LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Technical Note **LIGO-T1300088-v6** 2015/06/10

Calibration Uncertainty Budget Requirements for early aLIGO

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Calibration uncertainty budget requests and requirements

This section outlines the calibration requirements for the interferometers length degree of freedom which is most sensitive to gravitational waves in Advanced LIGO, known as the "DARM" or differential displacement of Fabry-Perot arm lengths.

Input was requested from the four search groups regarding their requirements for aLIGO and Advanced Virgo calibration uncertainties. The following are detection era values that cover the first few years of science runs or first few detections. These values will be reassessed after the first set of detections has been made. Below is a table summarizing those requirements.

Search group	**Frequency band**	**Amplitude**	**Phase**	**Timing**	**Latency**
CBC	10Hz-500Hz	10%	5°	–	$\sim$ 10s
Bursts	10Hz-2000Hz	10%	5°	50	$\sim$ 10s
Bursts	2000Hz-5000Hz	20%	20°	–	–
CW	10Hz-1500Hz	10%	18°	25	–
Stochastic	10Hz-500Hz	9%	9°	24	–

The following are the largest values that satisfy all groups and therefore the **calibration requirements for aLIGO**:

Frequency Band	**Amplitude**	**Phase**	**Timing**	**Latency**
10Hz - 2kHz	9%	5°	24	$\sim$ 10s
2kHz - 5kHz	20%	20°	– –	–

The uncertainties quoted correspond to the maximum $1-\sigma$ variation at any frequency over the appropriate frequency band.

The requirements quoted above are a single number that must be derived from a collection of measurements, historically taken over the course of years, arising from several different techniques – some taken sporadically, others often – over a large frequency span, and over several configurations of the interferometers.

In the past, quoting such a number proved difficult given these circumstances. Below, we briefly recap the S5 uncertainty estimate to show how measurement statistical variations and systematic uncertainties can vary between interferometers, over frequency, and with time. As such, in order to distill this information down to one number, the systematic uncertainties and statistical variations were added in quadrature for each frequency point, and the maximum uncertainty over a given frequency band was used.

The following two bode plots of the uncertainty budgets for H1 and L1 during the third calibration epoch of S5 illustrate the different components of the estimate of the overall uncertainty. As the plots show there was a large systematic uncertainty (dark blue line) as well as frequency dependent statistical variations, which were combined in quadrature into the overall uncertainty (black dashed line). The single values quoted were the maximum values of the black dashed lines across all frequencies. For more details see [1].

We expect the aLIGO measurement suite to be no different in diversity and complexity. As such we don't restrict the method for composing these numbers. However, the requirement is that for each frequency point in the 10-2000 [Hz] band, the overall, $1-\sigma$, uncertainty estimate is no larger than the values quoted above.

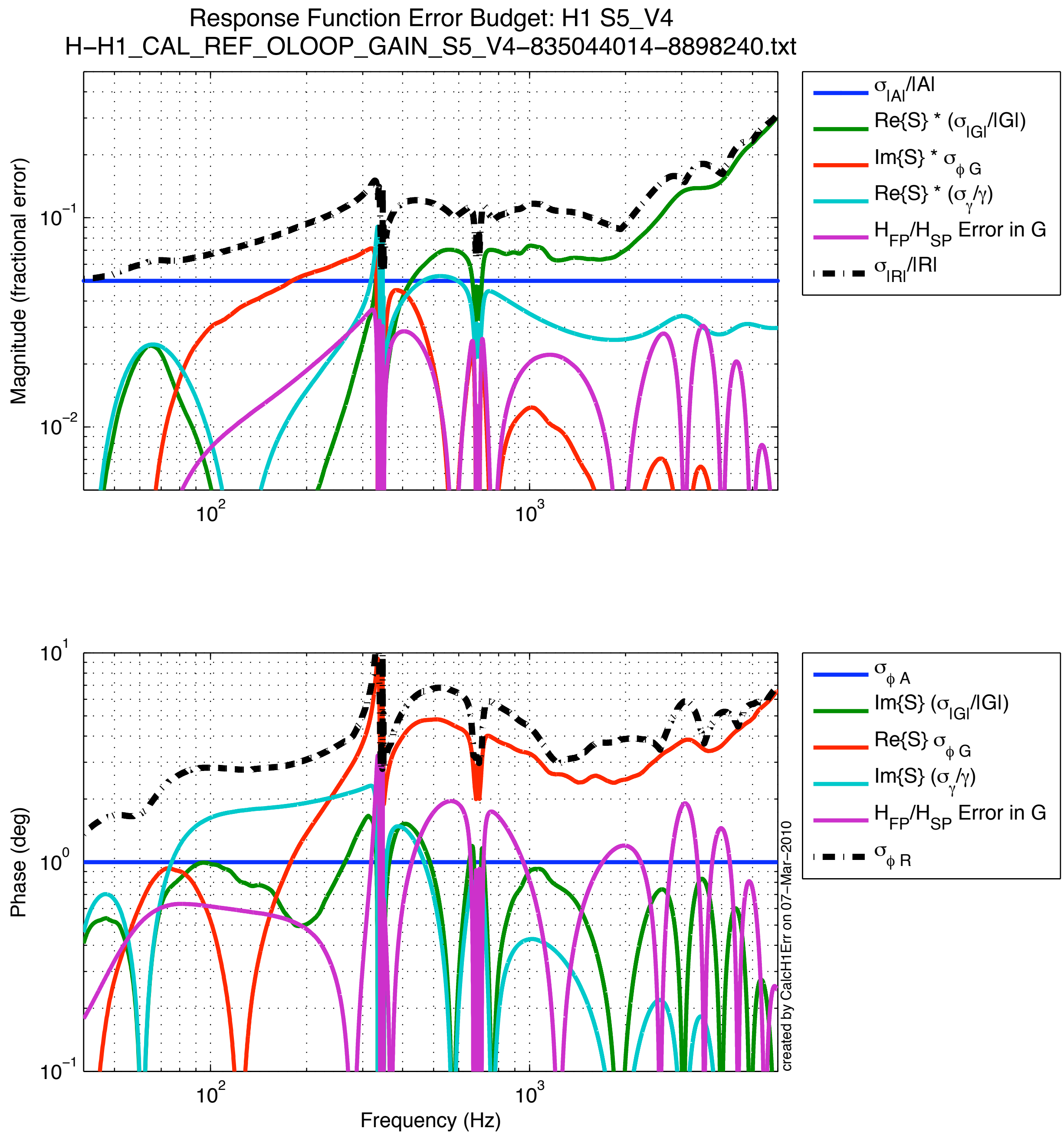

Figure 1: Bode plot for H1 during the third calibration epoch on S5. A large systematic uncertainty is shown with the dark blue line as well as a frequency dependent statistical variations. These were combined in quadrature into the overall uncertainty shown with black dashed line.

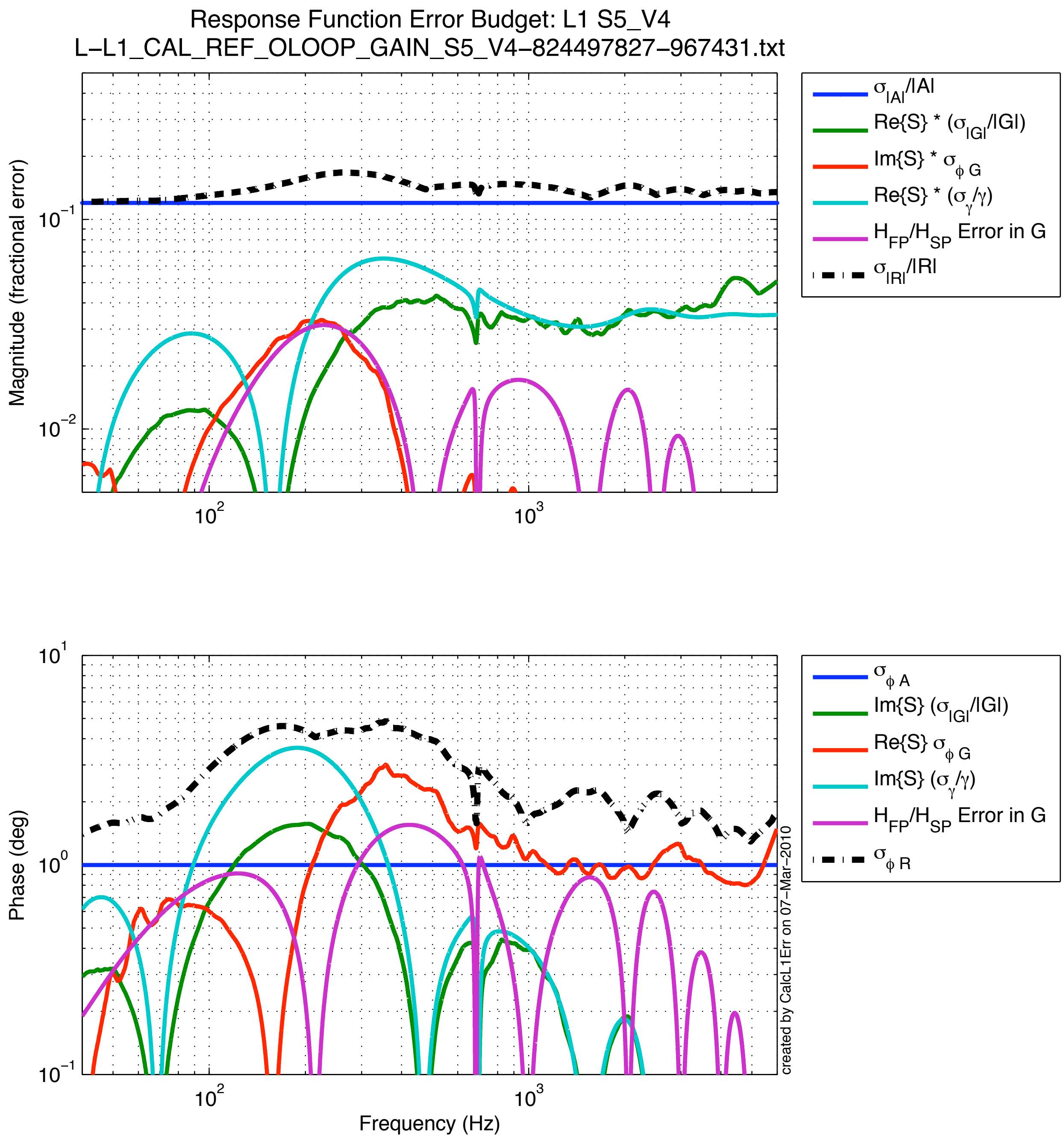

Figure 2: Same as Fig. 1 for L1

Ancillary Requirements

In addition to precise and accurate calibration of the DARM length degree of freedom, other, closely-related, required products are defined in this section. These products are either a by-product of, or can be easily produced by using, the tools developed for the DARM calibration. These include the following:

- **Inverse Actuation Function for Hardware Injections**: Hardware injections are simulated gravitational-wave signals added to the DARM control channel by physically actuating on the test masses. By testing to see whether these injected signals can be observed, hardware injections provide an end-to-end validation of our ability to detect gravitational waves: from the detector through to the interpretation of results from data analysis pipelines [3].

  Naturally defined in units of astrophysical strain née displacement of the test masses, these injections must be filtered such that they are summed into DARM control system in compatible units. This frequency-dependent filter is simply the inverse of the transfer function between the DARM control and test mass displacement, i.e. the Actuation Function – a transfer function already determined with high precision and accuracy for calibration of the DARM control loop. As such, the calibration group shall provide and install the inverse of this Actuation Function such that the Hardware Injection team need only provide the injections in the natural units of astrophysical strain.

- **Horizon Distance / SenseMonitor Range**: For convenience of assessing the overall performance of a detector with single, scalar, figure of merit as function of time, the calibrated amplitude spectral density of the detector output is often reduced to one of two quantities – the horizon distance or the SenseMonitor range. The horizon distance, D_H, is the maximum distance at which the gravitational waves from an optimally-oriented and optimally-located, equal-mass ($M_1 = M_2 = 1.4M_\odot$), compact binary system's inspiral would give an average signal to noise ratio (SNR) of $\rho = 8$ in a single detector [2]. A closely related figure of merit is the "SenseMonitor" range, D_S – the distance at which an optimally oriented, equal mass, compact binary system's inspiral would appear in the detector with $\rho = 8$, if averaged over all possible sky positions and orientations [4],

  $$D_H = 2.26\ D_S \tag{1}$$

  Given that both the horizon distance and SenseMonitor range well-defined and oft-used quantities to describe the interferometer performance, the input to which is the calibrated output of the interferometer, the calibration group shall also be responsible for producing this quantity with the equivalent precision and accuracy as defined above for the calibrated output.

References

[1] The LIGO Scientific Collaboration. "Calibration of the LIGO Gravitational Wave Detectors in the Fifth Science Run." https://dcc.ligo.org/LIGO-P0900120

[2] The LIGO Scientific Collaboration. "Sensitivity Achieved by the LIGO and Virgo Gravitational Wave Detectors during LIGOs Sixth and Virgos Second and Third Science Runs". https://dcc.ligo.org/LIGO-T1100338

[3] E. Thrane, et. al. "Documentation of the Advanced LIGO Hardware Injection Infrastructure." https://dcc.ligo.org/LIGO-T1400349

[4] P. Sutton. "S3 Performance of the LIGO Interferometers as Measured by SenseMonitor." https://dcc.ligo.org/LIGO-T030276