

Comparison of band-limited RMS of error channel and calibrated strain in LIGO S5 data

P R Charlton for the LIGO Scientific Collaboration

School of Computing and Mathematics, Charles Sturt University, Wagga Wagga NSW 2678, Australia

E-mail: pcharlton@csu.edu.au

Abstract. Many LIGO data analysis pipelines use either the DARM_ERR or AS-Q channels as the data source and use a response function $R(f)$ generated from time-dependent calibration measurements to convert to strain in the frequency domain. As calibration varies on a timescale of tens of seconds, the response function must be updated frequently. An alternative is to use time-domain calibrated strain $h(t)$. During the recent year-long LIGO science run (S5), preliminary strain data was published alongside raw interferometer output, typically within half an hour of the raw data being produced. As strain data is now available in highly-reduced form within the LIGO data archive, it represents a convenient alternative for LIGO search pipelines. This paper examines a measure of quality for calibrated strain data by calculating the band-limited RMS (BLRMS) difference between $h(t)$ and strain $h^e(t)$ as calculated directly from DARM_ERR in the frequency domain.

1. Introduction

The LIGO gravitational wave observatory has recently completed a science run (S5) with the aim of collecting a full year of data. Search pipelines are in place to look for a variety of gravitational wave signals, including binary inspirals, bursts, continuous waves, and the stochastic background. While most searches are described formally in terms of the gravitational wave strain $h(t)$, LIGO does not produce the strain directly. Instead, the output of the interferometer is in the form of an ‘error signal’ (the DARM_ERR channel) which may be combined with calibration information to produce the strain [1]. In searches, the calibration is often performed in the frequency domain, applying a response function $R(f)$ to the error signal $e(t)$ to produce the Fourier transform of $h(t)$ via

$$\tilde{h}^e(f) = R(f)\tilde{e}(f). \quad (1)$$

The response function $R(f)$ is constructed from two *fixed* reference response functions and one or two *time-dependent* calibration factors. The calibration factors are assumed to vary slowly enough that they can be considered constant over tens of seconds.

During S5, the LIGO calibration team published data files containing the calibrated strain channel LSC-STRAIN as a time-series derived from DARM_ERR and the time-dependent calibration factors. This process is described in [2]. The calibrated strain was published over LDR (the LIGO Data Replication system) typically within half an hour of the raw data being produced, making it possible for searches to do analysis directly on $h(t)$ in near real-time.

There are several advantages to using $h(t)$ over $e(t)$. It provides a ‘standard’ calibrated strain that all searches can use, with calibration lines automatically removed and short-term glitches eliminated by monitoring for bad calibration coefficients, and it releases search code authors from having to calibrate the data themselves, reducing the chance of introducing errors and eliminating differences of convention between research groups.

At present, the strain data is still under review and should be considered preliminary. Clearly it is important that the integrity of the strain data be verified. Since the amount of data being produced by LIGO is very large, an automated data quality check is preferred. The LIGO Data Monitor Tool (DMT) enables data quality information to be calculated on the fly and saved as time-series data, which may be used later to eliminate dubious segments of data from analyses. In this brief paper we examine using the difference between calibrated strain and the strain calculated directly from $e(t)$ in the frequency domain as a measure of data quality. A DMT monitor called StrainWatch has been developed along these lines by Ramon Armen at the University of Michigan [3].

2. The band-limited RMS norm

In this paper, $h(t)$ will always refer to the calibrated strain data, while $h^e(t)$ will (formally) stand for the strain as calculated directly from DARM.ERR, that is, the strain obtained via (1). It is not possible to directly compare these functions for several reasons:

- the calibrated strain is low-cut filtered below 40 Hz.
- calibration lines are automatically removed from $h(t)$, whereas they are present in $e(t)$ and hence $h^e(t)$ unless extra steps are taken to remove them.
- the noise floor of the strain is of course highly coloured, meaning that to obtain a meaningful comparison we should weight contributions at each frequency by the average noise power ie. the power spectral density.

A previous study on S4 data used a band-limited RMS (BLRMS) norm as a measure of difference [4]. An improved comparison which takes the spectrum of the data into account is obtained using a BLRMS norm weighted by the inverse PSD. For a function $x(t)$ we define the BLRMS norm $\|x\|$ via

$$\|x\|^2 = 4 \int_{f_0}^{f_1} \frac{|\tilde{x}(f)|^2}{S(f)} df \quad (2)$$

where $S(f)$ is the 1-sided power spectral density and f_0, f_1 represent the range of frequencies which contribute to the norm. When $x(t)$ is sampled at discrete points $x_k = x(k\Delta t)$, $k = 0, 1, \dots, N - 1$ we have

$$\|x\|^2 \approx \frac{4\Delta t}{N} \sum_{k=k_0}^{k_1} \frac{|\tilde{x}_k|^2}{S_k} \quad (3)$$

where \tilde{x}_k is the discrete Fourier transform of x_k , $S_k = S(k/(N\Delta t))$ and k_0, k_1 are frequency indices corresponding to f_0 and f_1 . Weighting the summation by the inverse PSD allows us to sensibly combine the statistics from each frequency bin. If x_k consists of Gaussian coloured noise then the contribution from each bin has the same distribution,

$$\frac{4\Delta t}{N} \frac{|\tilde{x}_k|^2}{S_k} \sim \chi_2^2. \quad (4)$$

If the summation in (3) covers m bins, then $\|x\|^2$ is distributed as χ_{2m}^2 , which for large m is approximately normal with mean $2m$ and variance $4m$.

Given two segments of strain data over the same time interval, we will compare them by looking at the relative error with respect to the BLRMS norm. If we take $h^e(t)$ to be the reference strain, our figure of merit for the quality of $h(t)$ will be

$$z = \frac{\|h^e - h\|}{\|h^e\|}. \quad (5)$$

Intervals where z is unusually large compared to empirically determined ‘typical’ values may be considered suspect.

3. Choice of data and processing pipeline

To generate an empirical distribution for z , we restricted our attention to a subset of the S5 ‘playground’ data. Playground data is data that has been set aside for testing and is never used in gravitational wave searches. The `segwizard` application from LIGOTools [5] was used to identify all playground data in the GPS time range 818090523–822785813, roughly December 8 2005 to January 31 2006. Further cuts were made to remove data that was less than 30 s from lock loss, and where calibration lines were known to be missing or dubious. The full set of data quality cuts applied in `segwizard` were:

CALIB_BAD_COEFFS_60	INVALID_DARMERR
CALIB_DROPOUT_1SAMPLE	MISSING_RDS_C02_LX
CALIB_DROPOUT_1SEC	OUT_OF_LOCK
CALIB_DROPOUT_AWG_STUCK	PD_OVERFLOW
CALIB_DROPOUT_BN	PRE_LOCKLOSS_30_SEC
CALIB_GLITCH_ZG	SEVERE_LSC_OVERFLOW

This left around 75 hours of data to analyse. Data from the $h(t)$ and $e(t)$ channels were read into a Matlab program which broke them down into around twenty thousand 16-second intervals for which z was calculated. In outline, the processing pipeline for each channel consisted of the following steps:

1. Read in a 256-second interval of $h(t)$ and $e(t)$ data.
2. Estimate the PSD $S(f)$ from $h(t)$ for this interval via Welch’s method.
3. Break the interval up into sixteen 16-second subintervals.
4. For each subinterval:
 - 4.1 Apply a Hann window to the time-domain data.
 - 4.2 Fourier transform to obtain $\tilde{h}(f)$ and $\tilde{e}(f)$.
 - 4.3 Apply a frequency mask to notch out calibration lines.
 - 4.4 Construct $R(f)$ for the subinterval and apply it to $\tilde{e}(f)$ to obtain $\tilde{h}^e(f)$ via (1).
 - 4.5 Calculate z using (5) over the frequency range $f_0 = 50$ Hz to $f_1 = 5000$ Hz.

The basic interval size of 256-seconds is chosen because it is short enough that we can treat the PSD as constant for the whole interval. It also reduces the amount of I/O needing to be performed, since most LIGO data files are of this length. The range of frequencies is chosen to cover the band used by gravitational wave searches, and where it is reasonable to expect the two data streams to be similar. Data below 50 Hz is not used because $h(t)$ is low-cut filtered below 40 Hz. Calibration lines are also notched out in the frequency domain since they are automatically removed by the process that produces $h(t)$. With the data channels sampled at 16384 Hz, this leaves a total of 79151 frequency bins in the summation (3).

To generate $R(f)$ for a subinterval, we used LIGO calibration data consisting of the reference response $R_0(f)$, the sensing function $C_0(f)$ and the open loop gain $\gamma(t)$. Since all the data is taken from the so-called ‘Epoch I’ period of the S5 run, the reference response and sensing

function are fixed. The open loop gain is slowly-varying and is provided as a time-series sampled at 60-second intervals. These functions are combined to form $R(f)$ via

$$R(f) = \frac{1 + \gamma(t) [C_0(f)R_0(f) - 1]}{\gamma(t)C_0(f)} \quad (6)$$

where $\gamma(t)$ is evaluated at the sample which lies closest to the center of the subinterval.

4. Results

Figure 1 show the frequency and cumulative distribution of the z values (as a percentage) for each interferometer: H1 and H2 at Hanford; L1 at Livingston. The frequency is expressed as a fraction of the total for each IFO. The horizontal axes have all been set to the range 2.65–4.5 for ease of comparison, but note that this excludes a few of the largest values in the results.

Table 1. Summary statistics for z values (expressed as a percentage).

IFO	Range	Mean	Median	P_{95}	P_{99}
H1	2.87–11.22	3.30	3.25	3.57	4.00
H2	2.67–6.15	3.32	3.27	3.88	4.27
L1	2.05–5.68	2.76	2.74	2.89	3.12

Table 1 summarises the statistics of the z values. The last two columns give the 95th and 99th percentiles, respectively. It is clear that the bulk of the differences were around 3% as measured by the band-limited RMS. The range of strain differences was greatest in H1, which produced a few large outlying differences. We have excluded the two largest of these, $z = 203.24\%$ in 818715279–818715295 and $z = 16.84\%$ in 821052589–821052605, because they corresponded to intervals where the calibration coefficients were outside the acceptable range $[0.3, 2.0]$. In generating $h(t)$, values of $\gamma(t)$ outside this range are replaced by either the previous value (if acceptable) or set to unity, so it is expected that the strain calculated directly from $e(t)$ will be different from $h(t)$.

Only thirteen z values remained above the H2 maximum of 6.15%. The largest value, $z = 11.22\%$ occurs in the interval 822460839–822460855. For this interval, $\gamma(t) = 1.067$, which is within the acceptable range. Figure 2 shows the absolute difference for this interval at each frequency, weighted by the inverse PSD. The difference for preceding interval is shown for comparison. All calibration coefficients were in the acceptable range for the intervals that produced the maximum z values in H2 and L1. Clearly, the best match was obtained for the L1 interferometer.

5. Conclusion

In this paper we have examined one way of monitoring the integrity of calibrated LIGO strain derived from the DARM_ERR channel. The histograms in Figure 1 give an empirical distribution of the relative difference between $h(t)$ and $h^e(t)$ as measured by the BLRMS norm for H1, H2 and L1. For all interferometers, the ‘typical’ difference for this sample is around 3%. While this discrepancy is small, it is yet to be understood entirely. It is partly due to differences in processing, such as the fact that $h(t)$ is generated using cubic interpolation for the calibration factors whereas we have used ‘nearest neighbour’ interpolation.

A closer examination of some of the larger deviations demonstrates the importance of monitoring the calibration coefficients, especially when they are being used to calibrate

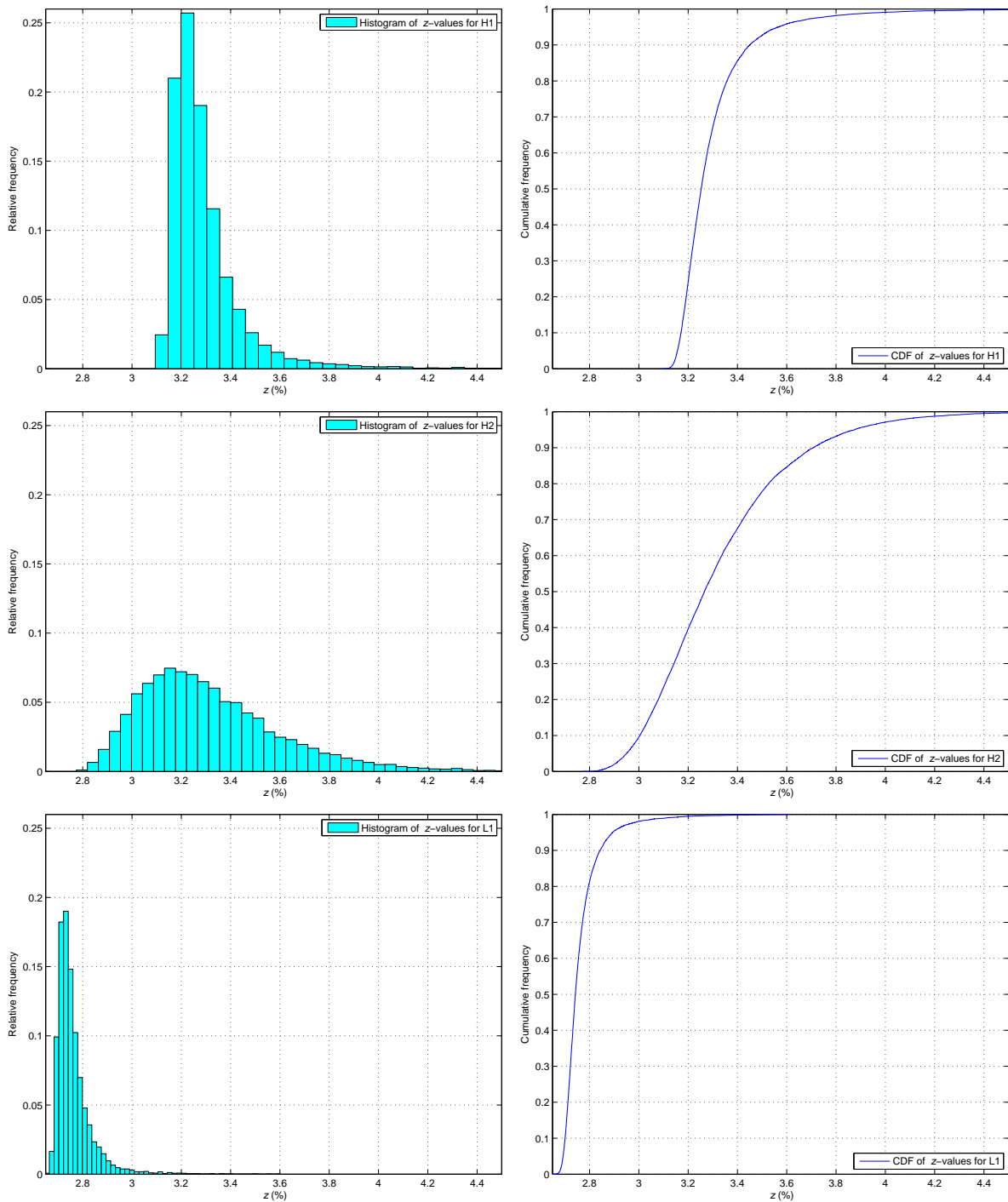


Figure 1. Frequency histograms and empirical cumulative distributions for z (expressed as a percentage).

DARM_ERR ‘on the fly’ in a search pipeline. The pre-calibrated $h(t)$ data seems more robust to due to the practise of discarding calibration coefficients outside of the acceptable range, however it does appear that on occasion large differences can occur even when the coefficients are within the acceptable range. Note that the reference response functions and calibration coefficients go

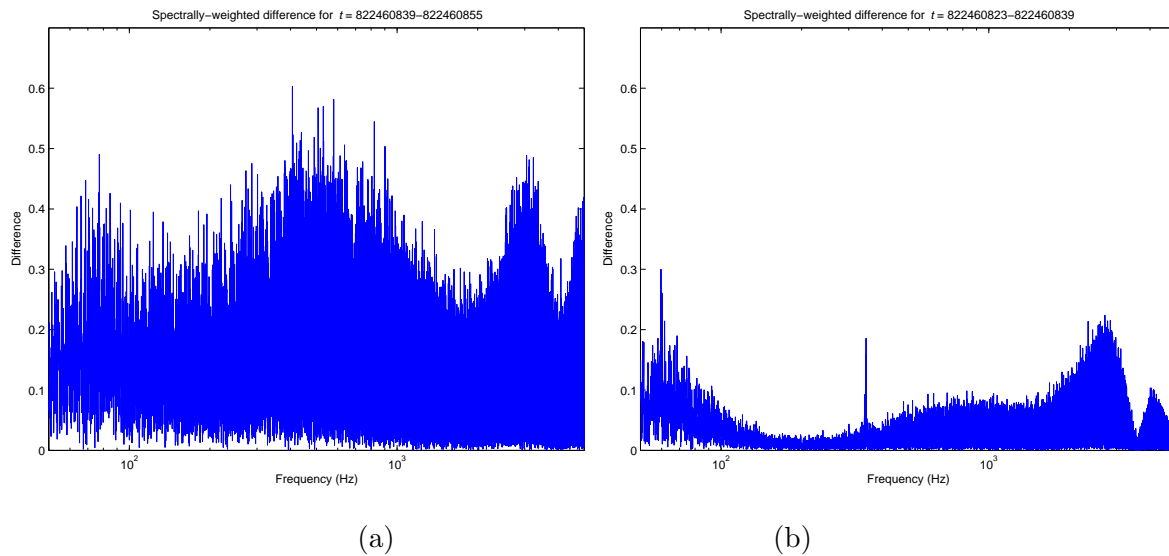


Figure 2. Pointwise difference $\frac{2|\tilde{h}^e(f) - \tilde{h}(f)|}{\sqrt{S(f)}}$ in H1 data for (a) the interval giving the largest z and (b) the preceding interval.

through several revisions – these results use V2 calibration data. We plan to repeat the analysis when the final calibration for S5 becomes available.

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