LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION

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LSC-Virgo Operations White Paper
(Summer 2019 edition)

The LSC and Virgo Commissioning, Calibration,
Detector Characterization, and Computing Groups

WWW: http://www.ligo.org/ and http://www.virgo.infn.it

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1 Overview and Executive Summary

The successful operation of the LIGO and Virgo detectors and key infrastructure are critical to enabling gravitational-wave astronomy. Gravitational wave detections are made possible by optimized instrument sensitivity and uptime, well-characterized noise, accurately calibrated data, and robust computational infrastructure that supports not only the detectors but also the data analysis pipelines used to identify and characterize gravitational wave signals. These activities are undertaken by the LIGO Laboratory in collaboration with the broader LIGO Scientific Collaboration, and the Virgo Collaboration. Coordination of efforts between LIGO and Virgo is organized through the Joint Run Planning Committee (JRPC) as well as between partner groups.

The LIGO and Virgo **Commissioning** teams work toward optimizing the sensitivity and uptime of the global detector network. The LIGO and Virgo **Detector Characterization (DetChar)** groups interface with the detector commissioning teams and work to improve GW signal searches by identifying and mitigating noise sources that limit sensitivity to astrophysical signals. The LIGO and Virgo **Calibration** teams produce fast a reliable calibration of detector data. The LIGO and Virgo **Computing** teams support the joint LIGO-Virgo software and computing infrastructure. The LIGO and Virgo **Joint Run Planning Committee** coordinates observing and commissioning schedules between the Collaborations

This *LSC-Virgo Operations White Paper* describes the planned activities for these efforts, in the context of the LIGO Scientific Collaboration Program 2019-2020.

Further details on the planned activities in collaboration between the DetChar and Calibration groups and the four LIGO-Virgo data analysis working groups (Burst, Compact Binary Coalescence, Continuous Waves, and Stochastic Gravitational-Wave Background) can be found in the *LSC-Virgo White Paper on GW Data Analysis and Astrophysics*, LIGO-T1900541 and VIR-0812A-19. The data analysis working groups also undertake tasks related to the Operations of the LIGO-Virgo experiments, described therein.

This Operations White Paper also complements the *Instrument Science White Paper,* T1900409, which covers the Advanced Interferometer Configurations Working Group (AIC) including Newtonian Noise and Interferometer Simulations, the Quantum Noise Working Group (QNWG), the Lasers and Auxiliary Optics Working Group (LAWG), the Optics Working Group (OWG), the Suspensions and Seismic Isolation Working Group (SWG), and the Control Systems Working Group (CSWG).

The LIGO Laboratory operates and maintains the LIGO Hanford and Livingston observatories through a Cooperative Agreement with the US National Science Foundation. The LIGO Laboratory makes major contributions to the LIGO Scientific Collaboration, including responsibility for delivering calibrated, well-characterized gravitational strain data at a target sensitivity during designated observing runs. The broader LSC, jointly with the Virgo Collaboration, is in turn charged with producing astrophysical results, including low latency GW candidate alerts. The **LIGO Laboratory Operations Activities** include activities which are deeply collaborative with the LSC (e.g., Calibration), those with some participation from the LSC (e.g., Commissioning), and others which are largely internal to the LIGO Lab (e.g., maintenance of the vacuum equipment).

1.1 Observatory Operations

During the period 2019-2020 LIGO Laboratory will be primarily operating the two detectors for the O3 observation run. Detection coordination efforts for the period through spring 2020 will focus on detector operation in science mode to maintenance the maximum possible coincidence uptime for the two LIGO nodes of the global network. This will entail providing support to real-time detection alerts, including rapid response team (RRT) review of detector status when events with sufficiently low false alarm rates occur that trigger issuing public alerts. The LIGO Laboratory science and engineering teams will be planning for the detector improvements that have been identified as targets for sensitivity improvement in preparation for the O4 observing run.

1.2 Detector Commissioning

LIGO Commissioning is the process of understanding the performance limitations of the instrument, and then improving the performance of the instrument through a combination of physical changes to the instrument and modifications of control software. It is typically iterative, and can lead to recognition of more significant required changes to realize improved sensitivity. It is undertaken by the commissioning team, the detector engineers, the LIGO Lab engineering group, and others as needed. LIGO Commissioning is a responsibility of the LIGO Laboratory, and is principally undertaken by LIGO Lab staff. Non-lab LSC members may be welcome to participate under LIGO Lab direction; LSC Fellows typically are engaged in commissioning as an example.

1.3 Calibration

1.3.1 LIGO Calibration

LIGO calibration includes all work to produce the calibrated strain time series, $h(t)$, that is used by all astrophysical analyses. This necessary work includes:

- creating accurate models of the detectors to calibrate the data
- maintaining the necessary infrastructure and performing the physical measurements needed to calibrate the detector models
- tracking and correcting for time-varying changes in detector configuration and performance
- providing uncertainty estimates on the calibration that can be used by astrophysical analyses to establish uncertainties in measured quantities
- producing a calibrated detector time series in low-latency
- providing infrastructure to re-calibrate the detector data using improved measurements or to correct problems with the low-latency calibration
- providing scientific support for the collaboration's astrophysical analyses on matters of detector calibration and its accuracy

Since the calibration of a GW detector changes in response to its day-to-day environmental and physical state, and in response to planned commissioning changes that improve its sensitivity, calibration of the data is an ongoing task that requires continuous activity both during and between observing runs.

LIGO calibration team activities are organized into two categories:

- **Essential:** These are items that must be accomplished in order to produce a calibrated data stream and associated data products required for all downstream analyses of LIGO $h(t)$ data. Current essential activiteis are:

  - Measure and understand the O3 interferometers
  - Maintain and upgrade the photon calibrator system
  - Revitalize and improve the calibration model software for better workflow from calibration measurements to uncertainty estimation
  - Revitalize and improve the software for determining calibration uncertainty estimates
  - Maintain and operate the low- and high-latency $h(t)$ data production software, currently both `gstreamer` based software and LIGO front-end based software
  - Maintain the LIGO calibration monitoring tools used for reviewing and diagnosing calibration issues

- **Research and development:** These are items that are critical for improving LIGO calibration infrastructure and ensuring that LIGO calibration uncertainty is not the limiting factor in downstream astrophysical analysis results. Current research and development actitivies are:
  - Improve the detector calibration above 1 kHz
  - Resolve any potential systematic error in the overall scale of the calibration and improve LIGO calibration precision and accuracy
  - Integrate LIGO calibration uncertainty estimates seamlessly into astrophysical analyses
  - Automate the generation of standard calibration precision and accuracy checks for more constant and effortless review
  - Advance and improve the low- and high-latency `gstreamer` and front-end based calibration software
  - Continue development of Newtonian Calibrator system as a second method for assessing the overall systematic error of the photon calibrator system.

1.3.2 Virgo Calibration

An important activity after O2 has been to improve Advanced Virgo calibration and reconstruct the O2 $h(t)$ channel with better precision. An online version of the reconstructed channel $h(t)$ was available during O2 for low-latency searches. An updated O2 $h(t)$ channel was released in September 2017 with improved calibration models and frequency noise subtraction. A second update was released in January 2018 with the addition of monitoring cavity finesses variations and better frequency noise subtraction. This version is being used for the latest and on-going O2 analysis. The estimated uncertainties for the second versions are 5.1% in amplitude and $40 \times 10^{-3} + 2\pi f(20 \times 10^{-6})$ rad in phase.

The goals for O3 are to provide a better online $h(t)$ reconstructed channel for low-latency analysis and provide the estimated uncertainties before the start of the run, aiming at 5% online uncertainty. This requires the calibration measurement to be done well in advance with an interferometer configuration stable during the four weeks preceding the start of O3. Weekly calibration shifts are planned in the commissioning planning, as well as nightly automated standard measurements. Additional improvements are planned for the photon calibrators.

A prototype Newtonian (gravitational) calibration system (NCal) has been succesfully tested around O2 and has given results consistent with the standard calibration. Going further with NCal is planned for O3 and beyond to improve the calibration precision and to cross-calibrate the LIGO and Virgo detectors.

1.4 Computing

1.4.1 LIGO

The LIGO instruments' primary output is a time-stream sampled at 16,384 Hz, recording the strain induced by noise or astrophysical gravitational-wave signals. This stream, and associated state information, are duplicated in low-latency from the observatory sites (LHO and LLO) to the central computing centre at CIT, where they are analysed by myriad algorithms to determine the presence of transient astrophysical signals. If signals are found, their parameters are uploaded immediately to a candidate event database, which in turn emits notifications used to start follow-up and data-quality investigations, and to inform external partners of the key information.

Alongside these strain data, auxiliary information from a large number of sensors and digital control systems are recorded to provide information about instrumental performance, noise sources, and data quality. This auxiliary data set is collected and recorded continuously at a rate of XX MB/s, and is made available to internal LSC users within 2 minutes of acquisition.

During a science run, all data are recorded in perpetuity, enabling 'off-line' analysis of data by both transient and long-duration signal search teams, with the strain data eventually released publicly through the Gravitational-Wave Open Science Center (GWOSC).

The LIGO Computing and Software Committee (CompSoft) works to enable the LSC's scientific Working Groups and Committees to carry out the LSC Program via:

1. provision and configuration of data analysis computing resources to complement those provided directly by the LIGO Laboratory;
2. development, maintenance, and support of LSC computing services, including identity and access management platforms, version control systems, wikis, etc; and,
3. data analysis software development, packaging, deployment, and support, including direct development of underlying infrastructure, and optimisation and packaging of scientific software developed by the Working Groups.

For the current observing run (O3), the highest priorities are the low-latency data distribution network between LIGO and Virgo observatories, and the development of a prioritised, fair-share batch computing model that allows rapid processing of the highest-priority tasks (as defined by the LSC Program).

In order to support future data-taking and analysis, there are a number of prototyping and research projects to investigate new and upgraded technologies for data transfer, software environments, containerisation, and distributed computing.

1.4.2 Virgo

Gravitational-wave alert triggers must be produced within seconds of the acquisition of data, in order to allow for rapid follow-up by electromagnetic telescopes. Each of these triggers will then be analysed within just a few minutes, in order to confirm that their origin is neither environmental nor instrumental. Deep searches and large-scale simulations are subsequently undertaken over timescales ranging from a few days to many months. These different timescales, when considered together with the geographical separation of the detectors means that a distributed cyber infrastructure is required. The Virgo Computing group is fully dedicated to the development and maintenance of such an infrastructure.

The group has defined the following top level tasks for the forthcoming period:

Highest priority tasks

- guarantee adequate storage and computing resources at Cascina, for commissioning, detector characterization and low-latency searches
- guarantee fast communications between Virgo applications at Cascina and aLIGO CCs/other detectors for low-latency searches
- guarantee reliable bulk data transfer to custodial storage in Tier1 AdV CCs
- guarantee reliable storage and computing resources for off-line analyses in the AdV CCs
- push towards the use of geographically distributed resources (such as Grid or Cloud sites), whenever appropriate
- push towards a homogeneous model for data distribution, bookkeeping and access
- enforce the necessary quality and configuration control in the computing software

High priority tasks

- push towards the use of industry-standard, widely used tools to minimize the development and maintenance effort by the collaboration

1.5 Detector Characterization

Detector sensitivity to gravitational-wave signals is limited by noise from the instruments and their environment. Robust detection of signals, the vetting of candidate signals, and the accuracy of parameter estimation is *crucially* dependent on the quality of the data searched and the collaboration's knowledge of the instruments and their environment. The Detector Characterization group (DetChar) groups are focused on working together with the astrophysical search groups and the detector groups to (i) deliver the data quality information necessary to avoid bad data, veto false positives, and allow candidate follow up for gravitational-wave searches and (ii) characterize the Advanced gravitational wave detectors to help to identify data quality issues that can be addressed in the instruments to improve future instrument and search performance.

The detector characterization teams are largely separate for LIGO and Virgo, but there are some common tools and ongoing exchange of ideas.

1.5.1 LIGO

Search Data Quality: LIGO data contain non-Gaussian components such as noise transients and quasi-periodic lines that adversely affect the astrophysical searches. Transient noise in the detector data can mimic or mask transient signals from Compact Binary Coalescence and more generic Burst sources, interfering with detection and the accuracy of the source parameters recovered. To minimize these negative effects, LIGO data analysis must account for transient data quality issues. While the DetChar group makes multiple types of data quality information are available to searches, offline analyses currently rely upon: *state segments* that indicate which data should be analyzed, based on the state of the instrument and its calibration; and *veto segments* that indicate periods of poor quality data or identify short durations where the data are likely to contain a non-astrophysical disturbance. Searches will use state segments to identify data suitable for analysis. Searches will use veto segments to either ignore problematic data or to reduce confidence in any search triggers associated with these times. For continuous-wave and stochastic backgrounds searches, frequency bins that are contaminated by non-astrophysical disturbances must be identified and removed, and low-level, broadband contamination from correlated magnetic noise must be mitigated.

Automation of Data Quality assessment: With the signal rate of O3, and the need for low-latency data to support multi-messenger astronomy, the Detector Characterization group must continue to develop automated approaches to identify the causes of instrumental problems and to provide data quality information in low-latency with minimal human supervision. This will continue to be a main focus of the group, with partners in the astrophysical search groups collaborating on both identifying pipeline needs and sensitivities to data defects.

aLIGO Instrument Characterization: The Detector Characterization group works with the detector commissioning and engineering groups to identify and resolve issues in the aLIGO subsystems related to glitch and noise contamination and auxiliary channel signal fidelity and robustness. This work has led to early data quality improvements and helped to train a wider pool of scientists who are familiar with the instruments. Continued work aims to facilitate aLIGO detections by ensuring that the detectors are well understood and that instrumental fixes for data quality issues are aggressively pursued. While the detectors are being upgraded, the DetChar group will provide commissioners with off-site assistance in any needed investigations as well as characterize changes in instrumental subsystems.

1. **Highest priority.** The highest priority of the LIGO Detector Characterization group is to provide timely data quality information to the LSC-Virgo search groups that designate what data should be analyzed, remove egregious data quality issues, identify periods/frequencies of poor data quality, and vet event candidates. Automation is central to success in this activity.

2. **High priorities.** Complement and collaborate on commissioning to help identify sources of data defects that limit sensitivity to transient and continuous wave (CW) gravitational wave sources. Use auxiliary sensors to find, quantify, and mitigate coupling between the gravitational wave strain data and the environment. Maintain and extend the software infrastructure required to provide needed data quality information to online searches.

3. **Additional Priorities.** Develop improved methods to uncover the causes of the noise transients which most impact the searches, with the goal of mitigating them or producing vetoes. Pursue exploration of well-motivated new approaches to data quality issues.

1.5.2 Virgo

Search Data Quality: A new Virgo data quality model has been developed and is currently implemented. This model defines workflows and procedures the group will follow to provide data quality products to searches. In particular, emphasis is made to produce and deliver search-specific data quality vetoes. On top of this, a new and ambitious online architecture is being implemented to provide vetoes to online search pipelines. We have developed with LIGO a common data quality segment database, to benefit the Burst and CBC groups, and it has been moved to production. Additional data quality needs specific to the CW and Stochastic search groups include the identification of noise source contributions to spectral lines or non-stationary and non-linear features. For this, we use automatic spectral lines identification tools already well tested, and a line database.

Early Advanced Virgo Characterization: The Virgo detector characterization team will begin noise and glitch studies on each commissioned sub-system as soon as they come online, in close collaboration with sub-system hardware coordinators and commissioners. A system of shifts has been organized. Periodically, a team of two shifters is on watch. They study transient and spectral noise using analysis tools developed by the group.

1. **Highest priority**
   The highest priority of the Virgo Detector Characterization team is to find and mitigate sources of noise and to provide data quality information to the LSC-Virgo search groups in order to reduce the impact of the remaining noises.

2. **High priority**
   Our current high priorities are the development of useful tools for commissioning and an early characterization of each sub-system of Advanced Virgo in order to reduce the need for vetoes in future searches. This will imply a coherent system of monitoring web pages, a spectral line database catalogue, identification of non stationary lines and a software infrastructure to provide useful online data quality information.

3. **Additional priority**
   Additional priorities for Virgo detector characterization are to develop improved methods to uncover the paths and the sources of the noise transients which most impact the searches, and to implement automated noise classification tools.

To accomplish these priorities, the DetChar groups require:

- astrophysical search group participation to report sensitivities in the analysis pipelines to data defects
- data quality experts to identify data defects and investigate their source as well as vet event candidates
- code developers to support and build key infrastructure and develop specific modules to recognize and flag data defects
- instrument characterization experts to quantify the sensitivity of the instrument to the environment, establish coupling coefficients between the gravitational wave data, the instrumentation, and the environment, and to identify mitigation strategies where needed

1.6 LSC Fellows

LSC Fellows are scientists and engineers who are resident at the LIGO observatories for extended periods of time [**?**]. The LSC Fellows program is entering its fifth year and has become a major success, enabling LIGO Laboratory to host junior scientists for at least a quarter and sometimes longer. This has provided the learning opportunity of gaining hands-on experience at either of the two LIGO observatories. The LSC Fellows carry out critical LSC activities supporting LIGO Laboratory commissioning and scientific operations, and can engage in a variety of activities, including: detection coordination efforts during observing runs; detector commissioning; installation of detector improvements; detector calibration; and detector characterization.

1.7 LIGO A+ Upgrade

The “A+ detector" project is a major upgrade to the existing Advanced LIGO detectors, beginning in 2019 and expected to continue through the end of 2023. The A+ project in 2019 will be carried out in parallel with the O3 observing run.

1.8 LIGO-India

LIGO-India is a project of the Government of India with primary responsibilities to build facilities and assemble, install, commission and operate an advanced LIGO detector provided by LIGO and the US National Science Foundation. Several important activities are expected to be completed in 2019-20: initiation of site construction activities, vacuum infrastructure prototyping, beam tube prototyping and testing, etc.

1.9 Roles in the Collaboration

The LSC has a complex organization, with many members serving different roles, such as leadership and management of working groups, participation in committees, performing non-science needed activities, etc. There is a wide range of activities undertaken by collaboration members which are organizational roles. Some of these have scientific elements, and some are simply necessary to maintain and propel the collaboration.

2 Observatory Operations

Op-2.1 LIGO Laboratory Operations

During the period 2019-2020 LIGO Laboratory will be primarily operating the two detectors for the O3 observation run. Detection coordination efforts for the period through spring 2020 will focus on detector operation in science mode to maintenance the maximum possible coincidence uptime for the two LIGO nodes of the global network. This will entail providing support to real-time detection alerts, including rapid response team (RRT) review of detector status when events with sufficiently low false alarm rates occur that trigger issuing public alerts.

Into 2021, the LIGO Laboratory science and engineering teams will be planning for the detector improvements that have been identified as targets for sensitivity improvement in preparation for the O4 observing run. Concurrently, the A+ construction project will be making preparations for a first phase of instrumentation installation during the O3-O4 break. The focus of this project will be making the necessary procurements and instrumentation designs to be prepared at the end of O3 to begin installing those elements of A+ that can be introduced without affecting preparations for O4.

There are many detector-related activities at the LIGO Hanford and Livingston observatories to support Observatory Scientific Operations:

- The Commissioning team is charged with bringing the detector configuration to a state that is appropriate to meet the upcoming run goals, and to document and transfer operating knowledge to the Detector group and operators. This activity is detailed below.
- The Detector group monitors, characterizes, maintains and repairs working detector configurations. Their goal is high-quality reliable uptime during runs. The Detector Group leaders manage Engineering Runs at the observatories, setting day-to-day priorities, scheduling work, approving interruptions, and tracking progress. The Detector Group leaders also chair the daily (or similar cadence) Engineering Run Management meetings and closely coordinate with the JRPC.
- The Detection Coordinators work for the best science outcome and lead Observational Runs at the observatories. Together with the LSC co-chair of the JRPC, they closely plan and monitor run readiness and performance, and act as the Lab's main liaisons with the LSC's detector characterization group.
- The Computing, Electronics, Facilities and Vacuum teams support operations both directly and indirectly related to the detectors. In general, these groups give priority to the operational phase currently underway, be it commissioning, running, or key preparations for these. During runs these groups' activities will be carried out in close consultation with Run Management. As they also support high-priority non-run-related activities, such as the safe stewardship of VE and infrastructure, cyber-security patching, and employee safety, not all of their work can be effectively overseen by Run Management.
- The LIGO Laboratory System, Optical and Mechanical Engineering groups are central to the planning of all activities related to the detectors, vacuum refurbishment efforts. Typical activities that will be undertaken over the next year will focus on particulate control, test mass point absorber R&D, improved automation of detector operation, and vacuum system recovery.
- The LIGO Laboratory Control and Data Systems (CDS) group maintains and updates the CDS suite of software used in real-time control and data acquisition systems deployed to the LIGO sites and

R&D facilities. This includes introducing updates to the software suite based primarily on changes in software packages not developed in-house and computer technologies (software improvement) and providing general support in the area of electronics design, fabrication, test and maintenance (electronics improvements).

The GEO Collaboration is responsible for the operation and maintenance of the GEO600 Observatory, taking data in “AstroWatch" mode while the LIGO detectors are being commissioned. Many technology developments to be implemented are first tested in GEO600, as was the case for the use of squeezing, now installed in Advanced LIGO.

Op-2.2 Virgo Detector Operations

Placeholder text for Virgo detector operations body — **virgoops.tex**

3 Detector Commissioning

Op-3.1 LIGO Detector Commissioning

LIGO Commissioning is the process of understanding the performance limitations of the instrument, and then improving the performance of the instrument through a combination of physical changes to the instrument and modifications of control software. It is typically iterative, and can lead to recognition of more significant required changes to realize improved sensitivity. It is undertaken by the commissioning team, the detector engineers, the LIGO Lab engineering group, and others as needed.

LIGO Commissioning is a responsibility of the LIGO Laboratory, and is principally undertaken by LIGO Lab staff. Non-lab LSC members may be welcome to participate under LIGO Lab direction; LSC Fellows typically are engaged in commissioning as an example. Mechanisms exist in the LIGO Lab's management of the commissioning and engineering processes to incorporate new elements of hardware and software in the operating instrument.

Site Commissioning leads manage the day-to-day and week-to-week commissioning efforts at their sites; mentor and coordinate team members, develop and maintain detailed knowledge of the detector performance and behavior; and devise ways to optimize it. The LIGO Lab Chief Detector Scientist coordinates overall strategy, oversees the commissioning teams, coordinates and mobilizes campus support, etc. In the context of run preparation, Commissioning is charged with bringing the detector configuration to a state that is appropriate to meet the the current and upcoming run goals, and to document and transfer operating knowledge to the Detector group and operators.

LIGO's third observing run (O3) began on April 1, 2019. O3 is planned to run for 1 year with a one month break in October 2019, thus ending early May 2020. A one month commissioning period may be scheduled for immediately after O3 to follow-up on instrument issues revealed during the run. During the run period, commissioning teams will contribute as needed to maintain detector performance at the levels achieved at the beginning of the run. In addition, there may be opportunities for short commissioning interventions to perform diagnostic tests to inform the post-O3 commissioning phase, or to make minor performance improvements. Up to 6h may be used each week for commissioning work during the Observing Run (see LIGO-L1800079). For an overview of how aLIGO-era runs are managed by the LIGO Lab, refer to LIGO-M1500247. In addition, during the run period teams across all four LIGO labs will work on Detector Improvements (DI) for O4. Commissioning activities planned during O3 include absorption monitoring, incremental increases in laser power, investigating mechanisms and paths leading to upconversion at LLO (during the day when seismic noise higher), and more PEM studies. Other than the potential commissioning month at the end of O3, the remaining 2020 period is devoted to Detector Improvements and A+ installation efforts; no commissioning will be conducted during this period.

Op-3.2 Virgo Detector Commissioning

Placeholder text for Virgo detector commissioning body — **virgodetcomm.tex**

4 Calibration

Op-4.1 LIGO Calibration

For the LIGO interferometers, *calibration* involves converting data streams from channels that monitor the feedback control loop that maintains the differential arm length into a derived time series that represents the inferred differential arm length variations, $h(t)$, which is normalized to the average arm length, approximately 4000m. $h(t)$ is referred to as *interferometer strain* or just *strain*.

Calibration of the LIGO interferometers is a task critical to the success of the data analysis algorithms, and the confidence associated with their results. As such, the LSC created in its bylaws a Calibration group, separate from the Detector Characterization group. The goal of the Calibration group is to provide calibrated $h(t)$ with sufficiently small uncertainties in amplitude and phase in both low and high latency, with the high-latency calibration typically providing the smallest uncertainty and the low-latency calibration being used for low-latency astrophysical searches and alerts.

Calibration of a detector is a complex task that involves instrumental hardware measurements, detector modeling, computer programs, and extensive validation and review. The time-domain calibrated data and its associated uncertainty is the main data product, and its generation is sufficiently complex that it needs a dedicated team for calibration and another one for review. The Calibration group is therefore co-chaired by two expert members of the calibration group, and the group includes LIGO Laboratory and other LSC scientists. It works along with a dedicated Calibration Review Committee which provides advice and vetting of this work. The Calibration group results are posted and documented on a web page[1] available to the LSC, and as with previous observing runs, will continue to be recorded in the electronic logs, software repositories, LIGO documents [2], and peer-reviewed articles [3, 4, 5, 6, 7, 8, 9].

As the interferometers improve in sensitivity, the era of precision gravitational-wave measurements will continue to intensify. The Calibration group is responding with intensified efforts to understand and reduce calibration uncertainty as well as to provide the most accurate calibrated data in as low-latency as possible. The need for a more precise high-latency calibrated data product is expected to remain in upcoming observing runs, however.

Activities planned for Advanced LIGO's third observing run include:

- **Calibration model software:** The calibration model software is being revitalized and improved in an effort to improve the workflow from calibration measurements, to model parameters, to generation of FIR and IIR calibration filters, to uncertainty estimation for a given gravitational-wave event. The new model software is written in the `Python` programming language and will be based off of the `Matlab` calibration software used in the first and second observing runs.

- **Calibration uncertainty estimate software:** The calibration uncertainty estimate software is being revitalized and improved. Notable improvements include automated generation of calibration uncertainty estimates with each significant gravitational-wave candidate and automated review checks on the calibration surrounding the time of each significant gravitational-wave candidate.
- **Calibration pipeline software:** The low and high latency calibration pipeline software requires constant maintenance to ensure smooth operation. Currently, the calibration pipeline software is a combination of front-end code and a `gstlal`-based code in low latency and `gstlal`-based code in high latency [9]. Planned improvements to the `gstlal`-based software include
  - implementing new methods for calculating time-varying calibration factors that will result in better accuracy.
  - improving the efficiency of on-the-fly FIR filter calculations where possible.
  - improving the computational speed and resource consumption of the pipeline.
  - reducing the overall latency of the pipeline.
  - implementing real-time monitoring into the pipeline.

  Planned improvements for the front-end based software include
  - implementing FIR filtering routines.
  - improving the accuracy of the front-end based calibration products.
  - continuing to develop a front-end calibration product that is corrected for all known time and frequency dependent parameters.
  - developing a front-end infrastructure for the new Newtonian Calibrator system.
- **Calibration monitoring tools:** The LIGO summary pages are used as the primary monitoring tool of the LIGO calibration outside of the control rooms. These pages need constant maintenance and upgrades to keep up with any changes and evolving checks on the calibration. For the next observing run, the Calibration group will be including the low-latency testing calibration data stream where new software changes are being prototyped onto the summary pages. Additionally, the group will develop real-time monitoring tools for the low-latency calibration pipeline and will develop and maintain tools for comparing different calibration versions during the review process.
- **Interaction of calibration with astrophysical analyses:** As more precise astrophysical and cosmological measurements are made from gravitational-wave events, calibration systematic error could become the dominant systematic error in these measurements. The Calibration group is partnering closely with astrophysical analysis groups to conclude what systematic errors could plague estimates of cosmological or astrophysical parameters. The tool being developed for these studies is the integration of calibration uncertainty estimates into the astrophysical parameter estimation pipelines. Feedback from studies on the effect of calibration systematic errors on astrophysical and cosmological measurements will inform how to proceed in improving the LIGO calibration. Additionally, studies that investigate the possibility of corroborating detector calibration using astrophysical signals, such as a binary neutron star event with an electromagnetic counterpart, are being revitalized.
- **Automate and standardize regular review checks:** The calibration review process is on-going as the calibration continues to evolve with the interferometers. In order to facilitate easier and faster review of the evolving calibration, the Calibration group will be automating calibration checks. In addition, the Calibration group will continue to maintain a repository of sensitivity curves that are vetted by members of the group.

- **NCAL:** We plan to continue development on a Newtonian Calibrator system as a promising support system / cross-check on the overall systematic error of the Photon Calibrator absolute reference. This includes installation and eventual use of the already-developed prototype with a functional H1 detector during O3, and a considerate effort in understanding all systematic error and designing the next generation with improved alignment references, assembly and installation techniques, and cross-coupling.

Op-4.2 LIGO Timing Diagnostics

Traceable and closely monitored timing performance of the detectors is mission-critical for reliable interferometer operation, astrophysical data analysis and discoveries. The Advanced LIGO timing distribution system provides synchronized timing between different detectors, as well as synchronization to an absolute time measure, UTC. Additionally, the timing distribution system must provide synchronous timing to subsystems of the detector. The timing distribution system's status is monitored continuously and is periodically tested in-depth via timing diagnostics studies.

Critical timing tasks include:

- verifying traceable performance of the timing distribution system,
- verifying the validity and accuracy of the recorded time-stamp,
- verifying the accuracy of the distributed timing signals,
- expanding the capabilities of data monitoring tools related to timing,
- availability of timing diagnostics for various subsystems,
- measuring and documenting the timing performance,
- reviewing the physical/software implementation and documentation of the timing distribution and timing diagnostics components.

Op-4.3 LIGO and Virgo Hardware Injections

Hardware injections are simulated gravitational wave signals added to LIGO and Virgo strain data by physically actuating on the test masses. They provide an end-to-end validation of our ability to detect gravitational waves: from the detector, through data analysis pipelines, to the interpretation of results. The hardware injection group is tasked with the development, testing, and maintenance of hardware injection infrastructure. This includes on-site software to carry out the injections at specified times. We also work with the search groups to maintain the software that generates gravitational waveforms suitable for injection.

Each data analysis group works with the hardware injection team, in different ways: Burst and CBC groups provide transient waveforms and determine suitable injection rates, the CW group selects the parameters for neutron star signals, which persist throughout the observing run, and the SGWB group typically carries out one or two $\approx$10 min injections during each observng run. The search groups analyze hardware injections during science and engineering runs to identify and solve problems as they come up, and the results of these studies are reported back to the hardware injection team so that adjustments can be made. Additionally, the LIGO and Virgo Detector Characterization groups collaborate with the respective hardware injection team to inject loud bursts, generally sine-gaussians, into h(t) to test coupling with auxiliary witnesses. This *safety* [10] information is used to inform DetChar analyses that identify, characterize, or model noise couplings between auxiliary witnesses and h(t).

Op-4.4 Virgo Calibration

During the Virgo science runs, the calibration measurements have been automated and extended to have some redundant data. It includes measurement of the absolute time of the Virgo data, measurement of the transfer function of the dark fringe photodiode readout electronics, measurement of the mirror and marionette actuation transfer functions and monitoring of the finesse of the arm cavities. The calibration outputs are then used (i) in the frequency-domain calibration, resulting in the Virgo sensitivity curve, (ii) in the time-domain calibration, resulting in the GW strain digital time series and (iii) for the hardware injections. Independent cross-check of the reconstruction has been done systematically during VSR4 using a photon calibrator. The methods used for Virgo will still apply for AdV after some tuning for the new configuration. Simulations have been carried on for the a priori most challenging measurements, i.e. the measurement of the mirror actuation response. They confirm that the Virgo methods can still be applied, putting some constraints on the minimum force to be applied on the AdV arm mirrors. In parallel a conceptual design of the new photon calibrator to be developed for AdV is being finalized before the setup is built and then installed. Critical calibration activities are:

1. development and improvement of instrumental measurements (in particular with the digital demodulation electronics of the photodiode readout),
2. prototyping and installation of a photon calibrator,
3. development of online tools to monitor the Virgo timing permanently,
4. upgrade the GW strain [h(t)] reconstruction method after the study of the impact of some parameters that were neglected during the Virgo era.

5 Detector Characterization

LIGO Detector Characterization

The LIGO detector characterization (DetChar) group has the dual responsibilities of investigating and mitigating misbehavior in the instrument, and providing data quality (DQ) information to the gravitational-wave searches to reduce the impact of artifacts in the data. In addition, the detector characterization group must help to validate the quality of the data around the time of candidate detections.

There are three top priorities: 1) contributing key work to the O3 observing run and search results, 2) supporting the upgrade and commissioning of the detectors during the commissioning break, and 3) preparing for future observing runs. In preparing for and contributing to O3, the highest priorities are automating event candidate validation, producing data quality infrastructure for low-latency EM alerts, developing key tools, monitoring data quality issues in the detector, vetting GW event candidates, and producing data quality products throughout O3. During the commissioning break, a high priority is conducting on-site and off-site investigations of interferometer and environment behavior to support the upgrade and commissioning efforts. The highest priorities in preparing for future observing runs are improved automation of key tools and event candidate validation, and improvement of monitors of known data quality features. Other high priorities are characterization of interferometer subsystems and auxiliary channels throughout O3, and curating data quality information for public data releases.

In parallel, the are a number of research and development tasks which have the potential to enhance the detector characterization mission. The highest priorities are investigation of which instrumental artifacts have the most severe impacts on each astrophysical search, development of existing machine learning and citizen science methods to identify the causes of noise transients, and the integration of various detector characterization tools into a central framework with common data formats. Longer-term goals are development of new methods, or improvement of existing methods, for noise identification and mitigation. This includes exploration of machine learning techniques and transient noise identification methods. All new methods should be performance tested with a data set and performance goals outlined by the DetChar group.

Overarching goals

- Continue to vet gravitational wave events and provide high caliber data quality products to astrophysical searches for the third LIGO-Virgo observing run (O3).
- Enabling investigations and innovation for future observing runs.
- Characterization of the LIGO gravitational wave detectors ahead of the third observing run.
- Automation of LIGO detector characterization tools and tasks and improved centralization and accessibility of tools and documentation.

The following sections outline the priorities for LIGO detector characterization work in 2019-2020 in terms of **O3**, or tasks necessary for the third LIGO-Virgo observing run, and **future observing runs**, or tasks required for the success of the next observing run and beyond.

LIGO detector characterization priorities are also specified as **central** or **critical research and development** tasks. **Central** tasks are any task required for the delivery of DQ products to the astrophysical searches and the public, and engagement in the detector commissioning. **Critical research and development** tasks are those undertaken to address noise sources problematic for a particular astrophysical search or search method, techniques that don't contribute directly to generating DQ vetoes, or exploratory research and development which is not yet certain to have a direct application to the central DetChar scope.

Op-5.1 LIGO Detector Characterization operations for O3

O. The third aLIGO observing run - O3

O.C. Prioritized list of central tasks

Highest priority tasks

O.C.1: DQ products for the astrophysical searches

- O.C.1.1. Developing, testing, and documenting offline DQ flags.
- O.C.1.2. Producing offline veto definer files, which define the DQ flags that are used to veto data for each individual astrophysical search.

- O.C.1.3. Reviewing offline veto definer files.
- O.C.1.4. Noise line studies to characterize line artifacts that impact searches for long duration gravitational waves.
- O.C.1.5. Support of online DQ products delivered with low latency h(t) frames; state information, data quality flags, iDQ timeseries, and veto definitions.
- O.C.1.6. Review of DQ products used to generate and evaluate DQ flags.
- O.C.1.7. Post-run investigation of worst offender noise sources. Particularly:
  - Blip glitches
  - Mid-frequency noise (e.g. 60-200 Hz non-stationary 'blue mountains')
  - Anomalous environmental coupling (e.g. airplanes, thunderstorms, periscope motion, beam clipping)
  - *See LIGO DCC P1600110 for more information on the noise sources.*
- O.C.1.8 Produce h(t) frames that have noise contributions linearly subtracted, when noise sources with auxiliary witnesses exist.

O.C.2: Vetting GW event candidates

- O.C.2.1. Using the automatically produced Data Quality Report (DQR) [11, 12] to vet the data quality around gravitational wave event candidates, including evaluating environmental couplings.
- O.C.2.2. Field a DetChar rapid response team to vet the data quality for low-latency gravitational wave candidate events.

O.C.3: Monitoring known or new DQ issues

- O.C.3.1. Contributing to conducting or mentoring DQ shifts: Data quality shifts will be the primary means of ensuring full coverage of h(t) data quality analysis for both detectors during O3, including limiting factors to interferometer performance such as weather or earthquakes. Data quality shifters must invest first in training, and a qualified mentor must be identified for new volunteers.
- O.C.3.2. Mentoring and training scientists participating in the LSC fellows program, which supports LSC scientists working at the site to improve the detector data.
- O.C.3.3. Maintenance and characterization of the Physical Environment Monitor (PEM) sensors.

O.C.4: Commissioning support

- O.C.4.1. Tracking issues that affect interferometer uptime, such as seismic motion.
- O.C.4.2. Investigating noise sources that limit detector sensitivity; for example, hour-scale correlations between h(t) and auxiliary channels or jumps in detector binary neutron star range.

O.C.5: Maintaining key tools

- O.C.5.1. Support of key tools, including user feedback and documentation for key infrastructure as listed below.
- O.C.5.2. Review of key tools, particularly those used to generate vetoes.
- List of key infrastructure and tools:
  - Fundamentally necessary services:
    - The summary pages [13]; an invaluable set of webpages containing key plots that describe the state and behavior of the LIGO detectors and their environment
    - The Data Monitoring Tool (DMT) [14], including the low-latency DMT DQ vector infrastructure
    - The segment database [15]; which stores state and DQ flag information used by the astrophysical searches
    - Omicron triggers [16], which identify transient noise triggers, including in low-latency, delivered with very high reliability
    - Data Quality Reports [11, 12], which automatically produce and display results from all tools necessary to validate the data quality surrounding candidate events. Many of the highest priority software tools are needed for this necessary service.
    - Safety information [10], which flags auxiliary channels that witness the gravitational wave strain readout, such that a passing gravitational wave might also induce a response in an *unsafe* auxiliary channel in addition to h(t). Accurate and up-to-date safety information is necessary for interpretation of any tools that correlate auxiliary channels with h(t) to model or infer noise couplings.
  - Highest priority software and services
    - iDQ [17]
    - GstLAL Feature Extractor [17]
    - GWpy [18]
    - GW-DetChar [19] (which contains Omega scans, LASSO, automated monitoring of scattering, ADC/DAC overflows and software saturations)
    - GWSumm [20] (which is used to generate the summary pages)
    - Stochmon [21]
    - STAMP-PEM [22]
    - Hveto [23]
    - ligoDV web [24]
    - Channel Information System [25]
    - Pointy Poisson [26]
    - VET [27]
    - Offline noise subtraction code [28]
    - Suite of remote access tools (remote MEDM and EPICS [29], remote DataViewer [30]
    - LigoCAM [31]
    - Automated safety studies [32]
    - GravitySpy [33]
    - FScans and dependent programs / scripts (spectral ratio, comb tracker)[34]

This list relies on software dependencies maintained by the LIGO Laboratory (e.g. the Guardian [35],), the LSC Computing and Software Committee (e.g. low-latency data distribution), the LSC Remote Access group (e.g. NDS2), and the Virgo Collaboration (e.g. Omicron, NoEMi). While those software elements are not in the scope of DetChar, continued maintenance of the software, adaptation for use on LIGO data, and operations on LIGO data are of the highest priority to enable LIGO science

- List of development standards for DetChar codebase:
  - Code is open source
  - Code is hosted on github.com or git.ligo.org to enable a github-flow-style development cycle
  - Code includes web-accessible documentation
  - Code includes unit testing
  - Code includes clear and complete installation instructions
  - Code configuration files are available and up to date
  - Python is recommended for development to maximize compatibility with existing tools, reducing duplication-of-effort and redundancy

O.C.6: Interfacing with commissioners, site staff, and search groups

- Interfacing with commissioners and instrument experts to propagate instrument changes and developments to detector characterization investigations and monitoring.
- Using the Fault Reporting System (FRS) and the electronic logs (alogs) to communicate results and request tests.
- DQ liaisons identified by each pipeline should identify and report sensitivities in the pipelines to data defects.

O.C.7: Characterization of interferometer and auxiliary channels throughout O3

- O.C.7.1. Evaluate the environmental couplings of the interferometers throughout LIGO's third observing run, O3.
- O.C.7.2. Characterization and documentation of interferometer subsystems.
- O.C.7.3. Maintenance of lists of auxiliary channels useful for DetChar studies.
- O.C.7.4. Maintenance of summary page content.
- O.C.7.5. Signal fidelity studies of auxiliary channels.
- O.C.7.6. Auxiliary channel safety studies throughout O3.
- O.C.7.7. Development and improvement of PEM sensors and sensor characterization.

The LIGO Detector Characterization subsystem leads, as described in 'LIGO DetChar Roles', will play a critical role here.

O.RD. Prioritized list of critical Research and Development tasks

Highest priority tasks

O.RD.1: Investigation of the search backgrounds

- O.RD.1.1. Studying how instrumental artifacts affect the sensitivity of a specific search or search method.
- O.RD.1.2. Developing search-specific techniques for noise mitigation.
- O.RD.1.3. Investigating the loudest background outliers for a specific search or search method.

The standardized metric for assessing the impact of DQ information on a particular search will be search volume-time (VT), measured by the effect on the background of each search and on recoverability of signals. Population model assumptions in these studies should be clearly documented.

O.RD.2: Machine learning for O3

- O.RD.2.1. Gravity Spy citizen science and machine learning classification to identify instrumental causes for glitch classes.
- O.RD.2.2. Machine learning classification studies targeting known O3 noise sources, e.g. scattering.

Op-5.2 LIGO Detector Characterization preparation for future operations

Future observing runs

F.C. Prioritized list of central tasks for future observing runs

Highest priority tasks

F.C.1: Automation of key tools

- F.C.1.1. Automation of DQ veto performance testing.
- F.C.1.2. Development of DQ products necessary for fully-automated EM alerts.
- F.C.1.3. Further automation of results displayed within the DQR, with the end goal of full automation (no or limited human intervention required for interpretation)

F.C.2: Characterization of interferometer and auxiliary channels during A+ installation and for future observing runs

- F.C.2.1. Evaluation of the environmental couplings of interferometer subsystems during A+ installation.
- F.C.2.2. Documentation of planned or newly installed interferometer subsystems and environmental monitors.

- F.C.2.3. Maintenance of lists of auxiliary channels useful for DetChar studies to include new subsystems and environmental monitors.
- F.C.2.4. Maintenance of summary page content to include new subsystems and environmental monitors.
- F.C.2.5. Signal fidelity studies of newly installed auxiliary channels.
- F.C.2.6. Auxiliary channel safety studies for new subsystems and environmental monitors.
- F.C.2.7. Development and improvement of PEM sensors and sensor characterization for A+ and future observing runs, e.g. magnetometers to monitor Schumann resonances in the Earth's electromagnetic field.

The LIGO Detector Characterization subsystem leads will play a critical role here.

F.C.3: Improve monitors of known DQ features

- F.C.3.1. Improving monitoring and reporting of digital and analog overflows, reaching software limits, and other kinds of saturations; monitoring and reporting of real-time data handling errors (timing, dropped data, etc).
- F.C.3.2. Improving monitors for excess mirror motion leading to scattered light.
- F.C.3.3 Schumann resonance studies.
- F.C.3.4 Develop tool to query stochastic monitors to find which auxiliary channels are coherent with the gravitational wave strain data at a given frequency.
- F.C.3.5. Optic suspension resonance 'violin mode' monitoring.

F.C.4: Curation of DQ information for public data releases

- F.C.4.1. Curation, documentation, and review of DQ vetoes for release by the GW Open Science Center (GWOSC) [36].
- F.C.4.2. Development and documentation of the "Detector status" public summary pages hosted by the GWOSC [13]

LT-5.3 LIGO Detector Characterization development

High priority tasks

F. C. 5: Predict noise performance based on instrument state using machine learning

- F.C.5.1. Change point detection

F.RD. Prioritized list of critical Research and Development tasks for future observing runs

Highest priority tasks

F.RD.1: Develop improved clustering for Omicron

- F.RD.1.1. Improve Omicron clustering scheme to more accurately report timing, frequency, SNR of excess power.

F.RD.2: Integration of key tools to be cross-compatible

- Wherever possible, all tools in common use (i.e. excluding those in the early stages of development) should share a well-maintained, well-documented, and accessible codebase.
- All triggers and data products will be stored in appropriate common data formats [37] and will be discoverable with common tools (see key tools listed in Section O.5). For instance, any data product should be accessible in a single function call on a site cluster.
- Improve documentation and support of key tools: All DetChar tools in common use should be fully and centrally documented, accessible on the LDAS clusters (or easy to install), and well supported by responsive experts.

High priority tasks

F.RD.3: Quantify the impact of transient noise on parameter estimation

- F.RD.3.1 - test the effects of transient noise on recovered source properties
- F.RD.3.2 - develop and test methods to reconstruct and remove from h(t) isolated glitches and other noise types without auxiliary witnesses

F.RD.4: Research and development of new methods for noise identification/mitigation
Any new methods are to be tested and validated on recent Advanced LIGO data in a performance test outlined by the DetChar group.

Additional priority tasks

F.RD.5: Development of improvements to existing tools/pipelines for noise identification/mitigation
For example, exploration of supplementary machine learning techniques for spectrogram image-based glitch classification or supplementary event trigger generators outside of software listed in O.C.5. Any new methods are to be tested and validated on recent Advanced LIGO data in a performance test outlined by the DetChar group.

LIGO DetChar Tools Policy

The major goals of this plan are to establish a framework for LIGO DetChar tools that maximizes the ease and efficiency of comparison of techniques as well as access to results. This plan should serve as a guide to facilitate involvement that will be maximally useful to LIGO detector characterization. This policy seeks to promote the application of tools and techniques to improve the data of the LIGO detectors.

Requirements for the DetChar group

- An infrastructure supporting common data formats should be developed, well-documented, well-advertised, and supported. A 'data format' committee is charged with this task and updating the DetChar group regularly.
- Evaluation metrics and 'mock data challenges' featuring common data sets and training sets to be used for testing should be supported for tools in development, including supervised and unsupervised machine learning work. These mock data challenge data sets should be well documented and well advertised to the group.
- Standardized safety protocol should be developed for all tools that use auxiliary channels.

Requirements for tool developers

- No restrictions or requirements will be made on methods or techniques for development, or input formats to these methods, with the exception of requiring use of standardized auxiliary channel safety information (where applicable).
- All DetChar tool developers are responsible for producing code and technique documentation, including the code itself and usable instructions for running the code.
- All DetChar tools should make results available for use by the DetChar group in the appropriate common data format(s).
- All DetChar tools that make use of auxiliary channels are required to use the standardized auxiliary channel safety protocol from the earliest stages of development.
- All DetChar machine learning and classification tools should produce results for DetChar evaluation metrics and mock data challenges in the common data format.

Any tools or techniques that meet the indicated requirements will be eligible to be counted as InfraOps for MOU reports (pending agreement by the MOU review committee), eligible to be included in any LIGO DetChar technique comparison papers with a full LSC authorlist, and the work will be counted as 'applied to LIGO data' for MOU reports and statements made in talks or papers that go through internal LIGO Presentations and Publications review.

LIGO DetChar Roles

There are many active roles within the LIGO detector characterization group, and often some people have more than just one role. There are two appointed DetChar chairs at present who oversee and steer the entire group. Working alongside them is a small committee who lead the data quality, instrument characterization, DetChar-specific computing, and event validation efforts. This committee is structured by the DetChar co-chairs, and members are appointed by the DetChar co-chairs. Within the instrumentation sub-group are subsystem leads, each of whom are responsible for understanding and maintaining the eleven subsystems from the DetChar perspective. Each subsystem typically has one lead person, however the more complicated subsystems have two leads. The review chair of the LIGO DetChar group manages the review of critical DetChar code and coordinates code configuration control with other working groups for observing runs. A small group of people also oversee, maintain and develop the key software required by the DetChar group. The structure of the DetChar group is viewable in the LSC Organisation Chart LIGO-M1200248.

Op-5.4 Virgo Detector Characterization

Placeholder text for Virgo detector characterization body — **virgodc.tex**

LT-5.4 Virgo DetChar developement

Placeholder text for longer-term development of Virgo DetChar.

6 Computing and Software

The LIGO-Virgo Computing Committee coordinates the provisioning of computing hardware, software, and services that enable rapid analysis of data and dissemination of information in support of the scientific mission of the LIGO-Virgo Collaboration. The primary goals for computing and software are:

- Maintain a stable computing environment on the LIGO Data Grid (LDG) that meets the needs of the Observational Science Working Groups while expanding available computing through the LIGO-Virgo Computing Grid (LVCG), Open Science Grid (OSG), and other resources.
- Develop and maintain data handling infrastructure for both low-latency and bulk (offline) analysis.
- Assist Working Groups in developing, maintaining, and distributing scientific software to perform analyses.
- Maintain necessary computing services for the collaboration(s) at large (wikis, voting, etc).

Op-6.1 LIGO collaboration support

In order to enable communication and management of the LVC on a day-to-day basis, the Collaboration(s) require a number of "back office" computing services. (Some of these services may also support data analysis computing, but all of them address needs of the collaboration independent of data analysis computing.)

Op-6.1.1 Operations

1. LIGO Identity and Access Management (LIAM)
   (a) Highest priority:
      i. Maintain LIGO Identity Management System (myLIGO) service
      ii. Maintain LIGO Group manager (Grouper) service
      iii. Maintain LIGO machine readable directory (LDAP) service
      iv. Maintain LIGO Kerberos system service
      v. Maintain LIGO Shibboleth Identity Providers (including backups)
      vi. Maintain Google Apps for Education services for LIGO.ORG
      vii. Maintain software to sync LIGO.ORG with LIGO Data Grid accounts
      viii. Maintain service to manage external collaborations (COManage)

2. Collaboration services
   (a) Highest priority:
      i. Maintain collaboration website (www.ligo.org)
      ii. Maintain collaboration mailing list server(s) (sympa.ligo.org)
      iii. Maintain robot credential creation system (robots.ligo.org) and associated credentials
      iv. Maintain remote participation systems (TeamSpeak)
      v. Maintain collaboration wiki (wiki.ligo.org)
      vi. Maintain collaboration VCS (git.ligo.org)
      vii. Maintain collaboration elections system (vote.ligo.org)
      viii. Maintain publications and presentations review system (pnp.ligo.org)
   (b) High priority:
      i. Maintain collaboration chat forum (chat.ligo.org)
      ii. Maintain collaboration roster web interface (roster.ligo.org)
      iii. Maintain shared secrets service (secrets.ligo.org)
      iv. LVC Computing Security Officer/s [unfilled]
      v. LVC Computing and Software Chairpersons
      vi. LVC LIAM Coordinator/s
   (c) Additional priority:
      i. Maintain collaboration Q&A site (ask.ligo.org)
      ii. Maintain legacy collaboration mailing list server(s) (AEI)
      iii. Maintain legacy collaboration bug tracking server(s) (AEI)

Op-6.1.2 Development

1. Develop and deploy infrastructure for federated (i.e. institutional) identity usage within LIGO
2. Advise and assist LIGO India to create an identity and access management system
3. Decommission legacy mailing-list server @ AEI (migrate to sympa.ligo.org)
4. Decommission legacy bug tracker @ AEI (migrate to git.ligo.org)
5. Migrate collaboration mailing-list server to cloud-based provision
6. Implement multi-factor authentication for LIGO services
7. Redesign recommended SP configuration to use Pyff, SaToSa and the new InCommon Meta-Data Query service
8. Enforce secured connections to LIGO LDAP hosts
9. Reorganise and consolidate LDG account management and credential services
10. Select a new observatory-independent international 2G GW computing network moniker and systematically update legacy names (LIGO.ORG, LVC, LVK, LVCG, LDG) for common LVC computing infrastructure (DNS, mailing lists, web services, documentation, collaboration management documents, etc.) wherever appropriate and possible.

11. Over the next six months, LIAM administered LDAP master and replicas will enforce connections over TLS and/or SSL (currently, most replicas accept plain text connections). LIAM will also work with other LIGO LDAP admins (e.g. observatory sites) to enforce this as a LIGO-wide policy. This will increase the security posture of LDAP. Over the subsequent six months, LIAM administered LDAP Master and replicas will enforce GSSAPI binding or local whitelisting for authenticated binds. LIAM will also work with other LIGO LDAP admins to enforce this policy.

12. Over the next six months, Grouper will be upgraded to at least version 2.3 in order to facilitate other intiatives within the LIAM group. As part of this process, we will investigate using the Docker image of Grouper provided by the InCommon Trusted Access Platform. This will reduce future upgrade and maintenance costs if it is successful. Finally, over the next year, we will begin the slow process of reorganizing the Grouper tree to separate authorizations groups from organizational groups to facilitate easier management and to allow broader leverage of these groups.

LT-6.2 LIGO collaboration support: research and development

1. Explore expanding gw-astronomy.org to possibly include one more collaborative work tools.

2. Integrate CILogon-managed COmanage instance dedicated to LVK IdM, and write plugins against COManage to provide the organizational logic that is currently encoded in myLIGO

Op-6.3 LIGO data analysis support

Op-6.3.1 Resource Provisioning

1. Provisioning, maintenance, and support of dedicated batch computing clusters (or dedicated batch computing allocations) of CPU or GPU nodes and storage for use by all authorized LDG users according to DAC scientific priorities and CompSoft scheduling. Note: effort necessary to provision, maintain, and support computing resources dedicated in advance to local LVC science priorities (rather than those prioritized by the Collaboration/s) is explicitly excluded as LVC work in this whitepaper.

Op-6.3.2 Operations

1. Data handling

   (a) Maintenance and support of stable low-latency data distribution from the LIGO observatories to CIT, and from CIT to other LVC low-latency computing centers
   (b) Maintenance and support of stable bulk data transfers between Tier-1 computing centres (LHO, LLO)
   (c) Maintenance and support of stable bulk data transfers to LVC computing centres
   (d) Maintenance and support of stable bulk strain data publishing to CVMFS
   (e) Maintenance and support of the Gravitational-wave Candidate Event Database (GraCEDB)
   (f) Maintenance and support of the LIGO-Virgo Alert (LVAlert) messaging service
   (g) Maintenance and support of the LIGOdv Toolkit
   (h) Maintenance and support of the Network Data Service server

(i) Maintenance and support of CVMFS repos for LVC containers
(j) Maintenance and support of public CVMFS repo for LVC software (currently OSG-hosted)
(k) Maintenance and support of private LVC CVMFS repo for proprietary data
(l) Maintenance and support of public CVMFS repo for open GW data
(m) Maintenance and support of public CVMFS repo for Conda software environments

2. Application building blocks

   (a) Highest priority:
      i. Maintenance and support of the Grid LSC User Environment (GLUE)
      ii. Maintenance and support of the LSC Algorithm Library Software Suite
      iii. Maintenance and support of the Frame File Access and Discovery Tools
      iv. Maintenance and support of the Frame File I/O Library
      v. Maintenance and support of the Data-Quality Segment (DQSegDB) Service
      vi. Maintenance and support of the Data Quality Database Client Tools
      vii. Maintenance and support of the LIGO Lightweight Data I/O Library
      viii. Maintenance and support of the Global Diagnostic System
      ix. Maintenance and support of the GraCEDb Command-line Clients
      x. Maintenance and support of the LVAlert Messaging Client Toolkit
      xi. Maintenance and support of the VOEvent I/O Library

   (b) High Priority:
      i. Maintenance and support of the Network Data Service Client
      ii. Maintenance and support of the LDG Docker/Singularity container
      iii. Maintenance and support of the low-latency, streaming data toolkit (gstlal)

   (c) Additional priority:
      i. Support, build, and publish new Debian binary distributions of critical GW software
      ii. Development of the Frame File Access and Discovery Tools

3. Engineering and Operations

   (a) Highest priority:
      i. Maintenance and support of interactive computing servers for LVC data analysis software development and testing.
      ii. Maintenance and support of interactive HTCondor computing servers for users to submit and manage data analysis workflows on the LDG and LVCG.
      iii. Maintenance and support of software package repositories to host RPM binary distributions of GW software for the LVC Reference Operating System.
      iv. Maintenance and support of Conda repository of GW software for LVC data analysis
      v. Coordinate control of changes to computing environments via the Software Change Control Board
      vi. Support, build, and publish new binary RPM distributions of critical GW software
      vii. Support, build, and publish new binary Conda distributions of critical GW software
      viii. Optimization Lead/Coordinator (incl. reporting of status and results to the NSF).

ix. Maintenance and support of the distributed computing infrastructure of the LVCG (HTCondor, CVMFS, GlideinWMS, Open Science Grid. etc.).
x. Infrastructure Monitoring Services
xi. Maintenance, and support of resource Accounting and Reporting Services
xii. GDS Service Operations

(b) High priority:

i. Maintenance and support of automated Build and Test (CI) Services
ii. Code Performance and Resource Optimization
iii. Workflow Portability/Migration
iv. LVCG Operations ("grid sysadmin/support")
v. LVC support for externally-developed tools (incl. liaising w/collaborator or vendor):
vi. HTCondor (Condor Team)
vii. Workflow Portability/Migration Infrastructure (Condor Team, OSG, IRIS-HEP)
viii. CUDA (NVidia)
ix. Intel Development Tools (icc, mkl, etc.) (Intel)
x. FFTW (FFTW community)
xi. Matlab (Mathworks)
xii. Expert optimization consulting in support of profiling and optimizing the most computationally demanding LVC DA pipelines.

(c) Additional priority:

i. Maintenance and support of hardware test stands (CPU and GPU) and software tools for code and workflow optimization and testing.
ii. Maintenance and support of software package repositories to host Debian 9 binary distributions of GW software for the LIGO Laboratory.
iii. Improve user documentation and tutorials for data analysis computing
iv. Expert consulting (on architecture, software engineering, optimization, etc.) to support the design, development, and improvement of data analysis workflows on the LDG and LVCG.
v. Document current best practices for data storage, access, and movement in LDG and LIGO-Virgo computing grid environments for common use-cases at a variety of scales (e.g., cluster filesystems vs. git vs. git-lfs vs. CVMFS vs. other).

Op-6.3.3 Development

1. Document the LIGO Data Grid and LIGO-Virgo Computing Grid architectures, services, best practices, near-term plans, and long-term vision for LVC users, LVC management, funding agencies, and external computing experts.

2. Develop and maintain an LSC Computing "Risks Registry" to be reviewed regularly by CompSoft and wider LSC management.

3. Simplify and consolidate LVC software packaging and deployment infrastructure and processes to lower FTE cost and improve robustness.

   (a) Continue to develop a cross-platform software distribution system (Conda)
   (b) Build LDG containers via Conda rather than via RPMs.

4. Code and resource optimization

    (a) In collaboration with the Condor Team, develop and test a solution for safely running offline data analysis jobs in the background on LIGO Data Grid resources provisioned for low-latency workflows, to capture idle cycles.

    (b) Develop an updated solution for running "backfill"-priority data analysis jobs on temporarily-idle CPU and GPU LIGO Data Grid resources.

    (c) In collaboration with the Condor Team, develop and test scheduling techniques to reduce the wall-clock duration of data analysis workflows by reducing the impact of "long tail" jobs.

    (d) Integrate new computing providers into the LVCG.

    (e) Identify and provision new hardware (CPU and GPU) and software tools for code and workflow optimization and testing.

5. Improve the robustness, scalability, and usability of the LIGO Data Grid and LIGO-Virgo computing grid

    (a) Develop, maintain, and extend user tutorials for running data analysis workflows on the LIGO Data Grid and LIGO-Virgo computing grid.

    (b) Improve cluster scalability and facilitate the convergence of local and distributed data analysis computing environments by designing and prototyping a hierarchical LDG cluster environment at CIT where available resources scale as a function of workflow portability with respect to data access and software dependencies.

    (c) In collaboration with the Condor Team, develop and test simpler and more powerful capabilities for selecting GPU devices and GPU capabilities by data analysis jobs.

    (d) Improve the efficiency of distributed data analysis workflows by maintaining and extending the LVC-specific grid site-commissioning test suite run automatically by pilot jobs on non-LVC resources before LVC jobs can be matched.

    (e) In collaboration with OSG, reduce the user and admin effort necessary to successfully run large, complex data analysis workflows by developing and testing simpler and more powerful tools to instrument, inspect, monitor, profile, and debug workflows (individually and in aggregate) during and after their execution.

    (f) In collaboration with the Condor Team, improve Condor's support for application-level checkpointing to optimize data analysis workflow efficiency and enable more flexible and efficient LVC resource scheduling.

    (g) Improve the robustness of production data analysis computing (and the flexibility of data analysis development and testing environments) by deploying interactive HTCondor computing servers at CIT dedicated to development, testing, and production.

    (h) In collaboration with the Condor Team, improve the portability and scalability of data analysis workflows by designing and prototyping a plugin mechanism for the LVC to define a first-class "GW" data type for job i/o integrated with gw_data_find and other LVC data management services.

    (i) Improve the completeness, accuracy, and usefulness of LVCG Resource Accounting and Reporting

LT-6.4 LIGO data analysis support: future research and development

1. Define requirements for non-distributed (local/dedicated) cluster environments from Detchar and the ”long-tail” of LVC data analysis pipelines (less compute-intensive workflows that are difficult/expensive to adapt to run on distributed resources), in order to inform plans for the future evolution and convergence of the LDG and LVCG environments.

2. Evaluate additional opportunities to improve the robustness of the production LVC data analysis computing environment (and the flexibility of data analysis development and testing environments) by deploying services dedicated to development, testing, and production activities rather than singular services supporting all three activities.

3. Identify opportunities and risks of transitioning non-GW-specific computing infrastructure and services from internal LVC management to external management by domain experts (institutional, NSF, CERN, OSG, commercial, etc.).

4. Identify opportunities and risks of unifying additional LIGO and Virgo computing infrastructure, services, and management to joint/centralized LVC (or broader 2G GW) management.

5. Evaluate opportunities to improve the efficiency and robustness of LVC data analysis by establishing/enhancing the continuous integration (CI) of LVC software and infrastructure via new build/test capabilities, consulting, etc.

6. Define roadmap for the LIGO_LW data format and its support.

7. Evaluate opportunities to reduce software binary packaging and deployment effort, and define a roadmap and timeline for LVC support of current software binary packaging systems (e.g., RPM, Debian, Conda, PIP) and/or repositories.

LT-6.5 Virgo Computing

In the Virgo Computing Model (CM) [38], during science runs the Cascina facility is dedicated to data production and to different detector characterization and commissioning analysis, which have the need to run on-line (with a very short latency, from seconds to minutes, to give rapid information on the quality of the data) or in-time (with a higher latency, even hours, but which again produce information on the quality of the data within a well defined time scale). The detector characterization activity gives support to both commissioning and science analysis. Science analyses are carried out offline at the AdV Tier 1 Computing Centers (CC), with the only exception of the low latency searches. Some analysis, due to the fact that we analyze data jointly with aLIGO for many searches, are carried on in aLIGO CCs. AdV CCs must guarantee fast data access and computing resources for off-line analyses. They must also provide the network links to the other AdV computing resources. For this goal a robust data distribution and access framework (based on file and metadata catalogs) is a crucial point. The AdV collaboration manages also smaller CCs used to run part of some analyses, simulations or for software developments and tests, in which the CM does not foresee specific data transfer and access frameworks. To face the huge computational demands of GW searches in the Advanced Detector Era (ADE), there will be the need to gather the resources of many CCs into a homogeneous distributed environment (like Grids and/or Clouds) and to adapt the science pipelines to run under such distributed environment. Another very important need is to provide a Grid-enabled, aLIGO-compatible Condor cluster for AdV people. We are also considering the possibility to run search pipelines in GPU clusters. The AdV CM will continue to guarantee (in at least one CCs where the raw data are archived) local access to the data and to the computing resources, as requested for the offline detector characterization studies and for software development and testing purposes. Most GW searches require the use of a network of GW detectors (at least AdV and aLIGO). As a consequence, these search pipelines must be able to run either in AdV or aLIGO CCs. It is therefore important to develop pipelines adaptable to different environments or interfaces which hide the different technologies to the users.

The following sections outline the priorities for the Online and Offline Computing in 2019-2020 in terms of the **O3** LIGO-Virgo observing run, **future observing runs** and beyond.

Op-6.6 Virgo Computing operations for O3

O. The third AdV observing run - O3

O.C. Prioritized list of central tasks

Highest priority tasks

O.C.1: Virgo Platform and Services

- O.C.1.1. Finalize the expansion of the Cascina storage farm to the agreed 1 year raw data buffer
- O.C.1.2. Improve systems reliability by pushing strongly further on on-line/out-of-line systems decoupling
- O.C.1.3. Monitor the existing bulk data transfer to Tier1 CC links in order to maintain the quasi-real time performances achieved
- O.C.1.4. Monitor the V1 aggregated hoft files transfer to CIT (based on LDR)
- O.C.1.5. Monitor Detchar and Low Latency pipelines (cWB and MBTA) performances

O.C.2: Software Management

- O.C.2.1. Maintain new software package version deployments and servers configurations under control
- O.C.2.2. Follow-up on SCCB procedures for all packages under its control

O.C.3: Low Latency data distribution

- O.C.3.1. Monitor the CIT <-> Cascina low latency links (currently based on Cm)

O.C.4: Multi Messenger Astronomy

- O.C.4.1. Increase the support to the LV Low Latency group in terms of software development and code review
- O.C.4.2. Support the development of an end-to-end low latency test pipeline

O.C.5: Offline Computing Services

- O.C.5.1. Transition into production for the capability to transfer O3 LV hoft data from CIT to Virgo CC via Rucio
- O.C.5.2. Verify and complete coverage of existing computing accounting mechanisms

O.C.6: Data Analysis Tools And Pipelines

- Progress with the capability to run LV pipelines into Virgo CC, in particular by using HTCondor as common submission interface
- Progress with the full integration of existing Virgo CC into the LIGO-Virgo Computing Grid (LVCG)

O.C.7: Open Science

- O.C.7.1. Prepare for O3 data release
- O.C.7.2. Improve existing web services for software and data release

Op-6.7 Virgo Computing preparation for future operations

F.C. Prioritized list of central tasks for future observing runs

Highest priority tasks

F.C.1: Virgo Platform and Services

- F.C.1.1. Transition bulk data transfer to EGI/OSG framework based solution (most probably Rucio)
- O.C.1.2. Transition V1 aggregated hoft files transfer from LDR to Rucio

F.C.2: Software Management

- F.C.2.1. Transition from Virgo Cascina SVN software archive to GW community git software archive
- F.C.2.2. Transition from CMT to CMake for software build
- F.C.2.3. Transition to Conda for software environment definition and software packaging
- F.C.2.3. Full deployment of CVMFS for software distribution from Virgo Cascina
- F.C.2.4. Use of containerization technology to support software distribution

F.C.3: Low Latency data distribution

- F.C.3.1. Transition to Kafka for all low latency data links

F.C.4: Multi Messenger Astronomy

- F.C.4.1. Keep increasing the support to the LV Low Latency group in terms of software development and code review

- F.C.4.2. Support the finalization and extention of the end-to-end low latency test pipeline
- F.C.4.3. Propose and implement alternative/redundant high reliability deployment solutions for critical components (possibly based on technologies such as kubernetes or similar)

F.C.5: Offline Computing Services

- O.C.5.1. Finalize design/test and transition into production for the general data transfer + data distribution solution (most probably based on Rucio + CVMFS + xCache)
- O.C.5.2. Define and implement the data cataloguing and bookkeeping solution (most probably based on Rucio)

F.C.6: Data Analysis Tools And Pipelines

- Generalize the capability to run LV pipelines into every Virgo CC
- Integrate any new computing centers joining the Virgo Collaboration into the LVCG.

F.RD. Prioritized list of Research and Development tasks for future observing runs

Essential

F.RD.1: Data Analysis Tools And Pipelines

- F.RD.1.1 - Identify a solution for High-level workload orchestration
- F.RD.1.2 - Identify a generic solution for Monitoring and accounting distributed computing

Exploratory

F.RD.2: Development of Machine and Deep learning technologies

- F.RD.2.1 - Transient signal classification
- F.RD.2.2 - Machine Learning for Multi Messenger Analysis

Virgo Computing group structure and roles

In term of organizational structure the Virgo Computing group is mainly divided in two areas: the AdVirgo Site Computing Infrastructure and Low-latency/Online Computing on one side and the Offline Computing on the other side. This has corresponded to the creation of two managerial profiles, under the recommendation of the EGO External Computing Committee (ECC), named AdV Data Processing Infrastructure (DPI, aka Online Computing) coordinator and AdV Computing and Data Processing (CDP, aka Offline Computing) coordinator. Details on the group organization in term of Work Breakdown Structure (WBS) can be found in VIR-0019C-19 [39].

7 LSC Fellows Program

Op-7.1 LIGO Scientific Collaboration Fellows

LSC Fellows are scientists and engineers who are resident at the LIGO observatories for extended periods of time [**?**].

The LSC Fellows program is entering its fifth year and has become a major success, enabling LIGO Laboratory to host junior scientists for at least a quarter and sometimes longer. This has provided the learning opportunity of gaining hands-on experience at either of the two LIGO observatories. The LSC Fellows carry out critical LSC activities supporting LIGO Laboratory commissioning and scientific operations, and can engage in a variety of activities, including: detection coordination efforts during observing runs; detector commissioning; installation of detector improvements; detector calibration; and detector characterization.

During O3 in 2019-2020, LSC Fellows will monitor the quality of the data and participate in investigations with the commissioning and detector characterization groups. As members of the local rapid response teams at each site LSC Fellows will perform investigations related to publicly announced event candidates. LSC Fellows work with on-site mentors or liaisons depending on their initial level of expertise and the nature of their project.

8 LIGO A+ Upgrade

Op-8.1 LIGO A+ Upgrade

The “A+ detector" project is a major upgrade to the existing Advanced LIGO detectors, beginning in 2019 and expected to continue through the end of 2023. The A+ project in 2019 will be carried out in parallel with the O3 observing run.

Design and procurement for A+ is underway, led by the LIGO Lab and international partners and with support by members of the LSC. The implementation of A+ has design, fabrication, assembly, and test of components in parallel with the observing runs, and with intensive installation during commissioning breaks. In the measure possible, A+ elements will be integrated with the existing aLIGO instruments to make incremental improvements in the performance. In particular, the A+ project plans to install the filter cavity between O3 and O4. This involves civil construction, vacuum system enlargements, installation of new seismic and suspension components, and commissioning.

Activities related to A+ operations are: testing frequency dependent squeezing at 1064 nm; designing measurement and implementation methods for Newtonian noise reduction; testing low noise control of the homodyne readout; reliability testing for higher stress silica fibers; and studying production of fused silica suspension fibers to ensure that frequencies of violin modes are sufficiently matched. Substantial efforts are underway to develop new optical coatings for A+ with improved mechanical loss. These coatings are expected to be amorphous oxide coatings deposited with ion-beam-sputtering techniques. Parallel efforts are underway to understand the fundamental loss mechanisms for these coatings, and to improve the loss with different compositions, nano-layered coatings, and modified deposition and annealing processes.

Results from these tests are expected to be implemented in A+, using frequency dependent squeezing with a 300 m filter cavity, balanced homodyne readout, implementation of lower loss coatings when developed, and installation of new test masses from upgraded pulling and welding systems for fused silica fibers. Details on A+ can be found in the LSC Instrument white paper [40].

9 LIGO-India

Op-9.1 LIGO-India

LIGO-India is a project of the Government of India with primary responsibilities to build facilities and assemble, install, commission and operate an advanced LIGO detector provided by LIGO and the US National Science Foundation. Formal approval by the Cabinet of the Government of India for LIGO-India was granted on February 17, 2016.

Several important activities are expected to be completed in 2019-20: initiation of site construction activities, vacuum infrastructure prototyping, beam tube prototyping and testing, etc. The LSC is also engaged in developing and training the LIGO-India scientific workforce and planning the integration of LIGO-India data into the full detector network.

10 Roles in the Collaboration

Op-10.1 LIGO Scientific Collaboration Roles

The LSC has a complex organization, with many members serving different roles, such as leadership and management of working groups, participation in committees, performing non-science needed activities, etc.

There is a wide range of activities undertaken by collaboration members which are organizational roles. Some of these have scientific elements, and some are simply necessary to maintain and propel the collaboration. The activities listed below are critical to the smooth running of the Collaboration.

Op-10.1.1 Chairing committees and working groups

Chairing, or co-chairing or serving as secretary of LSC Bodies, Working Groups, and Committees described in the by-laws [**?**] require at least 12 hours per week of effort.

Op-10.1.2 Committee participation and chairing subgroups

Participating in committees or chairing subgroups as detailed in the LSC organizational chart LIGO-M1200248, Chairing or participating in analysis review committees, and participating in ad-hoc Study Teams charged by the Spokespersons is included in this section.

Op-10.1.3 Participation in formal reviews of LSC activities

Participation in formal reviews of LSC activities is included in this section, e.g., reviews of LSC groups agreements (MoUs), reviews by funding agencies, presentations to LIGO's Program Advisory Committee.

Op-10.1.4 Administrative support of the LSC

Administrative support to the LSC organization (setting up e.g., MoU meetings, maintaining spreadsheets and LSC activity documentation, LSC Activities accounting and invoicing);

Op-10.1.5 Managing LSC groups

Management (by group leaders or their delegates) of LSC member groups.

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