a collection of auxiliary laser systems used to displace the detectors arms differentially via radiation pressure force. The laser power from these so-called "photon calibrators" are captured by their own, NIST-traceable, photo-detector systems, and their output is digitized

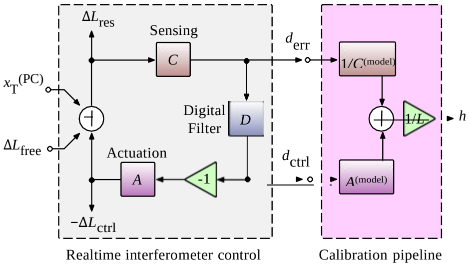

FIG. 1. Simplified diagram of the differential arm length control loop of the detectors. The digital error, d_{err}, and control, d_{ctrl}, signals are converted to an estimate of the strain on the detector in the absence of the control system, $h = \Delta L_{f\ ree}/L$. The model for such conversion is referenced to the photon calibrator system, which causes displacement, x_{pc}, equivalent to ΔL_{free}

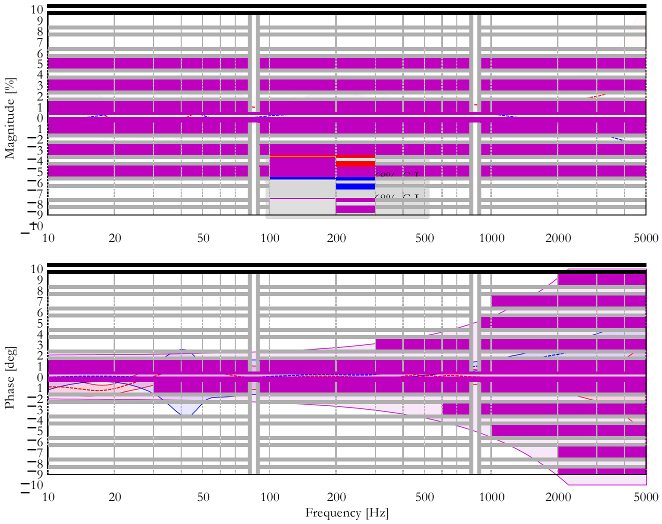

FIG. 2. Example, magnitude (top) and phase (bottom), 68% confidence interval bounds of uncertainty and systematic error of detector output, h, achieved during September 2019 for detector network. LIGO observatories, H1 and L1, and the VIRGO observatory, V1, are shown. Shaded region represents the 68% confidence interval bounds of the combined estimate of (a) statistical uncertainty, *(b) systematic error, and (c) uncertainty on that systematic error esimtate. Dashed lines are the median of that estimate [18].

and converted to a independent driven displacement estimate, x_{PC}, via their own sophisticated calibration scheme [19, 20]. The second dominant component (frequency-dependent): estimated systematic error (and its associated uncertainty) between the measured detector response and the limited analytic model. The final component (also, frequency dependent): the ability to resolve driven measurements in frequency regions outside the $f \sim 20 - 500$ Hz band where the detector noise increases rapidly, and timing synchronization uncertainty within a given detector limits phase estimates at high frequency (site-to-site timing uncertainty is currently negligible compared to achievable estimates of detector arrival-time for events at SNR $\sim$ 20).

The first component – the estimated uncertainty in the displacement created by the absolute reference system – can,

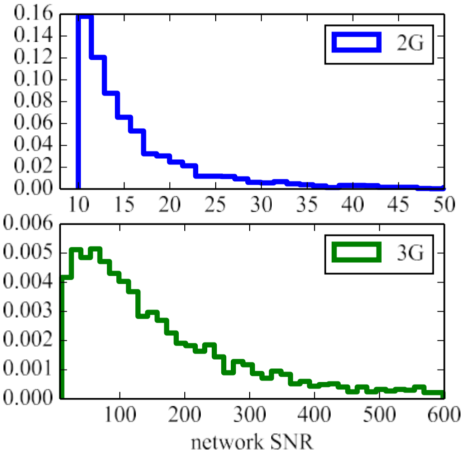

FIG. 3. Estimated distribution of detector network SNR for a theoretical distribution of events detected in a network of detectors at aLIGO target sensitivity (2G), and a network of detectors with a factor of 10 better sensitivity (3G) [27].

and will, continue to improve provided adequate time, personpower, and funding. However, we note that the latter two components are (a) detector configuration dependent, (b) model dependent, (c) time dependent (both that the unknown systematic error evolves in time when the detector configuration is stable due to natural alignment and thermal fluctuations, and also that it relies on amount of time spent understanding model discrepancies before the next detector configuration change), (d) and dependent on the detector sensitivity. Each dependency presents a unique challenge to the authors and their successors, and we anticipate no reduction in that challenge in the future.

II. THE FUTURE

The global network of gravitational wave detectors is constantly improving and expanding. The network's third observational run began in 2019 with the existing three functional detectors, L1, H1, and V1 with sensitivity improved by almost a factor of 2. The fourth detector, KAGRA or K1, [21], is will have joined the observing run in 2020 [22]. Funding for an upgrade beyond the second generation LIGO design [23] has already been funded and will begin installation just after the current observing run, mid-2020. A decade into the future, the network of 2nd generation ("2G") detectors be supplemented by an additional, fifth, LIGO-India detector, and may even have the its first of the 3rd generation ("3G") detectors in which the sensitivity has increased ten-fold [24–26]. In such a 3G network, we expect the network signal-to-noise ratios for events to swell well into the 100s; see Figure 3, [27].

In such an environment, it is imperative that calibration of the detectors is precise, accurate, self-consistent, and coordinated over the many, many promised detections in order to extract the maximum amount of astrophysics and cosmology from the measured population. Extrinsic event parameters like distance and sky-localization will be confused by 1% level if

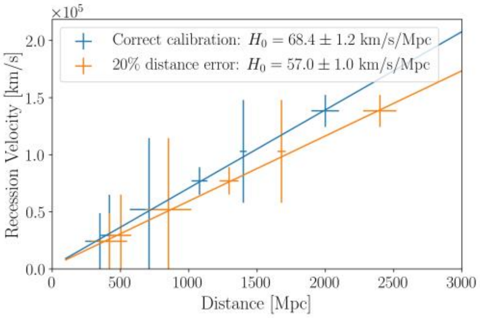

FIG. 4. A toy model of how the estimate of the Hubble constant, H_0, may be skewed by 20% systematic error in detector network calibration (20% is an exaggerated level of systematic error to demonstrate the effect). Error bars indicate individual events and their uncertainty (with presumed systematic error). The gold solid line indicates the resulting (biased) estimate of H_0. The blue line indicates an example “true” value of H_0.

network accuracy and precision remains at the current state-of-the-art. At worst, rare-but-plausible events with SNRs of 500-1000 will no more beneficial than SNR 100 events unless the level of calibration accuracy and precision is improved. Further, if *collections* of events are skewed by systematic error, then any reports on measurements of cosmological parameters may be skewed; see Figure 4 for example.

Research about how to better marginalize individual event estimates for progenitor astrophysical parameters over detectors’ calibration uncertainty is maturing. Research into the impact of the network’s calibration accuracy and precision as it evolves over time, on populations of events or cosmological statements, is still in its infancy. The photon calibrator systems remain the most promising of references, and all future detectors will remain outfitted with such a system. Projected uncertainties on these systems are already at an incredible 0.5%-level, with a renewed interest in improving them even further. As a supplement, continued development of a smattering of additional techniques also continues [28–30]. Yet, as described above, the absolute reference is not the only uncertainty and systematic error to be tackled: we look forward to the future challenges that await!

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