LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION

Document Type	**LIGO–T1400054** **VIR-0176A-14**

The LSC-Virgo White Paper on Gravitational Wave Searches and Astrophysics Executive Summary (2014-2015 edition)

The LSC-Virgo Search Groups, the Data Analysis Software Working Group, the Detector Characterization Working Group and the Computing Committee

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

Processed with LaTeX on 2014/11/21

1 LSC-Virgo Gravitational Wave Searches and Astrophysics

Gravitational-wave searches and astrophysics in the LIGO Scientific Collaboration (LSC) and Virgo collaboration are organized into four LSC-Virgo working groups: compact binary coalescences (CBC), generic transients (Burst), continuous waves (CW) and stochastic gravitational-wave background (SGWB). Each of these groups pursues distinct astrophysical sources of gravitational waves with different methods. Joint teams formed from the members of two or more working groups exist, where the science suggests overlap between sources or methods.

In addition to these astrophysics groups, the Detector Characterization group, which also collaborates with the detector commissioning teams, works to improve search sensitivity by identifying and mitigating instrumental noise sources that limit the sensitivity to astrophysical signals.

The goals, status and plans of the these groups are described in the *LSC-Virgo White Paper on Gravitational Wave Searches and Astrophysics*, which is revised and updated every year. This document is the white paper executive summary, which outlines, for each group, a mission statement and a ranked list of priorities both in terms of scientific targets and tasks in preparation for Advanced LIGO and Advanced Virgo.

Further detail on the scientific motivation, analysis methods, and necessary resources are provided in the science plans of each group, which will be included in the full white paper.

1.1 Searches for Signals from Compact Binary Coalescences

The inspiral and merger of a binary containing stellar-mass compact objects (i.e., neutron stars and black holes) generates gravitational waves which sweep upward in frequency and amplitude through the sensitive band of ground-based gravitational-wave detectors. The highly relativistic speeds and strongly-curved spacetimes of compact object mergers generate gravitational waves that will reveal the physics of strong-field gravity. The gravitational waves from mergers involving black holes will allow us to explore General Relativity and the nature of gravity. With densities of matter inaccessible to terrestrial experiments, mergers involving neutron stars hold the key to understanding the equation of state of nuclear matter. This is a crucial piece of fundamental physics missing from our understanding of the universe. Compact object mergers may also explain the origin and distribution of rare heavy elements and reveal the engine powering gamma-ray bursts. Measuring the masses and spins of a population of compact objects in the universe can help explain how stellar collapse forms neutron stars and black holes.

At design sensitivity, Advanced LIGO will be able to detect binary neutron star (BNS) mergers to a maximum distance of ~ 400 Mpc, neutron star–black hole (NSBH) binaries to ~ 1 Gpc, and stellar-mass binary black holes (BBHs) at distances over 2 Gpc. LIGO and Virgo conduct their searches jointly giving us a three-detector network that can be used to localize sources on the sky. A wide variety of electromagnetic counterparts are expected to accompany the gravitational waves from compact object mergers, ranging from radio, through optical to x-rays and gamma-rays. The joint observation of a source by LIGO, Virgo, high-energy satellites, optical, and radio observatories will be a watershed event in astrophysics.

The scientific program of the LSC/Virgo Compact Binary Coalescence (CBC) Group is designed to identify gravitational wave signals from compact binary sources in the detector data, measure the waveform parameters, and use detected signals study the nature of gravity and the astrophysics of nature's most compact objects. Detection and parameter measurement of CBC signals is carried out by the joint LSC-Virgo CBC working group. The CBC group's science program requires accurate modeling of gravitational wave sources to maximize detection rates, and to accurately measure parameters. The CBC group has an active collaboration with the theoretical astrophysics, source modeling and numerical relativity communities to address these challenges.

The LSC charter states that the mission of the LSC is *to detect gravitational waves, use them to explore the fundamental physics of gravity, and develop gravitational wave observations as a tool of astronomical discovery.* We prioritize CBC tasks both in view of this mission statement and in terms of their chronological importance in the advanced detector era. Accordingly, *highest priority* is given to the ability to detect the most probable CBC sources with the LIGO and Virgo detectors, followed by science with the first detections (*high priority*), and finally the detection of sources which in the current astrophysical paradigm may have a low rate within the detectors' volume reach, but whose discovery would nevertheless be of great astrophysical importance (*priority*).

1. **Highest priority**

   The detection of gravitational waves from compact binary coalescence using the LIGO and Virgo detectors is the main goal of the CBC group. The highest-priority sources are binary neutron stars, stellar mass binary black holes, neutron star–stellar mass black hole binaries, and the detection of gravitational waves from compact binaries in coincidence with an externally triggered short-hard gamma ray burst. The CBC group must be ready to measure the masses and spins of sources on first detection, to provide rate estimates for detected sources, and to provide rapid significance measurements of externally triggered gamma-ray burst events.

   Achieving these goals requires LSC/Virgo scientists in the CBC group to prioritize: data quality, search pipeline development, rates and significance measurement, waveform development, and parameter estimation for detected sources.

2. **High priorities**

   Once CBC sources have been detected, a significant amount of astrophysics can be extracted from the observed gravitational waves. Preparing to extract this information accurately is a high priority for the CBC group. This includes: precise measurement of masses and spins to understand the properties of compact objects and their formation; determination of the neutron star equation of state; tests of the genuinely strong-field dynamics of spacetime, a regime which can only be probed with direct gravitational wave detection; cosmological studies without the need for a cosmic distance ladder; and accurate measurement of coalescence rates for CBC sources.

   Although a coincident electromagnetic (EM) counterpart is not required to detect gravitational waves from compact binary coalescence, the coincident detection of an electromagnetic counterpart with a CBC event would add significant astrophysical information to our discoveries. Preparing for detections of EM counterparts to gravitational wave events is a high priority for the CBC group. This includes: development of low latency analysis pipelines, low-latency data quality assessment, low-latency significance estimation, sky localization for CBC sources, and preparations for joint gravitational wave/EM observations in the advanced detector era.

3. **Priorities**

   Priorities include expanding the CBC search to binary black holes beyond stellar mass (e.g. intermediate mass ratio inspirals, intermediate-mass binary black holes and eccentric binaries), which will necessitate the development of new data analysis algorithms and the implementation of associated template waveforms.

CBC group science plans are organized by the physics of the sources, although there is overlap in the way that searches are performed. Each science plan provides an abstract, scientific justification, publication plan, technical requirements and development plan and the resources required. The organization of the science plans is as follows:

- search for binary neutron star coalescences;
- search for stellar mass binary black hole coalescences;
- search for neutron star–black hole coalescences;
- search for intermediate mass black hole binary coalescences (joint with the Burst working group);
- search for gravitational wave counterparts to gamma-ray bursts (joint with the Burst working group).

1.2 Searches for Generic Transients, or Bursts

The Burst group's mission is to detect gravitational wave transients, or *bursts*, and gain new information on transient signal populations and emission mechanisms of astrophysical objects, as well as to test theories of gravity. The group aims to extract a broad range of observational results from early data from the Advanced gravitational wave detector network, building on the online and offline analysis experience and infrastructure developed for first generation interferometric detectors.

Some gravitational wave progenitors, such as supernovae, involve complex physics and dynamics for which no robust signal model currently exists. Other sources, such as the merger of intermediate-mass black holes, produce gravitational wave transients which appear as short bursts in the data. Therefore, the Burst Group implements a variety of methods to find transients in the data that are inconsistent with the baseline noise. These methods identify coincident excitations between multiple detectors to discriminate between gravitational waves and noise fluctuations. In a few special cases when an accurate signal model is available, such as for cosmic string cusps or neutron star or black hole ringdowns, a search can be done using matched filtering with a bank of templates. Otherwise, gravitational wave bursts can be identified in the strain data as excess-power localized events in the time-frequency domain.

Although burst search algorithms are designed to detect a wide range of signals, their tuning and interpretation benefits from considering how they perform for plausible astrophysical signals. Therefore, the group's science program involves an active collaboration with the theoretical astrophysics, source modeling and numerical relativity communities. Many gravitational wave burst sources should be observable in more traditional channels, from Earth-based astronomical data, through sensitive GRB/X-ray satellite detections, to neutrino signals. Knowledge of the time and/or sky position of the astrophysical event producing a gravitational wave burst increases the sensitivity of a triggered burst search compared to an untriggered, all-sky search, and the association with a known astrophysical event may be critical in establishing our confidence in a gravitational wave burst detection. Most importantly, joint studies of complementary data enable scientific insight that cannot be accessed through gravitational waves or other messengers alone. Therefore, in addition to searches using only the gravitational wave data, a significant part of the Burst Group's science program involves connecting with other observations and working closely with the astronomy and astrophysics communities.

In preparation for the Advanced Detector Era, the Burst Group have prioritized their activities into 3 categories. Burst activities that are listed as *highest priorities* are activities that must be performed leading up to the Advanced Detector Era and must be on time, targeting the widest possible survey of the gravitational wave transient sky or serendipitous astrophysical phenomena. Activities listed as *high priorities* are activities which will boost the scientific return in the early years of the Advanced Detector Era, targeting deeper searches for selected source classes or the most promising extensions of the searched transient parameter space with respect to the highest priority activities. Finally, additional *priorities* are activities that will achieve a high science potential according to the current astrophysical and cosmological framework once the Advanced detectors reach design sensitivity.

1. **Highest priority**

   The Burst group is focused on an eyes wide open approach to detecting gravitational wave bursts in the Advanced Detector Era. The goal is to identify the presence of gravitational wave transients in data acquired by the Advanced detectors over as broad a parameter space as possible, under the assumption that the gravitational wave signal searched for is transient in nature. The Burst group must also be ready to extract astrophysical information from any detected signal. Therefore, the highest priority activities will contribute to:

   - a statement on the transient gravitational wave sky; performing population studies if we have

several detections, reporting on a rare-event detection significance if we have one candidate or producing an upper limit on the rate of gravitational wave bursts if there is no detection;
- astrophysical interpretation of any detected signals, including the development of methods for signal characterization and parameter estimation;
- prompt burst analysis, trigger production and sky localization, for the electromagnetic follow-up of gravitational wave transients;
- prompt reports on astrophysically significant events, such as nearby gamma ray bursts, soft gamma repeater hyperflares, galactic supernovae as well as exceptional bursts of low- or high-energy neutrinos.

2. **High priorities**

   In addition to the eyes wide open approach, the Burst group will perform searches guided by information from various astrophysical sources. The additional astrophysical information reduces the parameter space over which the search must be performed, leading to a reduction in the false alarm rate and, consequently, an improvement in the search sensitivity. These activities will boost the scientific return in the early years of the Advanced Detector Era and should, therefore, be carried out with a high priority. They are:

   - searches for gravitational wave bursts from intermediate mass binary black holes, binary black holes with eccentric orbits and intermediate mass ratio inspirals;
   - multi-messenger searches for gravitational wave bursts in conjunction with signatures such as generic gamma ray bursts, fast radio transients, low- and high-energy neutrino observations, and electromagnetic observations of nearby core-collapse supernovae;
   - searches for gravitational wave bursts originating from cosmic strings.

3. **Priorities**

   Additional priorities are activities that will have the most potential for scientific impact once the Advanced detectors have reached design sensitivity. Such activities include the search for gravitational waves in association with neutron star transients (eg. pulsar glitches, type I X-ray bursts and soft gamma ray repeater flares) and testing alternative theories of gravity with gravitational wave bursts.

The Burst working group's wide parameter search for gravitational wave bursts across the entire sky is detailed in the All-Sky Burst Search plan. This search plan lays out the search's scientific justification, publication plan, technical requirements, development plan and resources required. Further to the All-Sky Burst Search plan, the Burst group has also formulated search plans for intermediate mass black hole binaries and gravitational wave counterparts to gamma ray bursts, jointly with the CBC working group. Additionally, members of the Burst, Continuous Wave and Stochastic groups have been working together on searches for long-lived gravitational wave transients.

1.3 Searches for Continuous-wave Signals

The LSC/Virgo Continuous Waves (CW) Group aims to detect and measure GW signals that are long-lived, nearly sinusoidal and extremely weak, believed to be emitted by rapidly rotating neutron stars in our galaxy. These stars can emit gravitational radiation through a variety of mechanisms, including elastic deformations, magnetic deformations, unstable r-mode oscillations, and free precession, all of which operate differently in accreting and non-accreting stars. Long-term simultaneous GW and electromagnetic observations of a galactic neutron star would support a rich astrophysical research program.

For known pulsars with measured spin frequencies, frequency derivatives and distances, energy conservation allows setting an upper limit on GW strain amplitude, known as the spindown limit, albeit with significant uncertainties due to poorly understood neutron star astrophysics. Previous searches in LIGO and Virgo data have obtained 95% confidence upper limits well below the spindown limits for the Crab and Vela pulsars. As interferometer sensitivities improve in the Advanced Detector Era, several dozen more known pulsars will become spindown-accessible, primarily at spin frequencies below 100 Hz. For suspected neutron stars with unknown spin frequencies, indirect upper limits based on estimated age or on estimated accretion rates can also be derived. Such indirect limits are more optimistic for non-accreting stars, but accreting neutron stars are more likely to be emitting near their limits.

Because there is so much astrophysical uncertainty in actual continuous GW emission and because electromagnetic astronomers have detected less than 2500 of the O(10^{8-9}) neutron stars believed to populate our galaxy, the CW group has established a broad program to search for GW emission from five distinct source categories, ordered below by decreasing *a priori* information known about the sources: 1) known pulsars with well measured timing; 2) other known or suspected isolated neutron stars with limited or no timing information; 3) known or suspected binary neutron star systems; 4) unknown isolated stars in any direction; and 5) unknown binary stars in any direction.

This ordering of categories corresponds to ordering by source strain sensitivity. Targeted searches using known ephemerides from radio, X-ray or γ-ray timing measurements can achieve strain sensitivities limited only by the intrinsic detector sensitivity and observation time spans with minimal trials factor corrections. Directed searches using known sky locations but having no *a priori* frequency information are degraded by trials factors that depend on the band size searched and on the assumed age of the source (which affects the number and range of higher-order spin derivatives to be searched). The sensitivity achievable with all-sky searches is still further limited by the need to make sky-location-dependent corrections for Doppler modulations of detected source frequency due to the Earth's motion (daily rotation and orbital motion). The number of sky points to search to maintain accurate demodulation grows rapidly with coherence time used in the search. The effect is severe enough to preclude all-sky searches using coherence times equal to the full observation spans of data runs. Adopting semi-coherent summing of data makes the computational problem tractable, but sacrifices additional sensitivity beyond that from the trials factor of exploring a larger parameter space. Directed searches for known binary sources with unknown source frequency must make similar sensitivity tradeoffs, and all-sky searches for unknown binary sources define the current extreme in sensitivity tradeoff for tractability.

In the case of known objects, we have identified sources that seem to be the most promising, and should priorities need to be set because of limited resources (labor or computing), those sources will receive the highest priority.

With these considerations in mind, the CW group plans a comprehensive search program in the Advanced Detector Era for all of these source categories, with the following priorities:

1. **Highest priorities**

   - Targeted searches for the Crab and Vela pulsars and any other stars for which the spindown limit is likely to be beaten to within a factor of two. High-interest stars likely to fall in this category include PSR J0537–6910 and PSRJ1813–1246, among many others, as detector sensitivities improve. These analyses will include searching at the stellar spin frequency and twice that frequency.

- Directed search for Cassiopeia A which is the youngest known neutron star in the galaxy, but for which the spin frequency is unknown.
- Directed searches for the X-ray binaries Scorpius X–1, Cygnus X–3 and PSR J1751–305. The first two are especially bright in X-rays, and in the torque-balance model, GW luminosity scales with X-ray luminosity, while there is evidence in the third object for a sharp X-ray periodicity that may indicate an r-mode oscillation.
- All-sky searches for unknown isolated stars. These searches necessarily suffer from degraded strain sensitivity relative to what can be achieved in the targeted and directed searches, but they cast a very wide net, offering a serious prospect of discovery.

2. **High priorities**

- Targeted searches for known pulsars for which the spindown limit is unlikely to be beaten.
- Directed searches for young supernova remnants other than Cassiopeia A, including Supernova 1987A, for sources near the galactic center, for sources in nearby globular clusters and for unidentified γ-ray sources with pulsar-like spectra.
- Directed searches for additional X-ray binaries.
- Spotlight searches of interesting sky patches, *e.g.,* the galactic center or other star-forming regions.
- All-sky searches for unknown binary stars. Because of the additional unknown orbital parameter space to search, these searches are most computationally demanding and must make the greatest tradeoffs in strain sensitivity for tractability.

3. **Priorities**

- Supernova post-birth search in our galaxy or a nearby galaxy.
- Other long-lived periodic signals (*e.g.,* sidereal effects, non-sinusoidal periodicity)

There is some overlap in CW search space with searches carried out in the Burst and Stochastic working groups. Long-lived transients can be considered to be short-lived CW sources. A small joint subgroup with members from both the CW and Burst groups is carrying out work in this area. CW sources with deterministic but unknown phase evolution, such as from a neutron star in a binary system with uncertain parameters, may be detectable via the “radiometer” method in use by the Stochastic group. Tradeoffs among search methods for such sources are being explored in a joint CW/Stochastic mock data challenge focused on the search for Scorpius X-1.

1.4 Searches for Stochastic Backgrounds

The prime objective of the Stochastic Gravitational Wave Background (SGWB) working group is to measure the stochastic background. A stochastic gravitational-wave background is formed from the superposition of many events or processes that are too weak and too numerous to be resolved individually, and which therefore combine to produce a stochastic background. A stochastic background can arise from cosmological sources such as inflation, cosmic strings, and pre-Big-Bang models; recent results from the BICEP2 experiment provide evidence for the existence of primordial gravitational waves in the form B-modes. Alternatively, it can arise from astrophysical sources such as compact binary coalescences, supernovae, and neutron stars.

Comprehensive searches have been carried out using data from initial LIGO and Virgo. No signal was detected, but our results constrain the energy density of the stochastic background to be $\Omega_0 < 6.1 \times 10^{-6}$ at 95% confidence. Advanced detectors are expected to have about $10\times$ better strain sensitivity than the initial detectors, as well as to extend the sensitive band from 40 Hz down to 10 Hz. Furthermore, the number of detectors operating in a worldwide network is expected to increase, eventually including sites at LIGO-Hanford, LIGO-Livingston, Virgo, GEO-HF (at high frequencies), KAGRA (Japan), and potentially LIGO India. The significant strain sensitivity improvements and wider bandwidth will enable real breakthroughs in the searches for the stochastic background, with a potential sensitivity of $\Omega_0 < 6 \times 10^{-10}$. The detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. The detection of an astrophysical background is not unlikely and would also be of great interest.

The SGWB group has built on the cross-correlation infrastructure, originally designed to carry out searches for isotropic stochastic backgrounds, to diversify and to carry out a wide range of interesting analyses. The SGWB directional search provides a method of distinguishing between different stochastic sources using sky maps of gravitational-wave power; the narrowband radiometer has been successfully used to search for gravitational waves from Sco X-1, the Galactic Center, and SN 1987A. The radiometer provides an important tool for gravitational-wave astronomy when there is significant uncertainty in the phase evolution of a neutron star signal (as is the case with the low-mass X-ray binary source, Sco X-1). The radiometer limits on Sco X-1 from initial LIGO remain the most constraining to date, and the Group continues to develop the search, in collaboration with the Continuous Wave Group.

The SGWB group has developed a pipeline to search for long-lived $\sim 10\,\mathrm{s}$–$1000\,\mathrm{s}$ gravitational-wave transients using cross-correlation. Long-lived gravitational-wave transients may be produced following the collapse of a massive star through rotational instabilities in the protoneutron star remnant or from instabilities in (or fragmentation of) the resultant accretion disk. A single long-lived gravitational-wave transient detection could provide an unparalleled glimpse into the moments following stellar collapse and the birth of a neutron star or black hole. Other scenarios have been proposed as well, including protoneutron star convection, rotational instabilities in merger remnants, and eccentric binary systems. In collaboration with the Bursts Group, the stochastic group has searched for long-lived gravitational-wave transients coincident with long gamma-ray bursts; the first long-lived gravitational-wave transient all-sky search is ongoing.

The SGWB group maintains an active role in detector characterization efforts. Current/recent work includes: noise line hunting, environmental monitors and subsystem coherence studies, correlated noise (Schumann resonance) studies, realtime data-quality monitor development, and participation in the hardware injection subgroup.

1. **Highest priority**

   The highest priority of the SGWB group are its two flagship searches: isotropic and directional. The isotropic analysis is the original *raison d'être* for the SGWB working group, and the detection of a stochastic background is the group's most compelling scientific deliverable. The directional search is an import as a tool for distinguishing between different sources of the stochastic background and a mature, long-established analysis, providing targeted radiometer results and of the gravitational-wave sky maps.

2. **High priority**

   We designate as high priority activities that are carried out in order to extend the science possible with stochastic observations. Current/recent work in this vein includes mock data challenges, modeling of different sources of the stochastic background, and parameter estimation. The group continues to support the development of a pipeline to look for non-standard polarization modes in the stochastic background. We also designate as high priority searches for long-lived transients, which will be increasingly coordinated with other search groups. In parallel, we are making preparations for long transient searches with advanced detectors. Finally, we designate as high-priority the detector characterization efforts that pertain directly to the stochastic background searches, including a fast time-domain cross correlation engines (with possible applications to transient searches), a real-time data-quality monitor, an environmental monitoring system based on the long transient search software (which has recently made its mark as helpful commissioning tool), and investigations into correlated noise between different detector sites.

3. **Priorities**

   We designate as priorities activities, which are in a earlier stage of development than those listed above. The SGWB group is interested in the development of techniques for measuring the non-Gaussianity of the stochastic background, exploring the deployment of a robust non-Gaussian analysis pipeline. The group supports the continued development of folded data products in which a full science run's worth of data is collapsed into one sidereal day. Finally, the SGWB group supports an ongoing effort to further upgrade the stochastic pipeline, to improve in-code documentation, and to improve the user experience while leaving the bulk of the code intact. This project is being carefully coordinated so that, at no point, we will find ourselves dependent on a untested, unreviewed pipeline.

There is overlap in the stochastic group's search for long-lived transients with searches being carried out in the Burst and Continuous Wave search groups. Continuous wave sources with deterministic but unknown phase evolution, such as from a neutron star in a binary system with uncertain parameters, may be detectable via the radiometer method in use by the Stochastic group, or methods being developed in the continuous wave search group. Trade-offs among search methods for such sources are being explored in a joint Continuous Wave/Stochastic mock data challenge focused on the search for Scorpius X-1.

1.5 Characterization of the Detectors and their Data

LIGO: LIGO's sensitivity to gravitational-wave signals is limited by noise from the instruments and their environment. In the early runs of Advanced LIGO, anticipated signals will be near the search detection thresholds, and so the success of detection, the vetting of candidate signals, and the accuracy of parameter estimation will rely heavily on the quality of the data searched and the collaboration's knowledge of the instrument and environment. The LIGO Detector Characterization group is therefore focused on working together with the astrophysical search groups and the detector groups to (i) deliver the data quality information necessary to clean the data sets, veto false positives, and allow candidate follow up for gravitational-wave searches and (ii) characterize the early Advanced LIGO detectors to help to identify data quality issues early enough that they can be mitigated in the instruments to improve future instrument and search performance.

Search Data Quality: LIGO data contain non-Gaussian components such as noise transients and quasi-periodic lines that have a negative impact on astrophysical searches. Compact Binary Coalescence sources are the most likely to be detected in early Advanced LIGO and transient noise in the detector data can mimic or mask their transient signals, limiting their detection probability and the accuracy of the source parameters recovered. The detection probability for burst searches is affected even more by the rate of transient noise in the detectors. To minimize these negative effects, LIGO data must be cleaned of transient data quality issues. The primary forms of data quality information that must be delivered to the astrophysical search groups are: *state segments* that indicate which data should be analyzed, based on the state of the instrument and its calibration; *veto segments* that indicate periods of poor quality data; and *data quality triggers* that identify short durations where the data are likely to contain a non-astrophysical disturbance. Searches will use veto segments and data quality triggers 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.

Early aLIGO Characterization: During initial LIGO, detector characterization was primarily done by looking at artifacts in the detector outputs or search results and trying to reconstruct their cause from the thousands of interferometer channels. Throughout aLIGO installation, the Detector Characterization group has worked with the detector groups to identify and resolve issues in the early aLIGO subsystems related to glitch and noise contamination, channel signal fidelity and robustness, etc. This work has led to some early data quality improvements and helped to train a wider pool of scientists who are familiar with the instruments. Continued work aims to expedite aLIGO detections by ensuring that the detectors are well understood and that data quality issues are aggressively pursued. In 2014-2015, this work will be very important as the LIGO detectors transition from installation to running and intense commissioning begins to identify limits to sensitivity and robustness in the instruments.

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

2. **High priorities.** Characterize early Advanced LIGO to improve future searches and inform the search data quality production. Complete a well-understood and documented physical environmental monitoring system. Develop and maintain the software infrastructure required to provide useful data quality information to online searches.

3. **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.

To accomplish these priorities, the LIGO Detector Characterization is organized two sub-groups: one devoted to search data quality and one devoted to instrument characterization.

Virgo

The search for gravitational signals requires a careful monitoring of the detector's response and the mitigation of noise sources. Noise mitigation, spectral lines identification, glitch reduction and vetoes production are, in coordination with commissioning and data analysis teams, the main tasks of the Virgo detector characterization. We also aim at a general understanding of noise features: its stationarity and Gaussianity as well as characterization of spectral lines or noise couplings. The detector characterization work is an interconnection between the commissioning team tracking down any limitation of the detector's sensitivity, the calibration team maintaining the calibration and timing accuracy to an acceptable level for GW searches, the Virgo data quality (VDQ) and Noise Studies teams providing noise information and vetoes to the data analysis groups and commissioning team. Along the previous scientific runs and commissioning periods, Virgo detector characterization already provided several tools, studies and vetoes which impacted positively both commissioning activity and astrophysical searches.

Search Data Quality: We aim to base future glitch studies and online vetoes on a standard trigger generator and on an efficient hierarchical veto algorithm. We develop, in common with LIGO, a database of data quality segments (DQSEGDB) which will be dedicated to transient signals for Burst and CBC search groups. We plan to use it also to identify families of glitches during commissioning. Other data quality needs are more specific to CW or Stochastic search groups and focus on identifying noise source contributions to spectral lines or non stationary and non linear features. We plan to use automatic spectral lines identification tools already well tested and the maintenance of a lines database which can be used by CW search group to veto the data and by the commissioning to find hints of noise sources.

Early AdvVirgo Characterization: We plan to start noise and glitch studies on each commissioned subsystem as soon as it starts to provide usable signals. This will be done in close collaboration with subsystem coordinators. To provide early information about the detector status, the noise level and the glitches impact, we have developed specific tools able to monitor in-time or online the various signals acquired, a standard trigger generator and an identification of possible correlation between the gravitational signal and the auxiliary signals. To help noise characterization, we developed also noise monitoring tools plugged in the framework NMAPI (Noise Monitor Application Programming Interface), most of them already tested on past Virgo Scientific Runs. These tools give information on spectral lines, non stationary or non linear noise and glitches rate. We developed a new pipeline (SiLeNTe) which finds the rank for non linear noise coupling between gravitational and auxiliary signals.

1. **Highest priority.** The highest priority of the Virgo Detector Characterization is to find and mitigate the 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 priorities.** 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 of vetoes in future searches. This will imply a spectral lines database catalogue, identification of non stationary lines and a software infrastructure to provide useful online data quality information.

3. **Priorities.** Develop improved methods to uncover the paths and the sources of the noise transients which most impact the searches. Setup automated classification tools for noise sources.

To accomplish these priorities, Virgo Detector Characterization is organized in two groups: one devoted to search data quality and glitch studies (VDQ) and one devoted to lines identification and noise hunting (Noise Studies).

1.6 Data Calibration

LIGO

Calibration of the LIGO interferometers is critical to the success of the searches and to the confidence associated with their results. It is a complex task that involves instrumental hardware measurements, detector modeling, computer programs, and extensive validation and review. Calibration is provided both in the frequency domain, as a frequency-indexed response function to be applied to the Fourier transform of the gravitational wave channel, and in the time-domain, as a derived digital time series representing strain as a function of time. The time domain calibrated data, along with an accompanying error budget, is the main calibration product. Early aLIGO critical calibration activities include:

- measurements of instrument transfer functions and calibration model parameters,
- development and improvement of instrumental measurements,
- estimation and reduction of the errors in the calibration data products,
- deployment and use of the photon calibrator as an independent cross-check of the calibration,
- development and improvement of time-domain data generation techniques, including use of gstlal and the aLIGO front-end system,
- development of pre-processed h(t) products, such as whitened, cleaned, and coherent data streams,
- development of on-line tools to monitor calibrated data quality, and
- a comprehensive review of entire calibration procedure.

The scope of the calibration team includes the timing of LIGO data. Traceable and closely monitored timing performance of the detectors is mission critical for reliable interferometer operation, astrophysical data analysis and discoveries. Critical timing tasks include:

- developing of injection techniques to determine accurate timing through direct test mass excitations,
- expanding the capabilities of data monitoring tools related to timing and phase calibration,
- enhancing the availability of timing diagnostics for various subsystems,
- measuring and documenting the timing performance of critical digital subsystems,
- measuring and documenting the end to end timing and phase calibration measurements of the detectors (e.g., through the photon calibrator, characterization of analog modules, etc.), and
- reviewing the physical/software implementation and documentation of the timing components of critical subsystems.

Virgo

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 output are then used (i) in the frequency-domain calibration, resulting in the Virgo sensitivity curve, (ii) in the time-domain calibration, resulting in the h(t) 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 in 2015. Among the critical calibration activities to be done, one can emphasize:

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

1.7 Hardware Injections

Hardware injections are simulated gravitational-wave signals added to LIGO and Virgo's strain channel 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 to the interpretation of results from data analysis pipelines. 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.

The Burst and CBC groups work with the subgroup to provide transient waveforms and to determine suitable injection rates. The CW group selects the parameters for neutron star signals, which persist throughout the science run. The SGWB group typically carries out one or two $\approx$10 min injections during each science run. The search groups analyze hardware injections during science and engineering runs to identify and solve problems as they come up. The results of these studies are reported back to the hardware injection team so that adjustments can be made.

While most injections are made known to the LSC, there are also blind injections. Blind injections are carried out by a separate team. However, the hardware injection group is in charge of maintaining the blind injection infrastructure, nearly identical to the regular injection infrastructure, and provide training. We aim to strengthen the collaboration between the hardware injection group and the blind injection team, e.g., by sharing one team member who can facilitate the flow of information between the two teams.

1.8 Computing and Software

LIGO

In the LIGO Computing model, data is acquired at the LIGO Observatories where it is processed locally to characterize the detector and allow timely identification and correction of problems with the instruments. Calibrated data is transferred over a dedicated low-latency network to the Tier-1 center at Caltech where it is processed to provide alerts to other astrophysicists within minutes of data acquisition. All the data is transferred over the LIGO Data Replicator (LDR) network to the archive at Caltech; calibrated data is transferred to the Tier-2 data centers where deep searches are run in batch mode.

During initial LIGO (iLIGO), the LIGO Scientific Collaboration (LSC) successfully established a collaboration controlled, distributed computing environment–the LIGO Data Grid (LDG)–to carry out prototyping, testing, and production data analysis activities. The current plan builds on that and leverages new opportunities to integrate shared resources, such as XSEDE, with the fabric of the LDG to accommodate our computational requirements as advanced LIGO (aLIGO) commissioning gives way to continuous observing runs in 2018. In this context, we refer to the computing facilities at the LIGO Observatories as Tier-1-Observatories; the computing facilities at Caltech as Tier-1-Caltech; shared resources (yet to be identified, but possibly including XSEDE) as Tier-2-Shared; and other dedicated computing facilities as Tier-2-Other.

Data analysis is assumed to proceed at the pace of data acquisition. This leads to the need for captive computing resources when the instruments are acquiring observational data. The location of hardware resources follows from the science drivers and the acceptable latencies between data acquisition and analysis for each of them. In particular, the Tier-1 resources (at Caltech and the Observatories) are used for low-latency and day-latency computing that will run essentially continually from 2015-2018. It is hoped that Tier-2-Shared facilities will carry out the deep, production searches and provide resources for rapid-turnaround data exploration and pipeline development. Full details of

The **highest priorities** for software and computing directly support O1 readiness. The following list of task flow directly from the science requirements stated elsewhere: a) provide an accurate determination of the computing requirements and optimizations for O1; b) identify and/or deploy hardware resources to support O1 science; c) deploy authorization infrastructure and tools for collaboration with electromagnetic partners; d) deploy and support a build and test environment that allows the scientific review teams' assessment of the correct behavior of software to be used in future science statements; e) define and deploy improved computing environment for detector monitoring; f) support and improve the low-latency data transfer network software and services; g) complete, deploy and support the new data-quality database; h) deploy and support segment generation, aggregation, publication and verification services; i) support data publication, replication and verification on the ligo-data-replication network; j) support application layer I/O and framework libraries including framecpp, gds, lalsuite, glue, pyCBC, gstlal, etc; k) support software development related to the Online Detector Characterization (ODC) infrastructure; l) support and enhance monitoring tools to provide insight into the status of computing and analyses; m) support and enhance the network data server infrastructure (NDS2); n) support and enhance the Gravitational-wave Candidate Event Database (GraCEDb) and associated tools; o) provide support to package and distribute software via the LSCSoft repositories; p) support the LIGODataFind services including data discovery; q) support and enhance the Channel Information System; r) support and enhance the data-quality summary service; t) support and enhance LIGO Data Viewer and LDVweb.

A detailed description of LIGO commputing and software can be found in the LSC Computing Plan (LIGO Document T050053).

Virgo

The Virgo Computing Model and the Implementation Plan describe in detail the Advanced Virgo computing infrasturcture. The purpose of Advanced Virgo Computing Model is to design, implement and maintain the computing infrastructure necessary to achieve Virgo's scientific goals. In this spirit, we make use of earlier Virgo Computing developments, but at the same time it is necessary to enlarge the range of computing activities and improve the various solutions.

Virgo computing and storage resources are part of the European Grid Infrastructure, as such are shared resources and are scattered around in various Computer Centers of the collaborating and / or supporting institutions. Virgo data analysis activities has also made use of LDG resources in the past.

Motivated by the above facts we define the following highest priority ones for the forthcoming period:

Highest priority tasks a.) clarify the and / or make more precise the exact computing needs of the various LIGO - Virgo scientific data analysis pipelines relevant for Virgo computing resources **b.)** ensure that the analysis pipelines that are ported and/or optimized to new, shared resources (such as for example XSEDE) remains executable on Virgo computing resources **c.)** ensure that all or at least big majority of the scientific data analysis pipelines can be executed on Virgo resources **d.)** make sure that pipeline developers are aware and in fact using new technologies which could possibly make their code more efficient and fast (such as for example GPUs, more efficient compilers, vectorisation, etc) **e.)** deploy and support a build and test environment that allows the scientific review teams' assessment of the correct behavior of software to be used in future science statements; **f.)** enable wider usage of Pegasus-based workflows inside the collaboration **g.)** develop closer integration of data transfer solution and file catalogs used by the offline pipelines **h.)** Create a new Virgo web page which can be used more efficiently by collaboration members, as well as by external visitors **i.)** install and maintain a nightly build or a continous integration server which ensures that software packages are always in a usable, clean state in the repository **j.)** upgrade to more advanced revision control system, such as for example git **k.)** replace our current (CMT based) software configuration and installation to a solution which is compatible with Linux standars **l.)** set up file catalogs in Computer Centers which are compatible with ligo_data_find queries so that pipelines using these tools can run **m.)** simplify the various authentication methods used, set up and integrate a new authentication system which is compatible with the LIGO solution **n.)** make it possible for LIGO colleagues to submit jobs to Virgo resources more easily **o.)** examine the various cloud and virtualisation solutions and perform evaulation studies how those can be useful for data analysis activities