O4 Calibration Requirements Document

LIGO Scientific Collaboration Calibration Group

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1 Introduction

1.1 Project overview

The output of a detector in the International Gravitational Wave Network (IGWN, hereafter “the Network”) must be calibrated in units of dimensionless strain. This document attempts to outline requirements on calibration systems for observatories participating in the Network during the fourth Observing run of the “advanced detector era” (“O4”). This includes requirements for participation in the Network’s low-latency search and alert system.

The requirements are intended to flow “top down” in the sense that they should be driven by the science goals of the project. However, explicit science-based requirements are not always available *a priori*. The most current listing of science-based calibration requirements can be found in the Joint Data Release Policy Committee Report (DCC LIGO-M2000290) and are summarized as follows:

- Modeled transient searches have no explicit requirement on calibration errors.
- Parameter estimation and follow-up analyses, such as tests of general relativity, for modeled transient events require that calibration uncertainties are known with a sophistication that can be folded into these analyses.
- Unmodeled transiet analyses require calibration errors in amplitude within 5-10%, with possible enhancement by a few percent for exception events.
- Long-duration searches greatly benefit from data cleaning efforst, such as line removal and broadband noise subtraction.

Additionally, communications with long-duration searches, have indicated a strong desire to to be provided with a systematic error and uncertainty estimation for the low-latency calibrated strain data.
Historically, Virgo calibration uncertainty estimates have been provided for the low-latency strain data but LIGO calibration uncertainty estimates have not met this standard.
It is a top priority for the LIGO calibration group to develop methods for providing the requested systematic error and uncertainty estimates on low-latency strain data in O4.
This document lists a requirement to provide a prototype for such a system in O4.

Where explicit science-based requirements are not available, requirements are filled in with what is known to be achievable, with an effort to push the envelope to enable more/better science in the future. These “bottom-up” style requirements have been set based on what was achieved during the third observing run (O3) for the LIGO detectors. Specifically, in O3, LIGO was able to produce a sophisticated, frequency-dependent calibration systemtic error statement along with 68% confidence intervals on the offline calibrated data streams. The upper limit on the systematic error and associated uncertainty was $< 7\%$ in magnitude and < 4 degrees in phase, with the systematic error alone estimated at $< 2\%$

in magnitude and < 2 degrees in phase, in the frequency range 20 - 2000 Hz. The strain data are not calibrated below 10 Hz and are in fact heavily high-pass filtered below 10 Hz, making the data below 10 Hz unusable for analyses.

The timescale for the delivery of the final calibrated data set along with its accompanying uncertainty estimation is limited by the person-power required to investigate, address, and resolve required changes to the calibration based on evolving detectors.

While much of this document should apply to all observatories participating in the Network, much of the specific requirements called out in the System Requirements section may be interpreted as applying primarily to the LIGO detectors.

1.2 Stakeholders

Stakeholders within the LIGO/Virgo/KAGRA collaboration include:

- Maintainers and operators of GW search pipelines
- Maintainers and operators of GW event follow-up analyses (e.g. sky localization and parameter estimation)
- Detector characterization group
- GW population inference (e.g. Rates & Population, Cosmology, Testing GR) working groups
- Paper writing teams
- GW Open Science Center (GWOSC)
- Policy makers (Data Analysis Council, Operations Group, Executive Committee)
- Member institutions with MOU commitments for calibration infrastructure

Stakeholders outside of LIGO/Virgo/KAGRA include:

- Any and all consumers of strain data (e.g. GWOSC)
- Science teams for future facilities and missions

1.3 Operational goals

The primary purpose of the various calibration groups across the Network is to be responsible for the generation of gravitational wave time series data calibrated into units of absolute strain. The calibrated time series channel is often referred to as "h(t)" or "h of t".

Their secondary purpose is to deliver these h(t) channels to the Network's search pipelines with sufficiently low latency to enable our primary O4 science goals. In order to achieve this requirement, several h(t) channels could be provided in O4.

- Front-end (or "raw") calibrated strain data
  - Latency: O(1 second)

  - Details: The front-end CAL model will produce a calibrated data stream for use by commissioning groups. This data stream is not suitable for follow-up analyses due to known and large errors in the phase of the strain data.
  - Cleaning: None
  - Uncertainty estimate provided? No
- Early-warning calibrated strain data
  - Latency: O(2-3 seconds)
  - Details: The gstlal calibration package will produce a calibrated data stream for use in early-warning transient searches. This data stream will meet the required latency for such searches, but this may come at the sacrifice of accuracy due to, for example, shorter filters that less accurately capture the DARM loop in order to satisfy latency requirements.
  - Cleaning: Calibration and power mains line removal
  - Uncertainty estimate provided? No
- Low-latency (C00) calibrated strain data:
  - Latency: O(5-7 seconds)
  - Details: The gstlal calibration package will produce a calibrated strain data stream intended for consumption by all low-latency analyses.
  - Cleaning: Calibration and power mains line removal
  - Uncertainty estimate provided? Prototype of low-latency error estimation
- Offline (C01) calibrated strain data:
  - Latency: $<$ 5 months (3 months of data taking followed by 2 months to finalize calibration and error estimates for that chunk)
  - Details: The gstlal calibration package along with appropriate data cleaning tools will produce a final, cleaned calibrated data stream that will represent the "best" calibration and cleaning achievable for that time period.
  - Cleaning: Calibration and power mains line removal, removal of 60 Hz sidebands, when applicable, broadband noise removal
  - Uncertainty estmiate provided? Yes - full frequency-dependent error and uncertainty estimation

As part of this process, the groups must identify and characterize their detectors to a sufficient degree that the systematic error in the estimation of h(t) at any given time has negligible impact on the group's stakeholders. The early-warning and low-latency h(t) channels in O4 will not necessarily be accompanied by a fully characterized systematic error estimate. Rather, the systematic error will be spot-checked using continuous calibration lines at the edges of the sensitive band, with only a full-frequency-band characterization on an approximately once-a-week cadence. However, it is a high-priority of the calibration group leading into O4 to make significant progress on developing a low-latency systematic error procedure that could provide sophisticated systematic error estimates across the sensitivity band on a once/minute cadence.

We note that limitations of the detectors means that their data will only be valid in a relatively narrow bandwidth above 10 Hz. All data provided by the Calibration groups will therefore be aggressively high-pass-filtered below 10 Hz.

1.4 Scope of the group

The delivery of h(t) requires real-time access to the control systems in each detector, and thus is considered an integral part of the detectors control system, in hardware, electronics, software, and data transmission/storage. Thus, the scope begins with the maintenance and commissioning of the instrument control systems, and any hardware needed to characterize those systems. The scope ends at the reliable delivery of h(t) with the latency and accuracy required by stakeholders.

Other than the strain channel itself, an additional status channel will need to be provided that indicates the fidelity of the calibrated data. The generation of this metadata channel is not entirely the responsibility of the calibration groups, but needs to be coordinated with the commissioning teams and detector characterization groups as well.

2 User Requirements (USR)

"Users" in this context are any interested party that would be consuming the calibrated strain channel (also referred to as "stakeholders"). The main thing differentiating the users is their requirements on the levels of systematic error and delivery latency.

2.1 Needs of the LVK collaborators

2.1.1 Commissioning group (USR-CMS)

The instrument commissioning groups require a real-time estimation of the calibrated strain so that they may evaluate the noise performance of the detectors.

USR-CMS-1 A roughly calibrated strain channel should be available immediately in the control rooms, for real-time evaluation of detector performance.

USR-CMS-2 The systematic error levels on the real-time calibrated strain should be low enough such that performance can be reasonably estimated, e.g. 20% in amplitude and 15 degrees in phase over the 20-1000 Hz band.

2.1.2 Detector Characterization group / Data quality (USR-DQ)

The iDQ system produces a low-latency data quality estimation on the calibrated strain channel. This data quality channel needs to be propagated with the calibrated strain channel to the downstream consumers (it is not the responsibility of the Calibration group to deliver this channel). The iDQ system also requires access to the calibrated strain channel with sufficiently low latency that the iDQ output channel can be combined with the calibrated strain channel in time to meet the latency needs of all downstream consumers.

The iDQ system does require access to a calibrated strain channel for machine learning training purposes. However, the iDQ system does not require precision calibration; it is sufficient for the process to consume the real-time calibrated stream coming off of the instruments before the time varying correction factors have been applied.

USR-DQ-1 The low-latency data quality estimation requires access to a raw version of the calibrated strain immediately after it is produced.

2.1.3 Low-latency search groups (USR-LLS)

The various "standard" low-latency transient searches (i.e. the main work of the CBC and Burst groups) require a continuous stream of calibrated data. The requirements of these groups include:

USR-LLS-1 A stable, conservative estimate of the systematic error that remains within the bounds of 10% amplitude, 10 degrees phase (68% confidence interval) during all observation ready times, between the frequencies of 20 and 1000 Hz.

USR-LLS-2 Calibrated data within these accuracy limits must be available within 10 seconds of real time.

USR-LLS-3 The calibrated data stream must be accompanied by a state vector indicating the fidelity of the data stream with equal latency.

USR-LLS-4 Real-time monitoring of the latency and fidelity of the calibrated data stream.

2.1.4 Early warning searches (USR-EWS)

In addition to the standard low-latency transient searches, the newer effort to conduct early-warning searches for transient signals has tighter requirements on latency. The requirements of the early warning systems are:

USR-EWS-1 A roughly calibrated data stream within 2-3 seconds of data acquisition.

USR-EWS-2 A stable, conservative estimate of the systematic error that remains within the bounds of 10%/10 degs (68% confidence interval) during all observation ready times, between frequencies of 20 and 100 Hz.

USR-EWS-3 The calibrated strain data can be less aggressively high-pass-filtered below 10 Hz to allow for the lower required latency.

USR-EWS-4 The calibrated data stream must be accompanied by a state vector indicating the fidelity of the data stream.

USR-EWS-5 Real-time monitoring of the latency and fidelity of the calibrated data stream.

Note: These requirements will be met on a best-effort basis.

2.1.5 Low-latency parameter estimation (USR-LLPE)

The parameter estimation groups are responsible for reconstructing parameters of the event sources. This includes sky localization which is critical for the low-latency follow-up effort. Parameter estimation requires access to the systematic error estimation.

USR-LLPE-1 The parameter estimation groups request an estimation of the systematic error on the low-latency calibrated data stream.

2.1.6 High-latency search groups (USR-HLS)

All high-latency searches (Continuous Wave, Stochastic, offline transient searches, etc.) require calibrated data as well. As there is more time to produce the calibration, the requirements on systematic error estimation can be made more stringent.

USR-HLS-1 Delivery of calibrated strain data, with a quantitative systematic error estimate of the calibration, shall be made within 5 months of when the raw data were acquired. This can be achieved with a model such as data collection for a 3 month chunk followed by 2 months to finalize the calibration and error estimation for that data chunk.

USR-HLS-2 Systematic error levels that roughly conform to what was achieved in O1 through O3, e.g. 7% amplitude, 4 degrees in phase (68% confidence interval) between the frequencies of 20 and 2000 Hz.

USR-HLS-3 A probability distribution (or sufficient, representative distribution properties) of the frequency- and time-dependent systematic error at the above described latency and systematic error level for any time within observation ready data over the entire relevant frequency band.

2.1.7 Parameter Estimation (USR-HLPE)

Final parameter estimation results are based off of the high-latency calibrated strain data, which typically contains the lowest level of systematic error and the most sophisticated and accurate characterization of the systematic error. Other requirements on the high-latency strain data match the above-stated requirements for high-latency searches.

USR-HLPE-1 The parameter estimation groups require a precise estimation of the systematic error on the calibrated data as soon as the high-latency calibrated data is made available.

2.2 Needs of external users and the public (USR-PUB)

There are no specific requirements on calibration from external users and the public beyond those of the LVK.

USR-PUB-1 External users of the calibrated strain channel need clear, unambiguous documentation of the calibration.

3 System Requirements (SYS)

This section attempts to present a set of overall system requirements that represent the union of all the User requirements presented in the previous section. The requirements listed here are the ones that the various Calibration groups in the Network will attempt to deliver for O4.

We note that the different detectors in the Network will ultimately have different sensitivities, and differing levels of ability to comply with these requirements. For instance, requirements on systematic error may vary depending on signal SNR. This section most specifically covers the calibration system to be delivered by the LIGO observatory sites.

3.1 Global system requirements (SYS-GBL)

SYS-GBL-1 The latency for the production of the fully calibrated data stream from the low-latency calibration pipeline shall be no more than **10 seconds**.

SYS-GBL-2 An estimation of the systematic error on the fully calibrated data stream, between 10 and 5k Hz in frequency, shall be made available.

SYS-GBL-3 The calibrated strain data must be high-pass filtered with a suppression of 5 orders of magnitude between 10 Hz and DC.

SYS-GBL-4 A "state vector" channel describing the zeroth-order fidelity of the calibrated strain channel must be provided alongside the calibrated strain channel. This is distinct from any other data quality channels provided by the Detector Characterization group.

SYS-GBL-5 A rough estimation of the systematic error and uncertainty on the low-latency, fully calibrated data stream shall be made on a roughly once per week basis.

SYS-GBL-6 A fully calibrated data set covering the entire run will be delivered within **3 months** of the end of the run. Throughout the run, final versions of the calibration will delivered in a 6 month cadence where 3 months of data will be processed at a time. We will aim to achieve the same level of systematic error on the calibration of this data as has been achieved in the past, notably 7% in amplitude and 4 degree in phase between the frequencies of 20 and 2000 Hz, and a frequency-domain estimation of the systematic error shall be included. The data will be high-pass filtered with a suppression of 5 orders of magnitude between 10 Hz and DC.

3.2 Instrument requirements (SYS-INS)

3.2.1 Real-time system

SYS-INS-1 The calibration system must be given sufficient dedicated resources in the detector "front end" computer system to produce a reasonable estimate of the calibrated strain in "real time". For the LIGO instruments this should be at least one dedicated, real-time front end process. This initial stream produced in the instrument need not have time-varying correction factors and other compensation filters applied.

SYS-INS-2 The relevant channels produced by the front end calibration process must be acquired by the data acquisition system (DAQ), and passed on to the low-latency pipeline.

SYS-INS-3 Inter-site timing accuracy between all detectors in the Network shall be no more than 25 microseconds.

3.2.2 Absolute reference

SYS-INS-4 The instruments shall provide a system capable of making high-SNR displacements or one or more test masses with absolute displacement accuracy of **1%** or better. For LIGO, this shall be the photon calibrator (PCAL) system.

SYS-INS-5 The absolute reference system shall be used to displace the test masses with single-frequency "calibration lines" used to continuously characterize the instrument at set frequencies.

SYS-INS-6 The absolute reference system shall be used to make intermittent full-frequency-band characterizations of the instruments.

3.3 Low-latency pipeline requirements (SYS-LLP)

3.3.1 Low-latency pipeline inputs

SYS-LLP-1 All channels from the instrument needed to produce the fully calibrated/corrected data stream, and any estimation of the systematic error, shall be made available to the low-latency calibration pipeline with a latency of no more than **2 seconds**. The channels required include the output of the first-stage calibration (see SYS-INS-1).

3.3.2 Low-latency pipeline processing

SYS-LLP-2 One dedicated computer with at least two CPU cores shall be made available for the production of the "compensation process" (based out of the gstlal-calibration software package), which compensates for systematic errors in the front-end calibration process.

SYS-LLP-3 One dedicated computer with at least two CPU cores shall be made available for the backup production of the compensation process.

SYS-LLP-4 One dedicated computer with at least two CPU cores shall be made available for testing of the compensation process.

SYS-LLP-5 All compensation process machines shall have access to the same low-latency data stream from the instruments (SYS-LLP-1).

3.3.3 Low-latency pipeline outputs

SYS-LLP-6 The compensation process shall produce a fully calibrated data stream with all time-dependent correction factors and compensation filters applied, with latency specified in SYS-GBL-1.

SYS-LLP-7 A downstream service shall exist to multiplex the fully calibrated data stream with the data quality stream produced by the low-latency data quality process (i.e. iDQ).

SYS-LLP-8 A service/infrastructure must exist to handle transporting the fully calibrated data stream to the downstream multiplexing process (SYS-LLP-7).

SYS-LLP-9 A low-latency distribution system is needed to handle distributing the fully calibrated data and data quality streams to all downstream processes (e.g. the low-latency search pipelines).

SYS-LLP-10 All output data products must be archived for later validation and use.

3.3.4 Low-latency pipeline diagnostics and monitoring

SYS-LLP-11 The calibration pipelines requires a monitoring, supervision, and logging system.

4 Appendix

4.1 Acronyms

CBC Compact Binary Coalescence, the primary search target of the CBC search groups

IGWN International Gravitational Wave Network

GW Gravitational Wave

GWOSC Gravitational Wave Open Science Center

LVC LIGO-Virgo Collaboration

LVK LIGO-Virgo-KAGRA Collaboration

O4 The fourth Observing run of the IGWN, scheduled to begin in mid-2022

PCAL Photon Calibration system

PE Parameter Estimation, produced by the various Burst and CBC PE groups

4.2 Definition of Terms

burst Unmodeled transient gravitational waves, the primary search target of the Burst search groups

commissioning The process of improving the detector sensitivity or up-time.

compensation process Component of the *low-latency pipeline* that compensates for time-dependent calibration factors.

detector Individual gravitational wave detector, part of an observatory.

h(t) The calibrated strain time series.

high-latency Times significantly delayed from real time (O(months)).

latency Any time delay after real time.

low-latency Times immediately after real time (~seconds).

low-latency pipeline The calibration pipeline that produces calibrated strain data with low-latency (~10 seconds). The output of this pipeline is supplied to the low-latency searches.

network E.g. *IGWN*, the international network of gravitational-wave observatories.

observatory A set of one or more gravitational wave detectors operated together under a single management structure (e.g. LIGO, Virgo, KAGRA, etc.).