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The LSC-Virgo white paper on gravitational wave data analysis

Science goals, data analysis methods, status and plans

(2007 edition)

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

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1 Introduction

The year 2007 is a time of great progress and optimism in the gravitational wave detection community. As of this writing, the LIGO and GEO 600 detectors (operated together by by LIGO Scientific Collaboration, or LSC) are entering the final months of their multi-year "S5" science run, while Virgo has made great strides in commissioning and has begun its first science run (VSR1). Searches for gravitational wave (GW) signals in the recent data are being carried out with mature methods as well as newer, more sophisticated ones. Furthermore, the LSC and the Virgo Collaboration have agreed to freely share the data from LIGO, GEO 600, and Virgo from 18 May 2007 onward, and to carry out all analysis of that data jointly.

According to the Memorandum of Understanding (and its Attachment) between the LSC and the Virgo Collaboration, joint data analysis working groups have been established, and all gravitational wave searches are now performed under the auspices of these joint groups. As in the past, there are four working groups which span the range of potential GW signals:

- The Compact Binary Coalescence (CBC) Group searches for GWs produced before, during, and after the merger of neutron stars and/or black holes. In the past this has been called the "inspiral group"; the new name reflects the inseparability of the different phases of the GW signal produced by a real astrophysical system of this type.
- The Burst Analysis Working Group searches for a very broad range of possible burst signals, using robust methods which are not dependent on having specific models for signal waveforms.
- The Continuous Waves (or Periodic Sources) Search Group searches for continuous-wave signals, such as would be produced by an asymmetric rapidly-spinning neutron star.
- The Stochastic Background Working Group searches for persistent, stochastic GW signals coming from the entire sky or from particular directions.

As outlined in the MoU Attachment, these data analysis working groups shall produce a "white paper" annually to describe their goals, status, and plans. The document is to be revised and updated every year in the summer by the search groups, and then finalized by early fall. This is the document for 2007. It is intended to facilitate:

- the understanding of the science that we are doing
- the identification of "holes" in our science plan and of tasks that demand more manpower
- the prioritization of our objectives
- the identification of areas when manpower should be shifted to and/or removed from
- the exploitation of synergies among the work carried out in different search groups
- an harmonious exploitation of common resources

A section is devoted to the plans of each of the four search groups. In addition, since the understanding of artifacts in our data is an essential part of the analysis work (allowing us to reduce the false alarm rate and increase our confidence that we have the tools to reliably interpret the output of the detector), we include a section on Detector Characterization, with subsections for the LIGO, GEO 600 and Virgo detectors. Finally, since data analysis work both drives and is constrained by the computing environment and facilities where it develops, the last section of this document describes the development and maintenance of software tools and the management of software and computing resources.

2 Searches for signals from compact binary coalescence

2.1 Gravitational waves from the coalescence of compact binary systems

The inspiral and merger of a compact binary system generates gravitational waves which sweep upward in frequency and amplitude through the sensitive band of the Earth-based detectors. The detection of gravitational waves from these astrophysical sources will provide a great deal of information about strong field gravity, dense matter, and the populations of neutron stars and black holes in the Universe. The scientific program of the LSC/Virgo Compact Binary Coalescence (CBC) Group is designed to identify GW signals from compact binary sources in the detector data, and estimate the waveform parameters with confidence in the correctness and validity of the results.

Compact binary systems which generate gravitational waves with frequencies above ~ 10 Hz are ideal candidates for gravitational-wave astronomy. These systems include binaries with total mass less than $\sim 200M_{\odot}$ composed of black holes, neutron stars, and perhaps other exotic compact objects with densities similar to or greater than neutron stars. The beauty of these systems for data analysis is that the waveforms can be computed within the context of General Relativity and/or alternative theories of gravity. The gravitational waves from these objects sweep upward in frequency and amplitude as loss of energy to gravitational waves causes the binary orbits to shrink, thus reducing the period of the orbit. This process is called the inspiral phase of the binary evolution. From an astrophysical perspective, these compact binary systems are expected to be clean with the inspiral dynamics controlled primarily by pure gravitational effects. For this reason, theoretical waveforms should provide accurate representations of the gravitational waves if the calculations can be carried out to high enough accuracy. At present, there is good evidence that post-Newtonian waveforms provide an accurate representation at frequencies below $\approx 700(2.8M_{\odot}/M_{\rm total})$ Hz. Various estimates suggest that inspiral waves should extend to frequencies $\approx 1600(2.8M_{\odot}/M_{\rm total})$ Hz. Since the band of optimal sensitivity for these sweeping signals lies in the range $40 - 800$ Hz for the current LIGO detectors, it is clear that post-Newtonian waveforms should be adequate to detect compact binary inspiral for masses below about $\approx 3.0M_{\odot}$. While the theoretical waveforms become less accurate for higher mass systems, there are a number of approximation schemes which may capture the essential features of the waves for these higher systems. Moreover, the breakdown of the post-Newtonian approximation is indicated by a loss in signal to noise ratio around 10% and does not invalidate the use of the waveforms in searches.

The gravitational waveforms received at a given detector depend also on the location of the source, the orientation of its orbital plane, the polarization angle of the gravitational waves, and the spins of the component objects. For a single detector, many of these parameters are degenerate either with the constant phase offset of the signal or the distance to the source. The spins, however, can produce significant differences in the waveforms allowing their direct measurement. With the ability to measure the spins comes the problem of searching for spinning binaries; this complicates many of the searches and is an area of ongoing development and research.

When a binary system with total mass above 1.4–$2.0M_{\odot}$ merges, it is likely that the end product is a single, perturbed black hole which rings down, by emitting gravitational radiation, to a stationary configuration. The ringdown waves are primarily emitted in the quadrupolar quasi-normal mode of the black hole; the frequency and quality factor of this mode depend on the mass and spin of the final black hole. Observation of these waves will enhance our ability to measure parameters of the binary and to test numerical and analytical models of the merger phase. Moreover, ringdown waves may be detectable even if the inspiral waves do not enter the LIGO/Virgo band. Perturbation theory provides waveforms emitted during this settling phase, the ringdown phase. These waveforms depend on both the mass and spin of the final black hole.

The merger of the compact objects is the subject of a vigorous research program in numerical relativity at this time. Recent results suggest that these efforts are on the verge of yielding accurate waveforms for binary black hole merger; there have also been successes modelling the merger of neutron stars. It is not yet clear to what extent tests of gravity theories, equations of state, and other physics of compact binaries can be extracted from this phase.

2.2 Science goals

The detection of gravitational waves from compact binary systems will bring a great deal of information about the component objects and populations of neutron stars and black holes in the Universe. The CBC group has identified the following topics to work on:

- Estimate the rate of compact binary inspiral in the Universe by direct observation of gravitational waves. In the event of a detection, this will take the form of a rate interval; in the absence of a detection, it can provide a rate upper bound.
- Measure the masses and spins of detected binary signals and develop a catalog of binaries from which further understanding of populations can be discerned.
- Measure the inclination, polarization, sky location, and distance as allowed by the use of multiple observatories, higher harmonic content and/or spin modulation.
- Determine the energy content of gravitational waves during the merger of binary black hole systems. In collaboration with the Burst Group, search for binary black hole sources in which both the inspiral and merger-burst can be measured. Search for ringdown waves in coincidence with such events.
- Probe the disruption of neutron stars during binary merger.
- Test alternative theories of gravity such as scalar-tensor theories which can result in modified phasing of the gravitational waves from binary inspiral.
- Bound the mass of the graviton by direct observation of the gravitational waves from binary inspiral.
- In the case of high-mass ratio binaries, develop and implement methods to map the spacetime structure of the more massive object by observing the gravitational waves.
- Use consistency of parameters determined from different phases (inspiral, merger and ringdown) to test strong field predictions of analytical and numerical relativity.

2.3 Search Methods

2.3.1 Matched filtering

There is a well developed theory and practice of searching for signals with a known waveform buried inside a noisy time series. For Gaussian noise with a known additive signal, this theory leads to the matched filter. In gravitational-wave astronomy, as in many other fields which use matched filtering, the signal is not known exactly. For compact binaries, the inspiral signal depends on many unknown parameters as follows:

1. The ending time t_0 and the ending phase Φ_0 of the inspiral waves are unknown in advance. Physically the first can be thought of as the time when gradual inspiral ends and the merger begins; similarly the phase is the angle around the orbit when this transition occurs.
2. The gravitational-waves also depend on the masses m_1 and m_2 of the compact objects and their spins $\vec{s}_1$ and $\vec{s}_2$. These parameters have strong effects on the evolution of frequency (and hence phase of the signal) with time. They also appear in a variety of combinations in the amplitude part of the signal.

3. The amplitude of the waveform measured in a given detector also depends on a combination of the right ascension α and declination δ of the source, the inclination ι, and the polarization angle of the waves.

We generate *triggers* by filtering the data from each detector with matched filters designed to detect the expected signals. At the single interferometer level, the angles can all be absorbed into the distance to the source giving an effective distance which is larger than the physical distance. Each trigger has an associated *signal-to-noise ratio* (SNR), coalescence time t_0, and parameters from the template that matched the data, such as the masses of the individual stars.

Since compact binaries with slightly different masses and spins would produce a slightly different waveform, we construct a *bank* of templates with different parameters such that the loss of SNR due to the mismatch of the true waveform from that of the best fitting waveform in the bank is less than 3–5%. The template banks for the mass-space are well in hand for searches using Post-Newtonian approximations; work is ongoing on including spins in the most efficient manner. We also explore the use of other approximations to the waveforms, which have a template bank designed in terms of the associated phenomenological parameters.

Although a threshold on the matched filter output ρ would be the optimal detection criterion for an accurately-known inspiral waveform in the case of stationary, Gaussian noise, the character of the real data is known to be neither stationary nor Gaussian. Indeed, many classes of transient instrumental artifacts have been categorized, some of which produce copious numbers of spurious, large SNR events. When the origin of the instrumental artifacts is known, through understood coupling mechanisms or correlations of auxiliary data and the gravitational wave channel, the times are *vetoed*. However, many data transients remain that are not understood and produce an excess of false alarms. In order to reduce the number of spurious event triggers, we adopted a now-standard χ^2 requirement when using physical waveforms: Instrumental artifacts tend to produce very large χ^2 values and can be rejected by requiring χ^2 to be less than some reasonable threshold. This test has proved to be one of the most powerful methods of dealing with noise glitches for the CBC group. Other signal dependent discriminators are being used in current analyses, and many others are being explored.

2.3.2 Analysis pipeline

While matched filtering is the core analysis method used by the CBC group to search for these signals, it only part of the complete detection pipeline which has been developed over the past five years. The current pipeline has the following steps:

1. Determine which data satisfies a minimal set of data quality cuts determined by operating charateristics of the instrument and bulk properties of the data. For example, we require (obviously) that the instrument function be flagged as nominal by the operators and scientific monitors and require that there are no flagged malfunctions in data acquisition. All data satisfying this minimal data quality cut is analyzed for signals.

2. Perform a matched filtering analysis on these data. The SNR $\rho(t)$ is computed for each template in the bank. Whenever $\rho(t)$ exceeds a threshold ρ^*, the local maximum of $\rho(t)$ is recorded as a *trigger*. Each trigger is represented by a vector of values: the masses and spins which define the template, the maximum value of ρ and corresponding value of χ^2, the inferred coalescence time, the effective distance $D_{\rm eff}$ (derived from the trigger SNR), and the coalescence phase $\phi_0 = \tan^{-1}(y/x)$. These are inspiral-level-1 triggers.

3. Triggers generated at the single interferometer level are then compared between all instruments that were operating nominally. Any triggers identified as coincident, in time and other parameters, between at least two instruments are kept and recorded as coincidence-level-1 triggers.

4. These surviving triggers are then used to determine templates which require further scrutiny. The single interferometer data is re-analyzed with this small number of templates and the value of χ^2 (if used), and other signal based vetoes, are computed. When a new trigger is found satisfying the new signal based vetoes, an inspiral-level-2 trigger is generated.

5. The inspiral-level-2 triggers are again subjected to the coincidence requirement and the coincidence-level-2 triggers recorded.

6. These surviving triggers are then used to compute a coherent signal-to-noise ratio between the multiple detectors and the final trigger and this statistic value is recorded for each trigger.

This pipeline has been developed and refined over S3 and S4 so that it is robust and available for immediate use on the S5 data set which is being acquired at the present time. The pipeline is designed and implemented to be both flexible and extensible. This pipeline has been described in the context of only the inspiral phase of compact binary evolution. It has been designed, however, to allow the easy inclusion of filtering techniques for the merger and ringdown phases. Prototype searches for the inspiral-merger phase combined have been performed, and the first end-to-end ringdown search is also nearing completion. These aspects of searches for signals from compact binary merger will be encorporated into this pipeline over the next year.

2.3.3 Background estimation

The nature of gravitational-wave detectors makes it impossible to go off source to estimate the background in a single instrument. The CBC group has adopted the time-slide method of background estimation for its analyses. This method applies an artificial time-lag to triggers from each interferometer and carries out all of the later stages of the analysis pipeline in exactly the same way as for the original data. This allow an estimate of the rate of coincident triggers satisfying all criteria used in the pipeline, but known to be false alarms. This process is automated in the current pipeline; the group has typically used 100 time-slides to estimate the background. This method is also used in other burst searches.

2.3.4 Instrumental and environmental vetoes

The complicated nature of interferometric gravitational-wave detectors means that instrumental and environmental effects produce non-gravitational-wave signals in the detector output. To combat this problem, the CBC group uses vetoes based on a large number of different approaches to the data. The CBC group has adopted the convention to divide these vetoes into different categories depending on the degree to which the instrumental or environmental disturbance is understood. For example, if an operator indicates that a piece of hardware was faulty or a truck was making a delivery at the site, this would strictly veto a trigger. Similarly, triggers which are associated with a subsytstem malfunction as identified by analysis of auxilliary channels would provide a strict veto if the path from the sub-system to the gravitational wave channel is understood. Other categories of vetoes provide weaker evidence that something was wrong with the instrument or the environment and are used to flag triggers as less likely to be of gravitational-wave origin. For blind analyses, vetoes are identified by reference to the set of level-1 single detector inspiral triggers, to coincident triggers identified as false alarms (from the time-slide analysis), and to coincident triggers found in a subset of about 10% of the data distributed uniformly over the run, called the *playground*. Also, the triggers studied are limited to large signal-noise triggers clustered over a window much broader than the expected resolution of a real signal. Identification and confident use of instrumental and environmental vetoes based on analysis of auxilliary data channels is the subject of continued investigation. A number of new ideas are being tested and our ability to use this information should continue to improve.

2.3.5 Uncertainties in theoretical waveforms

Theoretical waveforms such as Post-Newtonian approximations have limitations in their domains of validity. This does not invalidate the use of these waveforms in searches, it simply reduces the sensitivity of the search relative to filtering with the exact physical waveform. The CBC group has been following progress on computing waveforms and determining their domains of validity. Detection template families have been implemented to search for binary black holes with and without spin. To date, these methods have not been as useful as others in which signal based veto test have been implemented and tested. The CBC group continues to follow the theoretical literature on computing waveforms from compact binary inspiral, merger and ringdown, including the new waveforms produced by the numerical relativity community. As new waveform approximations become available, they are coded to allow simulated injections into the data stream. These simulations help identify weaknesses in the current search techniques and determine the urgency with which the new information should be incorporated into the search pipeline.

For higher mass systems where the primary gravitational-wave signal accessible to ground based detectors is from the compact object merger, techniques using burst style searches in combination with the inspiral searches to enhance the detectability of these signals are being developed. As more information becomes available from numerical simulations, it will be incorporated into the construction of template banks to filter for the merger itself and the techniques of stitching together the inspiral and merger will be adapted to this approach. At some point in the future, it may also be possible to provide a fully phase coherent approach to the detection of the inspiral-merger-ringdown. The current analysis pipelines can be easily adapted to do this.

2.4 Current status and goals

While a considerable amount of work is still needed to meet the science goals listed earlier, the CBC group already has active searches for binary neutron stars, black hole binaries in which the spin does not significantly affect the waveform, low-mass binaries composed of exotic objects like primordial black holes, and binary black holes in which spin is important.

In the years 2001-2006, the inspiral analysis group (LSC predecessor of the LSC/Virgo CBC group) commissioned a detection pipeline which can be used to analyze data from up to 5 interferometers. The search pipeline is designed to achieve the same sensitivity as a coherent search via a hierarchical pipeline that uses coincidence early to reduce computational cost.

This pipeline was most recently used to search for:

- binary neutron stars and primordial black holes in the S3 and S4 LIGO data sets, using Post-Newtonian waveforms;
- binary black holes with total mass $> 3M_{\odot}$ in the S3 and S4 data sets, using phenomenological waveforms;
- spinning binary black holes system in the S3 data set;
- ringdown after coalescence of spinning systems, in S4 data.

In the subsequent sections, we lay out a set of tasks which taken together form the program of research being followed by the CBC group. The group has steadily grown the number of searches it undertakes on any given data set, building on its core search for binary neutron stars.

2.4.1 Near-term development activities

The CBC group has developed most of its production codes in LAL/LALApps and more recently PyLAL. The pipelines are described with the aid of software tools in Glue. The following development activities are on the critical path for the group for searching the data from the S5 run currently in progress:

1. **Binary black hole pipeline development:** Theoretical calculations are limited in their domain of validity when applied to binary systems. The standard post-Newtonian expansion is expected to break down for systems with a coalescence frequency near ∼100 Hz. Thus, for binary black hole binaries with total mass $M >\sim 30 M_{\odot}$ that merge within the LIGO/Virgo band, current theoretical waveforms are not expected to accurately represent the phasing of the signal from astrophysical sources. To account for the errors in the waveforms, (phenomenological) detection template families have been developed. The detection template family has already been used to search for gravitational waves from binary black holes in S3 and S4, although the searches found an excess of false alarm significantly larger than searches of lower mass systems. This is due in part to the features of the template bank, and in part due to the absence of signal-based vetoes when using phenomenological waveforms. An effort is needed to reduce the background in these searches. Current efforts in this respect include: (i) using physical approximations (such as PN, EOB, Padé, etc.) for the searches, (ii) develop signal-based veto methods to reduce background, and (iii) determine the best tuning of the pipelines for detection.

2. **Ringdown waveforms:** The search for coalescence binary systems can be done looking for the ringdown that happens after coalescence, which has known waveforms parametrized by mass and spin (determining frequency and damping time of the ringdown). A first search was completed on S4 data, but more development is needed to be able extend the frequency range used, and to implement signal based vetoes.

3. **Search for coincidences with electromagnetic observations:** The pipeline used for other searches can be also used looking for coincidences with electromagnetic observations such as Gamma Ray Bursts (GRBs). Although the overall pipeline has been already developed for other searches, further tuning can be used to take advantage of the external trigger information, such as location in the sky and time of arrival. The interpretation of the results is also slightly different, making statements about likelihood of coincidence with external triggers. An effort to search for GRB coincidences in S5 data is currently in progress and expected to mature in the next year.

4. **Searches for spinning systems**: A search using template banks designed for spinning systems was done for the first time in LIGO S3 data and is expected to be completed by fall 2007. This search used phenomenological templates, although it covered a limited region of parameter space best suited for binary systems with significantly different masses. The experience showed that there is a need for more development in all the aspects of the pipeline, including template banks with physical and phenomenological templates, tuning of coincidence conditions, studies on background reduction, etc.

5. **Joint analysis of LIGO-Virgo data**: LIGO and Virgo started sharing data in May 2007, when the Virgo detector started its First Science run VSR1, in coincidence with the on-goaing LIGO-GEO S5 science run. We will perform studies on this data to test current LSC and Virgo pipelines, adapted to look for coincidences in the 5-detector network, and take advantages of the larger number of detectors. We will focus initial studies on the search for low mass binary systems.

6. **Coherent analysis:** Any triggers that survive the quality and coincidence stages of the inspiral pipeline are further examined by combining the gravitational wave data from all instruments into a combined coherent signal-to-noise. This step involves filtering each data stream with the same template and then combining those filter outputs with weighting which depend both on the instrument

and on the putative position of the source on the sky. An effort is needed to: (i) extend and test the coherent filtering code that has been developed for post-Newtonian template waveforms; (ii) develop coherent filtering code for other waveform families; (iii) understand and perhaps develop template placement code for gridding up sky positions.

7. **Signal-based vetoes:** When the signal-to-noise from a template exceeds threshold in a search, a variety of tests can be performed to determine the quality of this trigger as a potential gravitational wave candidate. A χ^2-test which measures the accumulation of signal-to-noise in the time-frequency plane is in broad use by the gravitational-wave community. Another signal-based veto based on the time series of the χ^2 discriminator has proved successful in the searches for low mass systems. Other signal-based tests are being developed, including a veto based on the structure of the templates triggered in the bank by a transient in the data , and a null stream veto, to provide further quality information. An effort is required to bring these methods to maturity and to explore similar methods which might allow signal to be better separated from noise.

8. **Detection checklist:** In the near-term, the most difficult aspect of the search will be identifying a detection with confidence. A current effort is in progress to apply and refine the group's detection checklist to candidates which arise in on-line and offline searches. As experience increases, many of these checks will be automatically performed inside the analysis pipeline. We envision this effort carried out in concert with other analysis groups so as to be on the most sound footing.

9. **Background estimation:** An important aspect of the search for gravitational waves is to understand the background present in the experiment. This is usually addressed by re-analyzing the data through the pipeline while applying time-lags to the data from each site. This method should provide an accurate estimate of the accidental background (from uncorrelated noise sources) for the experiment, but it does not necessarily measure the true (i.e. non-gravitational) background. Experience with this method in gravitational wave experiments often shows unexpected results. A significant effort is required to: (i) study and understand the time-lag method in the context of large parameter space searches like the inspiral search, (ii) study alternative methods of estimating the true background, such as filtering with time-reversed templates and (iii) investigate possible sources of bias in the background estimate from the environment.

10. **Auxiliary vetoes:** Instrumental and environmental artifacts excite the inspiral templates with high signal-to-noise. Coincidence between multiple sites remains the most powerful tool to veto such unwanted triggers. The next line of defense is a deeper understanding of the couplings and origins of these instrumental and environmental artifacts. A significant effort is required to: (i) identify auxiliary channels which show noise events which are correlated with inspiral triggers in the gravitational-wave channels; (ii) investigate the couplings between these channels and the gravitational-wave channel; (iii) understand and identify particular artifacts by the signature across all appropriate channels; (iv) invent some method to clean the data of such artifacts; (v) automate these methods within the pipeline and the on-line analysis.

11. **Automatic trigger and event generation:** As the LIGO detectors enter a phase of continuous operation, the automation of the inspiral pipeline to generate candidates with a latency of an hour (or less) is of major importance. A great deal of work has been done toward this goal by developing the suite of tools which can be strung together into pipelines in a flexible manner. A significant effort is needed to: (i) make the on-line analysis stable and robust, (ii) automate the posting of summary information on a daily and weekly basis, and (iii) automatically publish candidates to a database which can be updated with further information as the candidates are investigated.

12. **Effect of merger on matched filtering:** Perform a study of the effects that a merger phase may have on the inspiral search pipeline. This is part of the development of the inspiral-merger-ringdown pipeline that is under way. Stitching the results from each stage together incoherently is the first step in the development of the pipeline; future efforts might try to determine a coherent matched filter for the parameter estimation stage. There is also a great deal of work to relate any observations to numerical relativity simulations.

13. **Hierarchical Search Methods:** Hierarchical methods need to be implemented and tested within the inspiral analysis pipeline. Several different hierarchical schemes exist which search over coarse grained parameters in an early part of a search, following up on triggers from this coarse grained search with finer grained parameters. These pipelines have been studied theoretically; the inspiral analysis pipeline has been specifically designed to allow efficient hierarchical searches to be performed. An effort is required to: (i) provide code to translate triggers into hierarchical banks for injection and use by the filtering code; (ii) test and develop intuition for hierarchical searches using the current pipeline; (iii) develop tools to tune this hierarchical pipeline.

14. **Tuning of cuts:** The inspiral search pipeline is designed to identify candidate gravitational-wave signals by first analyzing single interferometer data to generate interesting triggers which are then checked to be coincident with similar triggers from the interferometers at other locations. A continuous effort is needed to: (i) understand the constraints and cuts that are placed in the coincident step and develop parameter-dependent cuts; (ii) understand the effects of calibration errors on parameter estimation so that tuning based on software injections is accurate.

15. **Template Bank Construction:** Template placement algorithms implemented in LAL/LALApps generate parameter lists which describe banks of gravitational waveform templates for use in matched filtering. Current template placement routines can be used to search for binaries of non-spinning compact objects using post-Newtonian (PN), Padé, and effective-one-body (EOB) approximations and phenomenological models. A template bank has also been developed to search for binaries consisting of spinning black holes, but only in a limited region of the parameter space. Some of our template placement routines suffer from design and/or implementation weaknesses which cause them to over-populate regions of parameter space. Hexagonal packing has recently been implemented in these codes, improving their behavior significantly. An effort is required to: (i) deal efficiently with the boundaries of parameter space, (ii) implement optimal placement algorithms for spinning black hole binaries, with searches involving both phenomenological and physical signal models, where the parameter space is larger than two and (iii) ensure that hierarchical template banks can be constructed for all inspiral template waveform families.

2.4.2 Intermediate term goals

The immediate issues facing the inspiral analysis effort address detection of gravitational waves from these binary systems. In the long term, the LSC and Virgo wish to exploit detections for the purpose of astronomy. To this end, we need to develop tools for parameter estimation and scientific interpretation of the data:

1. Joint analysis of LIGO-Virgo data: we will develop joint searches to prepare the time when enhanced LIGO and Virgo+ will be taking data coincidently, with sensitivities opening the possibility of truly initiating GW astronomy. The LSC-Virgo network will make it possible to accurately locate the source in the sky and determine the parameters of the binary system.

2. Perform large-scale Monte-Carlo studies to determine parameter estimation accuracy for a range of signal-to-noise ratios. This study should be carried out with real and simulated detector noise. It

should provide the results for a range of signal-to-noise ratios and signal models. In particular, it should include as many of the known approximations as well as numerical waveforms as possible.

3. Use Markov-Chain-Monte-Carlo technique to determine posteriors on the parameters of a detected signal. At the same time, study alternative approaches and determine the relative merits of each.

4. Understand the systematic effects of calibration errors on parameter estimation. This study must be carried out using real and simulated detector noise.

5. Based on experience from the Monte-Carlo studies, develop tools that are needed to estimate these errors for any detection candidate. Exercise these tools in the on-line analysis and offline searches.

Other searches and interpretational tools also need to be developed and tested during the lifetime of the current LIGO instruments:

1. Implement a search for small mass ratio inspirals using waveforms from perturbation theory. Typically, the commissioning of a new search takes about two years, so this is a long term project which has potentially great interest.

2. Determine a useful way to constrain alternative theories of gravity using the results from our core search pipelines. It is important to understand to what extent the existing searches can be used to achieve this, or is it necessary to perform searches using theoretical waveform templates from these other theories.

3. Implement tools to include higher-order post-Newtonian corrections to the waveform amplitudes, and hence other harmonic structure. It is known that the other harmonics can significantly enhance our ability to detect gravitational waves from binary systems as the mass ratio decreases. These harmonics also break degeneracies between many of the parameters. By including this information in an observation, it may be possible to better measure the binary parameters.

4. Using parametrized post-Newtonian signal model determine the validity of the post-Newtonian theory and determine how far into the strong gravity regime post-Newtonian theory is valid. This should help in developing analytical insights into and performing more accurate numerical relativity of the merger phase.

5. By measuring the spins and masses of the binary and the final black hole in different phases of the evolution – inspiral, merger and ringdown – test the models of mergers and predictions of numerical relativity.

2.4.3 Long term goals

As the Earth-based gravitational-wave detectors move into a phase where they are making routine astronomical observations, the nature of the analysis efforts will change:

1. Astronomical alerts will be provided with low-latency to allow observations of various events by other astronomical observatories if possible. Observing a source/event simultaneously in different windows has recently provided rich information about transient γ-ray events. Future gravitational-wave observations will benefit from such multi-messenger astronomy and requires these alerts to be provided quickly but also reliably.

2. A binary inspiral is an astronomers ideal standard candle: by measuring the frequency evolution one can determine the mass parameter(s) and thereby measure the luminosity distance. Inspiral events can therefore be used to build new distance ladders and to confirm the current ones. However, for sources at cosmological distances the mass is “blue-shifted” thereby requiring observations of the host galaxies to break the mass-redshift degeneracy.

3. Database catalogs containing information about all detected events will be developed; tools to interact with and interpret the results will be provided. Such a database could be used to study cosmological models and predictions and address important issues such as the compact binary population of the Universe, evolution of the star formation rate, equation of state of dark energy, etc.

4. Specific scientific investigations will be undertaken, such as bounding the mass of the graviton, testing alternative theories of gravity, doing cosmology, constraining population synthesis models for binary (and stellar) evolution.

5. The continued development of the multi-project analysis efforts and joint analysis projects is of critical importance to doing astronomy with Earth-based gravitational wave detectors. Analysis using multiple detectors make it possible to accurately locate the source in the sky and determine the parameters of the binary system.

3 Searches for generalized burst signals

Since the LIGO, GEO 600 and Virgo detectors are now exploring the gravitational-wave sky with greater sensitivity and frequency bandwidth than ever before, we must be open to detecting *any* type of gravitational-wave signal that may be present in the data, whether or not it has been modeled or anticipated by the astrophysical community. The mission of the LSC-Virgo Burst Analysis Working Group (also known as the “Bursts Group” or “Burst Group”) is to search as broadly as possible for transient signals, using data analysis methods which do not depend on modeling of signal waveforms. The Burst Group is complementary to the CBC Group, which focuses specifically on the family of signals expected from compact binary coalescences and performs matched filtering using the modeled waveforms. As described below, the Burst Group uses a variety of data analysis methods to pursue different science goals.

The group currently has over 40 active members, from over a dozen different LSC and VIRGO institutions, who work on several different aspects of burst searches, such as data quality studies, instrumental couplings and vetoes, algorithm development, data processing, simulations, statistical methods, and the astrophysics of potential gravitational-wave burst (GWB) sources. Most group members participate in a weekly teleconference, and many attend the “face-to-face” meetings held several times per year, often in connection with LSC-VIRGO collaboration meetings. Between teleconferences and meetings, a great deal of discussion takes place via the Bursts email list. Study conclusions and analysis results are generally recorded in the group’s electronic logbook or wiki.

The Astrophysically (or Externally) Triggered Searches subgroup (ExTrig) has over 20 active members and many more interested scientists on the group’s mailing list. The group conducts weekly teleconferences to coordinate work and discuss/develop ideas. The group follows triggered searches from novel ideas to completion as published papers. It also facilitates that triggered searches are presented to the whole Bursts group at mature forms. The group’s work overlaps and cooperates with the CBC group (e.g. short hard GRB search) and also has common interest with the CW working group (e.g. pulsar glitches).

3.1 Sources of Gravitational Wave Bursts

Gravitational Wave Bursts (GWBs) are time-varying strain signals that last a short time (milliseconds to seconds). Typical sources of this kind of radiation include astrophysical systems for which the resulting burst waveforms are either poorly modeled or remain completely unknown. Other anticipated sources of GWBs exist for which their waveforms are well modeled. The distinction from the unmodeled ones is primarily suggested by the computational means that are invoked for performing each search: on one hand the search for sources with unmodeled waveforms can make only minimal assumptions on the signal morphology and must invoke rather general burst-finding methods. For systems with well described waveforms, on the other hand, full utilization of the signal morphology can be folded into an optimal detection statistic using matched filtering [1].

Among the plausible sources of poorly modeled (as of today) GWBs is the core collapse of massive stars. Any departure of the collapse from sphericity results in a net quadrupole moment which gives rise to burst-like gravitational wave emission. Several studies have been performed in order to predict the waveforms of the gravitational wave bursts associated with it [2, 3, 4, 5]. More recent simulations have suggested a new resonant core oscillation mechanism, driven by in-falling material, which appears to power the supernova explosion and also to emit strong gravitational waves [6, 7].

Although these studies provide general features of the expected signal morphology, they are far from being considered accurate models. Typical signal durations predicted by these models are from a fraction of a millisecond to hundreds of milliseconds and with signal power in the frequency range from 50 Hz up to a few kHz. Current estimates of the signal strength are rather conservative and a realistic core collapse may result in more appreciable strain amplitudes, suggesting a significant possibility of detecting a Galactic core collapse supernova at high signal-to-noise ratio. The expected rate of these events is on the order of a few per century per galaxy, making this one of the key sources for a long-term observation of ground-based gravitational wave interferometers.

The merger phase of binary back hole systems is another class of sources that may result in large amount of gravitational wave emission. As described in Sec. 2, the CBC Group aims to search for compact binary coalescences using matched filtering, which requires that the waveform be rather well known, or at least reliably parametrized. Significant progress has been made in recent years by numerical relativists in calculating merger waveforms [11, 12]. Although an improvement with respect to previous calculations [8, 9, 10], merger waveforms still present difficulties for matched filtering, and therefore generic burst searches are desirable to provide coverage given the very real possibility that the true signal does not conform to the currently available models. As in the case of the supernovae simulations, binary black hole modeling predicts signal durations in the milliseconds to hundreds of milliseconds range. The characteristic signal frequency is inversely proportional to the mass of the system and for masses in the 10-100 $M_{\odot}$ range it spans the frequency band of best sensitivity for ground-based interferometers (100 Hz to $\sim$kHz). The waveforms of these systems involve both gravitational wave polarization components.

The data processing methods employed to search for unmodeled signals are capable of detecting a wide range of possible signal morphologies, opening up the possibility of detecting GWBs from completely unanticipated sources in addition to the specific examples described above. The sensitivity of such a search is primarily determined by the frequency content, amplitude and duration of the GWB signal.

Creation of compact astrophysical objects, such as black holes formed during merger of a binary system or the collapse of the stellar core, is expected to be accompanied by generation of gravitational radiation. Such predicted sources of gravitational waves may also be observed by other means: by electromagnetic and/or neutrino channels. For example short hard GRBs are linked to the merger phase of NS-NS or NS-BH binaries. Supernovae are commonly observed via optical telescopes and a Galactic supernova would generally be expected to be detected by neutrino observatories. Additionally, current observational evidence suggests that the progenitors for the long duration GRBs are core collapse supernovae. Additional astrophysical triggers of interest are pulsar glitches observed by radiotelescopes or GRBs linked to flares of soft gamma-ray repeaters (SGRs).

The detection of a GW within an astrophysically motivated time window around a received external trigger will provide important and direct information about the physical processes leading to and resulting from the cataclysmic event producing producing both gravitational and electromagnetic radiation and/or neutrinos.

Astrophysically triggered searches can focus on preferably close-by and/or highly energetic events detected by observatories not linked to LIGO. The available information changes widely from event to event. The knowledge of specific trigger times, expected frequency range (in some cases) and directional and progenitor information allows the recognition of gravitational waveforms with amplitudes closer to the noise floor level of the detector. Since the astronomical event rate should grow approximately with the cube of the detector's reach (sensitivity) a factor of 2 increase in analysis sensitivity shall give us nearly an order of magnitude in volume coverage. In many cases the source distance and energy radiated into certain regions of the electrogmagnetic spectrum is also available. Consequently, distinct searches are developed for each astrophysical event type (e.g. GRB, SGR, supernovae, pulsar glitch, neutrino, etc.) and preferably for each detected astrophysical event, as circumstances vary.

The Swift satellite (http://swift.gsfc.nasa.gov) in observing the GRB sky provides an enhanced sample of GRBs that is in overlap with current and future running of the LSC interferometers. This increases the chance of detecting a nearby and optimally oriented (with respect to the interferometers) GRB source for which a strong GWB may be plausible.

Sources of GWBs with well-modeled waveforms include black hole ringdowns and bursts resulting from cosmic string cusps and kinks. The most sensitive searches for these sources are based on matched filtering. Ringdowns result during the final phase of the coalescence of binary compact objects when the newly formed black hole undergoes quasi-normal mode oscillations [10]. Ringdowns may also result outside the binary coalescence from otherwise perturbed or accreting black holes [19]. The CBC group searches for ringdown signals in this context using matched filtering. Cosmic strings come about as the result of phase transitions in the early universe in symmetry breaking models of high energy physics. They are also a prediction of string theory inspired brane-world inflation scenarios. If they exist, they could emit powerful GWBs detectable by first generation ground-based interferometric gravitational wave detectors such as LIGO. The bursts we are most likely to be able to detect are produced at cosmic string cusps [20]. These are regions of string which acquire phenomenal Lorentz boosts and emit a powerful burst of gravitational waves in the direction of motion of the string. The formation of cusps on cosmic string loops and long strings is generic, and their gravitational waveforms simple and robust.

Carrying out population-based analyses and electromagnetic (radio/optical/X-ray) follow up studies can naturally build a direct bridge to observational astronomy. This is valuable from the point of view of attracting graduate and undergraduate students to GW astronomy. This bridge need not be a one way one since the needs of the GW analysis could guide the observing program of an astronomical facility [32].

3.2 Science Goals of the Bursts Group

The goal of the search for GWBs is their unequivocal detection. Extracting the source and wave parameters are integral parts of this endeavour. This will be the first and necessary step to what will become astronomical observations using gravitational waves, including bursts. In absense of any detections, upper limits on the rate and strength of GWBs are attained. Inseparable from the group's mission is the utilization of data from the LSC-VIRGO detector network in a way that provides best observing results for GWBs. Several data analysis methods are employed in reaching these goals.

Astrophysically triggered searches: Direct correlation in time and direction between events detected by LIGO/VIRGO and astrophysical events detected in the form of electromagnetic radiation and/or particles by independent observatories would greatly increase the confidence in the collaboration's claim of detection and the sensitivity of the searches. On the other hand, the sensitivity of LIGO detectors and that of the current search pipelines allows significant astrophysical statements for triggered searches corresponding to close-by events. Currently astrophysical triggers are utilized in distinct ways with differing scientific goals:

Event-by-event analysis: We focus on preferably close-by and/or highly energetic events detected via independent astrophysical observation. Such events are likely to produce significant astrophysical results, upper limits may allow us to distinguish between source types or competing theories on source dynamics. As in most cases precise direction is known, GW burst candidates—within the astrophysical time window—that do not correlate with the known direction of the event can be vetoed.

Statistical analysis of large number of astrophysical events of similar/same type or source: An example of such approach is the analysis of GW data coincident with a large ensemble of GRB events [21] or analysis of GW data coinciding with frequent flare activities of specific soft gamma-ray repeater (SGR) sources. Even if no GWs are detected, the availability of good statistics might provide the possibility of obtaining astrophysical information on GW event rate limits and for the SGR flares limit on the energy reservoir of the specific source.

Coincident analysis of GW candidate events and candidate events in other astrophysical channels: This method utilizes frequent but low confidence level events of both GW and other independent observations and finds the statistical significance of possible events coincident in time and/or direction. Such a search would certainly enlarge the scientific scope of both type of observations. An example for this approach would be coincident analysis of GW and high-energy neutrino events.

All-times, all-sky search: Given that the gravitational-wave sky is unknown, a search that makes no *a priori* assumption on the GWB source location, timing and accompanying signal morphology is essential. This search proceeds through the analysis of all the data collected by the interferometers. Search parameters may be tuned in such a way that a very low number ($<< 1$) of background events is expected over the duration of the observation. Any signal events (foreground) resulting from this analysis constitute detection candidates for which further and exhaustive investigation is performed in order to understand their origin. This process is expected to establish "gold plated" events as GWB detections. In the absence of any such events, upper limits on the rate and strength of GWBs can be obtained with the use of upper limit statistics and source and signal simulation Monte Carlos. Upper limits may be constructed using frequentist and Bayesian approaches. An alternative way of pursuing this search is through the statistical analysis of the amplitude distribution of signal and background GWB candidates. This distributional analysis approach can improve the potential for discovery by using lower-amplitude events that fall below the high thresholds nominally used in the "all-times, all-sky" searches. It can also enhance in principle the sensitivity to specific source populations, such as the galactic disk and GWB repeaters.

Astrophysical and cosmological model motivated searches: Searches for GWBs can fold information on the astrophysics of plausible sources in many ways. This can improve the sensitivity of a search as well as present the opportunity of interpreting search results within a richer astrophysical context. Such searches may tune their parameters for a particular class of signal waveforms. General algorithms or matched filtering—when appropriate—may be used to custom-tailor searches targeting astrophysical systems such as core-collapse supernovae, mergers, ringdowns or cosmologically motivated cosmic string cusps or others. Population models of assumed GWB sources can also be folded in the interpretation of upper limits (independent or not of the tuning of the search for a specific source waveform). To measure sensitivity in astrophysically-relevant terms requires comparision to models for the spatial distribution of sources. Our ability to simulate GWB sources sampled from a specific distribution, e.g., a galactic disk population for core-collapse supernovae, or binary merger population out to tens of megaparsecs, will be essential for the astrophysical interpretation of the search results. Other means of involving the astrophysics of specific GWB sources includes the tailoring of searches to galactic point sources (directional searches) or performing a sidereal analysis of GWB candidates.

Instrument commissioning, tuning and planning: Beyond the analysis of data collected by the LSC-VIRGO detector network, the Bursts Group expects to play a role in the commissioning of enchanced instruments by providing prompt and detector-oriented analyses of early data collected by the instruments while commissioned. The group has traditionally maintained strong contribution and intimate relation with the detector characterization effort since the early commissioning of the first generation instruments. This is intended to continue in the regime of commissioning next generation detectors. Moreover, the Bursts Group will undertake studies and provide feedback on how next generation instruments should be designed and ultimately operated for best sensitivity to GWB (e.g., narrow band vs broad band, tuned for specific sources, role of collocated detectors and others).

3.3 Recent science results

Astrophysical searches for GWBs have been carried out within the LSC as soon as interferometric data of good sensitivity and in coincidence among the instruments were collected. Results from searches were published in journal publications [22, 23, 24, 25] while others were presented to LSC collaboration conferences as internal reports.

The search for gravitational wave bursts in the fourth science run (S4) of the LIGO instruments is now (May 2007) complete and has been submitted for publication [26]. It covers 15.5 days of triple coincidence data collected by the LIGO instruments in February-March 2005. The search follows the methodology established in the second (S2) and third (S3) science runs. An excess power method working in the wavelet domain simultaneously among the three LIGO detectors has been used to provide the initial set of triggers. These triggers were then checked for consistency of their waveform using a cross-correlation statistic between pairs of detectors. No gravitational wave bursts were detected and an upper limit of 0.15 events per day (at the 90% confidence level) on their rate at the instruments was established. With S4, the burst search all-sky sensitivity in terms of the *root-sum-square* (rss) strain amplitude has reached the level of $h_{rss} \sim 1.3 \times 10^{-21} Hz^{-1/2}$ at 153 Hz.

An extension of the S2-S3-S4 methodology for the all-sky, all-times search has been applied to 54 live-days of triple coincidence data collected by the LIGO instruments during the first 5 months of their fifth science run (S5: Nov 4, 2005 and on-going). Preliminary sensitivity (about a factor of 2 better than in S4) and background measurements were presented at the April 2007 APS conference in Jacksonville, FL, and a paper is being prepared.

Gravitational wave bursts in coincidence with GRBs have been searched using cross-correlation techiniques. GRBs from S3 and S4 have been combined with ones from S2 in a single publication that presents the search on a total of 39 GRBs. No gravitational wave bursts associated with them have been detected. Upper limits on their signal strength have been established and preliminary results were presented at the April 2006 APS conference in Dallas, TX. The paper publication detailing the analysis and the attained results is in its final stages of internal review and will be submitted for publication soon.

More than 100 GRBs that occurred during S5 have gravitational wave data from 2 or more LIGO instruments and their analysis is ongoing in near-real time. GRBs detected by Swift, and those by other satellite experiments, are used as external triggers to search for gravitational-wave bursts which are coincident with GRBs. For the near-real-time GRB-GWB analysis, based on crosscorrelating data from pairs of interferometers, the search sensitivity to sine-gaussian signals centered at 250 Hz is $h_{\rm rss} \approx 6 \times 10^{-22} {\rm Hz}^{-1/2}$. Preliminary sensitivity measurement of the search was presented at the April 2007 APS conference in Jacksonville, FL.

Soft gamma-ray repeaters (SGRs) located in our Galaxy at the order of ten kpc distance have proven to be highly exciting objects due to their close proximity and the substantial amount of precise data available on their flare activities. SGRs (likely to be highly magnetized neutron stars) sporadically emit brief and bright gamma-ray flashes. Since the most widely accepted model predicts that flares from these objects are accompanied by catastrophic non-radial motion in the star matter, they are attractive candidates for production of detectable gravitational waves. LIGO data coinciding with the 2004 Dec. 27th hyperflare of SGR1806-20 was analyzed. Both the instantaneous gravitational emission at the burst and plausible GW emission associated with the quasi-periodic oscillations (QPOs) observed in the pulsating tail of the giant flare event can be addressed.

QPOs in X-rays that are plausibly attributed to seismic modes of the star that might have given rise to gravitational waves as well. We have searched for gravitational wave emission related to the QPOs. No candidate signals were observed and the lowest upper limit was set by the 92.5 Hz QPO observed in the interval from 150 s to 260 s after the start of the flare. This corresponds to a (90% confidence) RSS strain amplitude of $h_{rss} = 4.5 \times 10^{-22} Hz^{-1/2}$ on the gravitational waves in the detectable polarization state reaching the Hanford (WA) 4 km detector. The characteristic energy in gravitational wave emission that we would expect to be able to detect is 7.7×10^{46} erg (or 4.3×10^{-8} solar mass equivalent) which is of the same order as the total (isotropic) energy emitted in the electromagnetic spectrum. This is also the first broadband asteroseismology measurement using a GW detector.

Major emphasis is given in the near real-time analysis of data from LIGO's fifth science run (S5) that started in November 2005 and is continuing to collect data. This included the analysis of numerous auxiliary interferometric and environmental channels for the purpose of understanding detector artifacts that might be affecting the overall data quality and the search for bursts in particular. In addition, a real-time search for astrophysical events of high amplitude with respect to the detector's noise level is also being performed for both the triggered and untriggered searches.

3.4 Search pipeline overview

Several analysis pipelines implement the science goals and the pursuit of astrophysical GWB sources that we described in the previous sections. In this section we will review the status of the fundamental building blocks that are present in all of them. This includes the signal detection algorithms, the data quality and event-by-event vetoes, the signal simulation, the calculation of background and the criteria for establishing detections.

3.4.1 Algorithms

The signal-processing algorithm is the heart of any search for GWBs. On the basis of the algorithm, searches can be divided into three broad categories: (a) general time-domain and time-frequency methods looking for statistically significant excess of signal power or signal amplitude, (b) cross-correlation methods that check the relatedness of multiple detectors' output by projecting one's data stream onto another's and their generalization to fully coherent methods for an arbitrary network of detector and (c) matched filtering methods [1] where the known astrophysical waveforms are used as the basis for projecting the detector's output. These methods can be applied both in a triggered and an untriggered type of search for GWBs. All three classes of burst-finding algorithms are well developed within the LSC and/or Virgo.

Several general burst-finding methods that are nominally redundant and complementary have been put forward and applied to simulated and interferometric data. All methods are nominally expected to be applied to future data from the instruments in a detection-oriented search. However, in the absence of any plausible detections, upper limit results within the context of each search are expected to be reported to the scientific community and in publications by a single method only. This is generally expected to be the most mature, simple and sensitive method over the broadest class of plausible signal waveforms that is also fully documented and internally reviewed. Results from other methods will be fully documented in writing and presented to the collaboration for the purpose of sharing the outcome of research activities as well as providing increased confidence and validation to the delivered results.

It is essential for all burst-finding algorithms that they couple to the same simulation engine (see sec. 3.4.3). This provides a common denominator for their comparison. An integral part of this comparison and for the burst search altogether is the ability to do in a unique and commonly-defined way the signal parameter estimation of events selected by the various burst-finding methods. Standardized parameter estimation as a stand-alone tool is now in a mature state and has been integrated in the S5 burst searches. It should be noted that matched filtering provides the optimal detection statistic once a specific target signal waveform is assumed. For this, it provides a benchmark for comparison for any other search algorithm and should be integrated within the methods-comparison effort.

Cross-correlation methods for aligned or nearly-aligned detectors—as is the case of the three LIGO instruments—have been implemented within the context of a triggered and as part of the untriggered search. Extension of this methodology to a more heterogeneous network of interferometric detectors with different alignment and sensitivities has been under development in recent years and will continue to receive the highest attention of the Bursts Group.

With the availability of sensitive data from the LIGO-GEO-VIRGO network of detectors, use of fully coherent techniques for extracting maximum scientific benefit has become a priority for the Bursts Group. Additional detectors provide increased observation time with multiple detectors operating, better sky coverage, decreased background, and increased confidence in detection. A fundamentally new advantage is that networks of differently aligned detectors can determine the source position and waveform of a GWB via coherent analysis [40], which is expected to become a high priority in the near future. Coherent analyses have the further advantage that they can in principle achieve higher sensitivity than traditional trigger-based searches; in particular, the sensitivity of a coherent search is not necessarily limited to that of the noisiest detector.

The larger observation time with multiple detectors operating can also be helpful in astrophysically triggered searches (e.g., GRBs), by increasing the number of triggers that can be studied and the scope of astrophysics to be extracted.

Several fully coherent methods have recently been developed by members of the Bursts Group; these methods offer ability to perform burst detection or vetoing, source localization, and waveform extraction. Some of them explore the Gürsel-Tinto technique [40], generalizations of it as well as pursuing alternate coherent analysis strategies for arbitrary detector networks [41, 42, 43]. These methods are maximum likelihood analyses with or without constraints. In the case of the Maximum Entropy variant, a maximum likelihood analysis with a Bayesian prior that favors maximum entropy is used to address the source location and waveform extraction in the network analysis problem. All methods are in the process of application to real interferometric data.

Quasi-coherent or incoherent network analyses may be more viable than coherent analyses for large-scale searches over data when computational requirements and the cost of increased complexity of the algorithms are considered.

Matched-filtering searches for burst sources benefit a lot from the algorithmic infrastructure of the CBC Group (see sec. 2) and are being developed in close connection or entirely within that group. This includes the search for ringdowns and cosmic string cusps. Similar searches using catalogues of supernovae waveforms are being pursued.

A wide range of astrophysical observations, plausibly related to gravitational waves, are accessible from external sources ranging from optical telescopes, through excellent GRB satellites to neutrino detectors. We had extensive use and advance on this front in the past and we expect an even wider set of related possibilities in the future. Since the available information from astrophysical triggers can vary event-by-event and several event and/or source types are considered, specific search algorithms have been developed in the recent years in order to address the particular scientific goals of different astrophysically triggered searches.

A highly exciting close-by event may happen when not all the interferometers are operating in the science mode and this situation was certainly prevalent and we should expect to face hard issues beyond

S5. In some cases only Astrowatch data was/will be available, potentially only from a single large scale detector, as was for the case of the Dec 27 2004 giant flare of SGR1806−20 (although GEO has also provided coverage for the kHz region). Therefore, algorithms for astrophysically triggered searches range from modified versions of excess power type searches on the time-frequency plane using only single detector data through two detector based cross-correlation methods to fully coherent network based searches using a single sky direction.

Additionally, information from the more frequent but low signal-to-noise ration GWB candidate events can be used in hierarchical searches. We must look for hot spots on the sky (e.g. gravitational wave repeaters). Collaborations need to be formed where information on events (obtained from GWB trigger event generator algorithms) are used in conjunction with astrophysical observations from independent observatories to detect candidates and to extract astrophysical information.

It is clearly not trivial to translate raw gravitational wave observations to astrophysically meaningful quantities, especially at low signal to noise ratios. Consequently, LIGO needs a comprehensive set of well-tested and exquisitely sensitive methods that are able to infer as much information as possible from recorded data segments that correspond to an astrophysical trigger. For example, methods for determining precise directional information from coincident observation in separated GW detectors should be developed and then used to veto candidate events and in case of a detection to verify the astronomical source location. Additionally, the interpretation of the specific astrophysical process/dynamics of detected events relies on the recovery of the different polarization components of the gravitational waveform. Waveform recovery, separation of different polarization components and the determination of power in different polarization components will all be mission critical in case of a detection. Development and and careful tests of such methods should happen ahead of time. These methods may also be exercised on significant candidate events in the data and then the deduced waveforms compared to available waveforms based on numerical relativity calculations.

3.4.2 Data quality and vetoes

Environmental and interferometric causes may result in data-taking periods of elevated overall noise limiting the sensitivity to GWBs and/or impulsive events imitating GWBs. The data quality and vetoes study is essential in identifying and removing as much of these as possible. Determination of the coupling between the external causes and the gravitational wave channel—when possibile—is of particular importance. It not only provides information in establishing data quality and veto conditions but it will play an essential role in the case of a detection. All the data quality and vetoes studies with the Bursts Group are taking place within the Glitches Investigation Team of the Detector Characterization Group (see sec. 6.1).

One of the immediate goals of this study is to establish data and event selection criteria that will lead to as much stationary and Gaussian instruments as possible. Moreover, it is expected to provide the necessary methodology for the study of an exhaustive list of auxiliary channels that will confirm or refute GWB detection candidates.

A significant increase in the number of auxiliary channels processed and key steps toward the automation of this procedure were accomplished during the S4 run. This has paved the way to S5: approximately 200 auxiliary channels per detector site are analyzed nearly online and fully automated. The analysis of trends and transient events from these channels may establish the statistical correlation between them and the gravitational wave channel. For this, single-interferometer based analysis pipelines are essential and expect to play a key role in characterizing the noise of the instruments and contributing in the close to real-time search for GWBs. The two collocated LIGO detectors at Hanford provide a significant handle in identifying environmental couplings. This study has already shed light on magnetic and power line couplings and is expected to contribute additionally as the H1-H2 analyses complete. At the same time this work may quantify the advantages and disadvantages of collocated detectors.

Within the context of the present S5 analyses as well as in future running, the extension of the burst search beyond the current $\sim$ 1 kHz upper frequency bound is pursued (see sec. 3.5). This will require data quality and veto studies to be extended accordingly so that the broader frequency range of search to be supported.

3.4.3 Simulations

A flexible GWB signal simulation package is essential for the success of the Bursts Group's science goals. These simulations are necessary for tuning a search for a specific analysis goal, studing its sensitivity and interpreting its results.

Such an infrastructure, called GravEn, has been developed. It supports both internally-generated GWB signal morphologies as well as the use of pre-generated waveforms from input files. It uses astrophysically-detailed gravitational wave propagation for multi-detector injection and allows per-injection sky location specification for source population simulation. After several years of experimentation, the most efficient way for generating and distributing among LSC computing sites simulated data sets was determined to be through the generation of frame data that include the signal-only (i.e., free of any real or simulated noise) time-series. These frame files contain the digitized signal both in strain units as well as in ADC counts after folding the inverse response function of the interferometric loops that sense the gravitational wave signal with the highest sensitivity. These signals can then be added in software by each search method at run-time either on real or otherwise simulated interferometric data. The same infrastructure can produce frame files with simultaneous injections into all ground interferometers (LIGO, GEO, VIRGO, TAMA). In order to avoid any systematics in the search results, it is generally expected that multiple streams (corresponding to various signal morphologies) of simulated data will be produced over the *entire* duration of the observation. The computational requirements of the simulation infrastructure are rather small. Their creation time on a 3 GHz CPU is $\sim$2 hours for one day of observation time. This can be greatly accelerated via the use of automated pipeline that is run on LSC grid computers. Moreover, their distribution to the LSC computing centers is fully automated through the use of the Lightweight Data Replicator (LDR) (see sec. 7).

It is expected that existing and forthcoming methods searching for GWBs will couple their simulation tasks to the aforementioned infrastructure. This will minimize the review requirements, avoid repetitions and make available to the whole Bursts Group community a richer sample of simulated data. In the S5 running of the LSC instruments this simulation engine has provided simulated data for the burst searches as they have been progressing and as soon as credible calibration of the instruments is available.

In addition to simulations performed in software, the LIGO interferometers provide the ability to mimic the passage of any gravitational wave signal, including burst-like ones, via wiggling of the mirrors that form the interferometric arms. Such "hardware" signal injections play a significant role in burst searches. They are used as an end-to-end check that the analysis pipeline can successfully recover signals in the data and to measure cross-coupling into auxiliary channels which might be used for vetoes. They are generally not used to map out efficiency curves in detail; that is done using software signal injections. However, before proceeding with extensive and detailed software simulations, the comparison of hardware and software signal injection outcome is essential in gaining confidence and cross-validating the procedure.

We expect hardware signal injections to be performed throughout future runnings of the LSC instruments as well as Virgo. Defining, executing and analyzing in near real-time a hardware injection program is among the top priorities of the Bursts Group.

In many cases coincident data may not be available or may not be suitable for characterization, tuning and optimization of data analysis approaches. Often tests of methods on simulated surrogate data is more than adequate and for comparison of search methods it is highly desirable. Current experience based on analysis of simulated data shows that beyond the main spectral characteristics, the statistical glitch and first order correlation properties of generated surrogate data can be replicated. The development and use of realistic simulated data should be considered.

3.4.4 Background

Detailed understanding of the background is an essential part of the search for any GWBs. The background in the search for GWBs is generally assumed to be due to random coincidences among the interferometers. It can be estimated by artificially shifting the raw time series of one instrument with respect to the rest. This is referred to as the time-slide (or time-shift) method.

In the case of astrophysically triggered searches the available lock segment containing the astrophysical trigger is normally divided into an on-source (that is the signal region time window, motivated by astrophysics and/or theoretical/experimental uncertainties) and background or off-source segments assumed to reproduce the statistical properties of the on-source region. The analysis is carried out on the very same way in the on-source, off-source and time shifted off-source segments. The statistical significance of on-source candidates is evaluated based on the results obtained from the ensemble of off-source type segments.

Studies towards understanding the role of non-stationarities, the use of Poisson estimates to calculate coincidence rates (independent from time-slides) and the correlated environment of the two collocated LIGO Hanford detectors may shed light into this aspect of the analysis.

3.4.5 Detection criteria

Maturing the criteria of what will constitute direct detections of GWBs is a center-piece of the LSC-Virgo Bursts Group's research plan. For this reason, the group maintains and continuously updates a comprehensive check-list that describes the procedure and tests that are envisioned to be undertaken in the event of a GWB candidates. Event outliers or overall oddities are expected to be checked through this list in order to gain experience and insight in going through these steps.

In order to establish the scientific requirements for declaration of an eventual detection and internally evaluate discovery claims the LSC has a standing Detection Committee where Burst group members contribute.

3.5 Status and prospects of S5 burst searches

In this section we will discuss the status and prospects of burst search pipelines within the context of triggered and untriggered searches expected to be applied on data collected by the LIGO-GEO-VIRGO network in the LSC fifth science run (S5). Although S5 is expected to end in mid-Fall 2007, analyses of this data will almost certainly continue well into 2008 when we expect final S5 publications to be submitted.

3.5.1 Triggered searches

It is widely believed that gravitational wave sources are also observable in more traditional channels. Directly relevant astrophysical observations are in abundance, ranging from Earth based astronomical data, through sensitive GRB/x-ray satellite detections to neutrino signals.

The baseline GRB search pipeline invoked in the near real-time GRB-GWB analysis is expected to continue for the rest of S5. During the S5 run, Swift and IPN have detected hundreds of GRBs, providing an adequate sample for a coincident GRB-GWB search. The larger the GRB sample size, the greater the chances of getting GRB triggers which are nearby and within the reach of LIGO I's sensitivity. Approximately 80% of these GRB triggers occur during double-coincident science mode data, and approximately 50% occur during triple-coincident science mode data. The method is expected to be used during S6 to provide near real-time first hand results at with a factor of $\sim$8 greater chance for detection.

GRB triggers as received in near real-time initiate an end-to-end search using LIGO data within an hour of the astrophysical trigger. It usually takes less then two hours to obtain preliminary results. It is desired that nominally within 24-36 hours (depending on human availability) an executive summary is prepared for the LSC on extraordinary events. The availability of a large sample of GRB triggers collected during the S5 run facilitates the use of statistical methods to search for GRB-GWB association.

In the absence of a loud GWB signal from astrophysical triggers, it is still possible to increase the confidence level of weak gravitational wave signals through a statistical search. Such a statistical search looks for the cumulative effect of weak signals which individually will not comprise a detection. A statistical search on candidate events within the trigger window for an adequate sample of GRBs or SGRs can in principle target weaker GW signals that the one required for a gold-plated detection. These studies will be undertaken for S5 events and continue throughout S6 at an increased potential for discovery.

We foresee to carry out joint LIGO-VIRGO astrophysically triggered searches for specifically selected cases, on which the two collaborations will jointly agree and for which such analysis will be recognized as a powerful tool to improve the final astrophysical bounds. Such joint analyses will likely to be carried out by using both the standard coincidence approach and the coherent method. While the latter will certainly represent the most powerful tool to obtain astrophysically interesting bounds, the former will allow to have robust results against possible non-stationarities and to compare the output of different burst search algorithms developed by the two collaborations.

It is also essential to execute high sensitivity specialized off-line searches for trigger times received from close-by and highly energetic astrophysical events. To achieve optimal results these investigations will require significant human effort and therefore we will work down the list picking and evaluating the most promising external trigger candidates first. This approach proved fruitful and productive in the past and makes sense for the future. One of the best recent example is the search and astrophysically interesting bounds on the GRB070201 event. Such opportunistic and scientifically beneficial analyses will be continued during S5,S6, between and beyond.

Triggers from Soft Gamma-ray Repeaters

The available data for the 2004 hyperflare of SGR1806-20 was of limited quality from two GW observatories (Hanford 4km and GEO600 for the kHz frequencies). We expect significantly better results for the more recent SGR flares (order of 100 events) coinciding with S5 run as in many cases multiple detectors were observing at a better sensitivity. The technique used in the analysis of the Dec. 2004 event has been adopted for use with multiple data streams and the search for GWs associated with quasi-periodic oscillations during S5 SGR events is ongoing.

Searches for GWs associated with the transient initial phase of SGR flare events observed during our ongoing S5 run can also be used on a single and a coherent 2-detector way, depending on the availability of data. Upper limit estimates for close by SGR sources (up to $\sim$15 kpc) based on the GCN (Gamma-ray Coordinates Network) circulars will be obtained.

Triggered searches for GWs associated with SGR flares will continue throughout S6.

Searches tuned to GRB models

The search for GRB-GWB correlations can be tuned for specific assumptions of the GRB models. This is currently being developed for e.g. the long GRBs based on the model of long gamma ray bursts by van Putten, et al. Two novel and general methods, the so-called Locust and the generalized Hough algorithms, were developed in order to search for quasi-monochromatic signals of moderate frequency evolution and limited duration in GW datastreams. The methods addresses quasi-monochromatic gravitational wave signals of limited duration, as predicted by van Putten [28, 29] for long GRB events, but can essentially be applied for any search where similar time-frequency evolution is expected. These types of signals give rise to curling traces of local maxima in the time-frequency space that can be recovered via image processing methods (Locust and Hough). Initial tests of the algorithms in the context of the van Putten model was carried out and it is expected that the methods will be applied for interesting long GRB triggers from S5,S6 and beyond.

Low threshold gamma ray triggers

An alternative approach to cross-correlation based searches around the times of individual GRBs, is the statistical analysis of an ensemble of them, if low-threshold gamma-ray triggers are available in large quantities. In this case a search can be undertaken for a particular class of signal: a GRB which was close enough to be seen in gravitational waves, but whose jet axis was pointed away from the earth in such a way that the gamma-ray emission was weak. Since GRB's are believed to be "beamed", with a beaming factor of several hundred, there should be many more off-axis GRB's than observed GRB's in the sky. Since gravitational waves are predicted to be much less directional than gamma rays for these objects, there is a possibility that an off-axis GRB went undetected by gamma-ray satellites but was detectable in gravitational waves. After the high confidence level GRB events during S5 are analyzed the search to harvest low confidence level GRB events occurring during S5 can proceed via the already developed methods.

Similarly to the GW-Neutrino search, one can also use low-threshold triggers from both a gamma-ray satellites and the interferometers. Relying on general burst event trigger generators is relatively simple and it is low in computational cost. Both samples of triggers are expected to contain primarily fluctuations on noise, and so any observed coincidences in time and direction must be compared with expectations of a background from accidental coincidences. Most likely a discovery using such a method would be of a single, rare, nearby GRB (a "lucky" event); although rare, the only way to discount the occurrence of such an event is to conduct the search and find out.

Optical Supernovae as Astrophysical Triggers

Core collapse supernovae are interesting candidates for detectable gravitational wave sources. Although they are rare events, Galactic supernovae can also be associated with a neutrino burst/trigger. For extragalactic supernovae the external trigger must be derived from data from an early optical detection, leading to a large uncertainty on the derived event time (order of several hours), making the data analysis task challenging. The information on distance and direction is often well-known thus we can use directional search analysis methods. The large number of extragalactic supernova discoveries makes this line of analysis a possibility, even though the theoretical motivation is still evolving.

To develop, to implement and to execute a specialized search algorithm to search for gravitational signature of observed optical supernovae is a priority. Observed core collapse supernova events during S5 are monitored and certain close-by events, corresponding to core collapses are selected for analysis. Methods were also devised to reconstruct supernova lightcurves with a special focus on estimating the start of the supernova event, necessary for providing a trigger time and analysis time window. Such analyses are expected to continue during S6.

Neutrinos and other Astrophysical Triggers

Source direction for high energy neutrinos and ultrahigh energy cosmic rays are routinely reconstructed while their precise arrival time is also recorded by dedicated observatories. There may also be gravitational wave candidates of the LIGO detector network, which are coincident in time and direction with events from such independent observations. The feasibility and expected performance of such search is needed to be investigated to a great detail. For example initial simulation results show that with typical 2 neutrino events per day and with the triple coincident trigger rate in LIGO trigger event generators, the background IceCube-LIGO coincidence rate can be set to extremely small values (e.g. 1/100 year). Thus highly confident detection of astrophysical events producing both GWs and high energy neutrinos (such as GRBs, etc.) is possible. Such analysis can expand the scientific reach of both experiments.

It is also important to maintain a prompt and automatic analysis pipeline to take immediate advantage of a possible trigger [35] from neutrino detectors [36, 37]. Such trigger has a limited probability, however, such a close by event would have enormous scientific payoff (e.g. direct measurement of the neutrino mass [38, 39]). Once again, this pipeline is somewhat unique, as the pointing information will not be accurate, however, the timing information should be spectacular (neutrinos are expected to leave the collapsing core within $\sim$0.1 s of the gravitational waves).

Pulsar Glitches as Astrophysical Triggers

There is a possibility that the burst of gravitational waves generated by pulsar glitches will be strong enough to be observed by LIGO and/or Advanced LIGO. Although the details of the models are still uncertain, a targeted search for a quasi-sinusoidal ring-down signal from the excited neutron star is consistent with our understanding of the signal's form. Clearly, a precise prediction of the time at which this signal should be seen is important for maximising sensitivity and reducing the search parameter space. There are several pulsar timing programmes worldwide and, with varying degrees of precision, the times of glitches from pulsars are readily available. Our ongoing collaboration with the pulsar group at Jodrell Bank Observatory can supply much of these data. In particular they carry out near-continuous observations of the Crab pulsar (a regular glitcher), with a time resolution of $\sim$ 10 minutes. Other glitching pulsars are observed more sporadically, but collaborations are developing with the X-ray community to give better glitch timing for PSR0537-6910. We have developed a new technique for identifying the gravitational ring-down signals from pulsar glitches based around Bayesian model selection (Clark et al., 2007 in press). This method is coherently expendable to multi-detector networks and we intend to make it fully robust against the influence of a wide selection of instrumental glitches that could otherwise severely affect search sensitivity.

Population study of astrophysical sources using data from other detectors

The objective of this analysis is to infer properties that characterize a population of astrophysical sources as a whole rather than any one individual member. The sources would be known from observations of their electromagnetic or particle signature or could be candidate GWB events themselves obtained from detectors that work in a different frequency band than LIGO (called *external triggers*).

It is likely that GRB central engines have significant GW luminosity. As shown in [21], we can derive astrophysically interesting results about the population average of the GW luminosity of GRBs. The idea of a population study has been recently extended to pulsars [31]. In the following it is important to keep in mind other possibilities for triggers as well as future improvements in detector sensitivity.

There are several compelling reasons for LIGO to pursue population studies. An important feature of a population study is that its signal to noise ratio increases monotonically with the number of triggers. Hence, eventually, such an analysis might yield either a (*statistical*) detection or an astrophysically interesting upper limit. Since individual sources need not have a strong GW signature, data where no strong signals were seen is not '*wasted*'. A population study is complementary to the detection and analysis of individual coincident events and both analyses are necessary in order to better understand a given class of astrophysical phenomena.

The application of population study has been demonstrated on data from the S2, S3, S4 runs. The method was implemented as a post-processing step on the output of the baseline cross-correlation based triggered search. Cross-correlation values corresponding to GRBs that occurred when H1 and H2 were in science mode were combined following the prescription developed in [44] using a maximum likelihood approach.

A more mature analysis is under development for GRBs that occurred during the S5 run. Among the improvements will be the use of a coherent statistic being developed specifically for triggered searches so that L1 data can be used optimally, and a separation of the sample of short-hard and long-soft GRBs in the analysis in order to account for the different nature of their progenitor populations.

3.5.2 Untriggered searches

Through the remaining of the S5 run the Bursts Group expects to continue the near real time look at data as they are collected by the LIGO-GEO-VIRGO instruments. This includes the study of outlier events on a single-detector basis, correlations with auxiliary interferometric and environmental channels and the study of overall data quality. This effort provides prompt feedback to the running of the instruments and the timely definition of data quality flags. Much of this work relies on real-time monitors or quick turn-around searches that provide this first look at the data. At the same time we intend to continue to look at high threshold, low probability coincidence events for the purpose of identifying promptly a loud astrophysical event.

As already described, the “all-times, all-sky” search pipeline for GWBs has matured over the previous science runs of the LSC instruments- during S5 it will include the following improvements:

- Feature single-instrument, hierarchical and fully coherent search methods where data from the LIGO-GEO-VIRGO detector network is best used to optimize the search for GWBs. All methods will apply coherent follow-ups for all candidate events.
- Analyze all detector networks with at least two instruments in coincidence, thus maximizing the search observation time. This increase in the available observation time remains the primary advantage of such searches, something that may possibly lead to improved upper limits and improved prospects for detection.
- Develop a specialized, hierarchical analysis starting with the two LIGO Hanford detectors. Such a search may take advantage of strong consistency tests that are independent of source location. However, the effects of calibration error on consistency tests and the potential background due to a common environment require care.
- Address statistical issues surrounding the combination of upper limits from different detector networks with different livetimes, background and sensitivities.

New directions in the “all-times, all-sky” search pipeline for GWBs that are currently being investigated with simulated and real data include:

- Rethinking our upper limit statistics both within the context of classical frequentist and Bayesian formulation. A Bayesian approach forms detection and upper limit probabilities simultaneously. It also supports the addition of posterior vetoes in a straightforward manner.
- Perform an astrophysical interpretation of the search results assuming a source population and gravitational wave emission model.
- A distributional analysis that tests for statistically significant differences in the amplitude distribution of signal and background GWB candidates. This analysis requires identification of a suitable distributional statistic, measure of signal amplitude, target event rate, and sensitivity to different astrophysical source models. These aspects of the distributional analysis are currently being worked out.
- Increasing in the upper frequency coverage of existing search algorithms in order to use the full available bandwidth of the LSC-VIRGO detectors. This is referred to as the high frequency search (HFS).

Beyond the nominal "all-sky, all-times" search, several other untriggered searches are being investigated and are expected to produce scientific results using S5 data. These include:

- Investigation of targeted quasi-coherent or fully-coherent searches for bursts from specific sky positions. Such directional searches may materialize as a variant on the basic coincidence or fully-coherent all-sky search. Possible benefits include further reduction in the background via tighter time and amplitude and waveform consistency tests. This approach, when applied to the whole sky may yield gravitational wave maps that establish upper limits and sensitivity as a function of sky position.
- Work in collaboration with the inspiral group in searching in a "back-to-back" way for the inspiral, burst (merger) and ringdown signature of the binary coalescence (see sec. 2). This approach is expected to achieve higher sensitivity from each of the searches separately and plans to use best estimates of simulated waveforms capturing the final seconds of the binary evolution in order to benchmark the search.
- Search for bursts from cosmic string cusps. This is a templated search, which is designed to run in coincidence using data from all the interferometers. The pipeline and codes have been validated and run on a prototypical search on S4. This is expected to be extended in the S5 data. In the absence of any plausible GWB candidates revealed by this search, its goal is to produce upper limits on some of the parameters of string evolution, such as the mass per unit length of strings or the probability of reconnection.

3.6 Plans for beyond S5

The Burst Group will maintain its activities beyond the nominal end of the S5 data-taking (expected mid-Fall 2007). These will focus on existing and new scope the group is envisioning, especially in preparation for S6. In particular the group plans to:

- complete the S5 analyses described in previous sections and submit final publications,
- analyze astrowatch data from the detector networks remaining on line beyond S5 and before S6 (currently,GEO and H2 expected),
- apply externally triggered searches on close-by and/or highly energetic events detected by electromagnetic/optical/particle channels during astrowatch times,
- contribute in the enhanced instrument commissioning by analyzing engineering data as they are collected,
- work out tuning scenaria for advanced instruments,
- refine detection criteria based on lessons learned from S5 and expectations from enhanced/advanced instrument performance,
- develop optimal searches for foreseen scenarios of astrophysical trigger and data types
- undertake any major analysis software redesign, including consolidation of postprocessing tools,
- undertake any network methods comparison,
- continue studies on waveform extraction, position localization and its application in doing source astrophysics,

- investigate advantages of the coincident use of low level triggers of LIGO and external observatories and initiate collaborative effort where useful,
- undertake source population modeling for binary compact objects and supernovae and fold these into the simulation engine,
- prepare for searches with the advanced detectors,
- work out and validate infrastructure for robust, real time burst search with the start of S6,
- mature internal thinking and develop infrastructure and procedure to allow follow-up observations in the electromagnetic spectrum,
- continue the pursue and enhance both on- and off-line astrophysically triggered searches, and
- develop specialized searches able to dig deeper into the noise.

4 Searches for continuous-wave signals

Rapidly rotating neutron stars are the most promising sources of continuous gravitational wave signals in the LIGO and Virgo frequency band. (We use the term "neutron star" broadly, keeping in mind that some such stars may contain quark matter or other exotica.) These stars are expected to emit gravitational radiation through a variety of mechanisms, including elastic deformations [50, 51, 53], magnetic deformations [52, 56], unstable r-mode oscillations [54, 50, 55], and free precession [60], all of which operate differently in accreting and non-accreting stars. We present a review of these emission mechanisms in [49]. Indirect upper limits on gravitational wave emission inferred from photon astronomy are more optimistic for non-accreting stars, but according to present theories accreting neutron stars are more likely to be emitting at or near the indirect limits.

Our searches fall into four types: non-accreting pulsars, accreting stars (pulsating or not), non-pulsating non-accreting stars, and heretofore unobserved objects. For each type of search, we know or can infer properties of the source population and of single objects, including indirect upper limits on gravitational wave emission which LIGO or Virgo have to beat in order to claim a novel result. From our point of view, each type of object presents a distinct data analysis challenge which is directly constrained by more conventional astronomical observations. In particular, as most of our searches are computationally limited, their sensitivities are directly dependent on the constraints that come from conventional astronomy.

4.1 Non-accreting pulsars

This type includes objects for which pulsations are observed in radio, X-ray, or other electromagnetic radiation, with the exception of accreting millisecond pulsars. Photon astronomy can tell us precisely the sky positions, frequencies, and frequency changes of these objects, meaning that our analyses need search only a small parameter space and are not computationally limited. Photon astronomy also sets an upper limit on the gravitational wave strain we could see from a known pulsar, assuming that all of the observed spindown is due to gravitational waves. In terms of the distance D, gravitational wave frequency f and its time derivative $\dot{f}$, this indirect limit is [49]

$$h_{\mathrm{IL}} = 8.1 \times 10^{-25} \left(\frac{1\ \mathrm{kpc}}{D}\right) \left(\frac{-\dot{f}}{10^{-10}\ \mathrm{Hz/s}} \frac{100\ \mathrm{Hz}}{f}\right)^{1/2} \left(\frac{I}{10^{38}\ \mathrm{kg\ m}^2}\right)^{1/2}. \tag{1}$$

Here I is the star's moment of inertia, as estimated by theory but not directly observed, and could be higher than the fiducial value by a factor of up to 3. For most pulsars the distance D is uncertain by at least 20%. By the end of the current (S5) LIGO data run we will beat this indirect "spindown limit" by nearly a factor of five for the Crab pulsar ($h_{\rm IL} = 1.4 \times 10^{-24}$), and could just beat it for PSRs J0537-6910 and J1952+3252 with another run at comparable sensitivity [57].

4.1.1 Time domain Bayesian method

This method has been developed to tackle targeted searches, that is searches for gravitational wave emission from radio pulsars of known position, rotation frequency, spin down rate, and binary orbital parameters where necessary. This additional information greatly reduces the size of the parameter space over which we must search, and allows us to perform a fully coherent search for signals over all the available data. Timing accuracy is sufficient to maintain coherence both during and between science runs, and the relative phasing of the interferometers is also sufficiently well determined for us to be able to combine data from all runs and all detectors coherently, resulting in some of the lowest signal sensitivities achieved by LIGO. This method has been applied successfully to data from the first four LSC science runs [46, 47, 63] and is currently being used to produce incremental results on data from the fifth science run. A detailed discussion of the method can be found in [62], with the implementation of the inclusion of binary system parameters in [64].

The method is designed to carry out robust signal extraction and optimal parameter estimation, rather than perform well in a large parameter space search. Its primary purposes are

- to perform searches for signals from known pulsars and,
- to determine the astrophysical parameters of candidate sources.

The method comprises a heterodyne and filtering stage to extract interferometer data in a tracked 1/60th Hz band centered on the expected gravitational wave signal, followed by a Bayesian parameter estimation stage. This second stage delivers an upper limit to the strain amplitude of any signal and an estimation of the signal's parameters, should one be detected, in the form of marginal posterior probability distributions for the signal parameters. The method has successfully determined the parameters of the injected signals in all our science runs. The most computationally intensive part of the search is the heterodyning and downsampling of the raw data. Currently this takes about 25 min per pulsar per detector on a single computer per day of data.

At present the search is carried out over the nearly 100 pulsar candidates that have sufficiently well determined parameters to be matched by a single template and with expected gravitational wave frequencies that lie within the LIGO band. These include the Crab pulsar which is both the youngest, and the most rapidly spinning-down, candidate within our sensitivity range. The relatively large amount of intrinsic timing noise for this pulsar is tracked and corrected for within our search method [63, 64].

We have a strong collaboration with the radio group at Jodrell Bank, UK, who generate timing solutions for our pulsar candidates over the LIGO observing runs, and check that no glitches have occurred in these pulsars. We have initiated a collaboration with X-ray groups to be able to target promising X-ray objects. This has already provided useful discussions and timing information for the young X-ray pulsar J0537−6910, which is another pulsar for which we could soon beat the spin-down limit. We are sounding out other radio pulsar groups for possible collaborations. This could as much as double the number of pulsars with good enough timing to be searchable by the end of S5, and will prepare us for the upgraded S6 run.

Over the next 12 months we expect to publish a specific analysis of the Crab pulsar over the first half of S5, following on for the recently accepted paper on the S3 and S4 runs. In addition, a full analysis of all pulsar candidates from the S5 run will follow in the new year.

Presently, the timing data is not sufficiently complete to take account of the covariance between source parameters, limiting us to candidates that show very small uncertainties in their individual parameter values. We intend to extend the timing model so that these ∼25 candidates are included in our searches. In addition, we will account for glitches in pulsars by adapting the timing model to allow for step changes in rotational phase at these points. Finally, the targeted search will be extended to frequencies other than twice the rotational frequency of the neutron star, including the fundamental rotation frequency and, in combination with the F-statistic search, the r-mode oscillation frequency of $\sim 4/3$ the rotation frequency.

4.1.2 Wide Parameter Search of the Crab Pulsar

Gravitational wave emission from pulsars may not be phase-locked to radio pulse-emission. As a compliment to the single template Time Domain Search of the Crab pulsar, we have performed initial searches of a wide parameter space around the observed radio pulses in frequency and spindown. This parameter space search employs the same fully-coherent method and code used in the Einstein@home hierarchical scheme, described below. At present, the search includes data from the beginning of S5 until August 2006, when a large glitch was seen in Crab pulsar timing data. The parameter space is chosen by considering several constraints including computation time, sensitivity degredation due to the use of more templates, and possible physical mechanisms such as free precesion or a two-component model. Those considerations lead to the current parameter space, or a $6 \times 10^{-3} Hz$ frequency band centered on the Crab pulsar's radio pulse frequency, along with a $1.2 \times 10^{-13} Hz/s$ band in 1st spindown and $10^{-23} Hz/s^2$ band in 2nd spindown parameter space. Currently the search is undergoing code review and will be re-run on data with the latest calibration when available.

4.1.3 Virgo targeted searches

A procedure for coherent analysis is being developed as part of the pipeline for blind searches, see Sec. 4.3.3. However, it can be also used for targeted searches of objects for which parameters are known and, in fact, the core of the procedure has been already applied to data of the resonant detector Explorer [65]. The method is based on a database of "short" FFTs which are then coherently combined. The correction for Doppler shift and spin-down is done in the time domain, on the *analytic signal*, and at this stage also timing information from radio telescopes can be accounted for. The use of a matched filter in the frequency domain is foreseen to take into account the amplitude modulation due to the detector radiation pattern and the change of the received polarization angle due to the Earth rotation [66]. Another code, fully based on a time domain procedure, is under development and will be used to compare results.

Provided the sensitivity of the Virgo detector approaches its design level, we plan to perform targeted searches also in the low frequency band, say below 80 Hz, where the sensitivity would be better than that of LIGO, and where many interesting sources, like Vela or Crab could emit. Then, we support the need to do commissioning in order to rapidly reach this goal.

4.2 Non-pulsing non-accreting neutron stars

This type includes point sources such as central compact objects in supernova remnants as well as highly localized regions such as the innermost parsec of the galactic center. Photon astronomy can provide sky positions for these objects, but since no pulses are observed they cannot provide us with frequencies or spindown parameters. Since we must search over many frequencies and spindown parameters, sky-survey positional errors (such as ROSAT) are not enough: We require sub-arcminute accuracy to keep down the computational cost of a long integration time and thus a deep search. Although no f and $\dot{f}$ are observed for these objects, we can still define an indirect limit we need to beat. If we assume an object has spun down significantly from its original frequency and that this spindown has been dominated by gravitational wave emission, we can rewrite Eq. (1) as

$$h_{\rm IL} = 2.3 \times 10^{-24} \left(\frac{1\ \rm kpc}{D}\right) \left(\frac{10^3\ \rm yr}{a}\right)^{1/2} \left(\frac{I}{10^{38}\ \rm kg\ m^2}\right)^{1/2} \tag{2}$$

in terms of the age a, which can be inferred in various ways. Initial LIGO can beat this upper limit for several objects of this type, including the youngest—the object in supernova remnant Cas A ($a = 326$ yr, $h_{\rm IL} = 1.2 \times 10^{-24}$)—and the closest, Vela Junior ($D > 200$ pc, though the precise value is uncertain). Several more objects have indirect limits attainable with advanced LIGO, including Supernova 1987A ($h_{\rm IL} = 3.2 \times 10^{-25}$)—however, the putative neutron star being only 20 years old would require a search over a large parameter space including six or seven frequency derivatives. Searches over small sky areas (single "pixels") are computationally the same as searches for known point sources, and for several of these (such as the galactic center) even initial LIGO could beat indirect limits.

We are presently searching Cas A and shortly will start searching the central parsec or so of the galactic center, an area which is likely to contain young neutron stars. We are collaborating with several photon astronomers on constructing more complete target lists of point sources and small areas, both for initial and advanced LIGO. It is useful to maintain ties because x-ray and gamma-ray astronomers are beginning to find many point source neutron star candidates, and thus it is likely that the interesting target list for LIGO will expand substantially even before advanced LIGO.

The searches so far have used the $\mathcal{F}$-statistic code with a single integration of $O(10)$ days. For young sources even such an integration time requires up to the second frequency derivative; thus metric-based methods and code for tiling parameter space in multiple dimensions are important to reduce the computational cost. In the near future we will try hierarchical searches (see other searches below) which will require algorithm and code development to adapt to the needs of this search. We will also investigate the potential of resampling methods to not only reduce the computational cost for a given search but also the cost's scaling with integration time. This, combined with hierarchical methods, may allow us to search a significant fraction of the S5 data set rather than $O(10)$ days. In the further future (advanced LIGO), the prospect of searching a large seven dimensional parameter space for SN1987A encourages exploration of non-grid methods such as Markov-chain Monte Carlo searches.

4.2.1 Virgo semi-targeted search

We are working on a Doppler correction tecnique which is independent of the source frequency and then suitable to be used for semi-targeted search, where the source position is known but the frequency, or the spin-down, are uncertain. It is based on the removal, or doubling, of single samples of the detector digitized signal so to keep synchronization between the observer proper time and the rest clock.

4.3 Previously unknown objects

These are objects which have not been previously identified at all, and thus we must search over various possible sky positions, frequencies, and frequency derivatives. These are believed to constitute the overwhelming majority of neutron stars in the galaxy, although most of them are not believed to be good sources for LIGO. Although photon astronomy has nothing to say regarding any particular star, one can argue based on the observed supernova rate and inferred population of neutron stars in the galaxy that the indirect limit on the strongest signal from this population is no more than

$$h_{\rm IL} = 4 \times 10^{-24} \left(\frac{30\ \rm yr}{\tau}\right)^{1/2}, \tag{3}$$

where τ is the mean time between supernovae in the galaxy. The latest and most detailed derivation of this upper limit is given in [49].

It is useful here to briefly explain the computational challenge that must be overcome for these searches. The parameter space for blind searches for weak signals from unknown isolated neutron stars is very large. The number of templates N_p, required to cover the entire sky, a large frequency band, and a range of spin-down parameters and using data which spans a duration T, is roughly proportional to T^5. The computational cost therefore scales as $\sim T^6$. In fact, for any reasonable volume of parameter space, N_p becomes so large that using our existing coherent integration code and using the full computational power of our largest computational platform `Einstein@Home` running for a few months, it is not possible to consider values of T larger that a few days. Even if we were able to speed up our coherent demodulation algorithm by, say, a factor of 100, T would increase only by a factor of $100^{1/6} \approx 2.2$. On the other hand, we require T to be a few months to have a realistic chance of detection. The situation is, naturally, even more demanding for neutron stars in binary systems.

For this reason, different methods using a combination of coherent and semi-coherent techniques have been designed. The basic idea is to break-up T into smaller segments which are analysed coherently, and to stitch together these segments using a semi-coherent technique. Three methods are now used for carrying out "blind" searches: 1) a quick-look semi-coherent method known as PowerFlux using incoherent sums of strain spectral power from many 30-minute "Short Fourier Transforms" (SFT's), 2) a hierarchical algorithm using Einstein@Home, based on phase-preserving demodulation over many $\sim$day long intervals, followed by a Hough or StackSlide step (see below), and 3) a hierarchical method, developed in Virgo, based on the alternation of coherent and incoherent steps. Even with semi-coherent methods, computational savings due to efficient parameter space coverage and choice of parameter ranges are helpful as they increase the coherent integration time and thus the sensitivity of the search.

4.3.1 The PowerFlux, StackSlide and Hough searches

For a monochromatic, constant-amplitude sinusoidal wave in Gaussian noise, summing the strain power from M short Fourier transforms improves the sensitivity (strain value for a fixed signal-to-noise ratio) by a factor $\sqrt[4]{M}$. In contrast, a coherent search based on a single Fourier transform over the entire M intervals gives a sensitivity that improves like $\sqrt{M}$. One strong advantage of the semi-coherent methods is their robustness against unknown source phase disturbances, such as from frequency glitches due to starquakes.

The searches we must perform are more complicated than simple power sums. Frequency and amplitude modulations that depend on source direction are relatively large. The frequency modulations arise from the motion of the detectors with respect to the source, with components due to the Earth's rotation ($v/c \sim 10^{-6}$) and to its orbital motion ($v/c \sim 10^{-4}$). The amplitude modulation arises from the changing orientation of the interferometer arms with respect to the source direction as the Earth rotates. As a result, an all-sky search requires a set of finely spaced templates on the sky with varying corrections for these modulations. In general, the number of templates required for a given coverage efficiency scales like the square of the source frequency.

Within the last few years, we have explored three related methods for incoherent strain power summing: StackSlide [58], Hough [74, 48], and PowerFlux[75]. These methods take different approaches in summing strain power and in their statistical methods for setting limits, but their performances are quite similar. Because PowerFlux has been found to yield somewhat better efficiency than the other two methods for most frequency bands, it has been chosen as the quick-look semi-coherent algorithm used on data from the S5 science run. A draft article based on applying all three methods to the S4 data is under collaboration review[76].

In short, PowerFlux computes from many thousands of 30-minute SFT's an average strain power corrected for antenna pattern and with weighting based on detector noise and antenna pattern. Its signal estimator is direct excess strain power for an assumed source direction and polarization, using one circular polarization projection and four linear polarization projections. PowerFlux, like Hough or StackSlide, corrects explicitly for Doppler modulations of apparent source frequency due to the Earth's rotation and its orbital motion around the Solar System Barycenter. Source frequencies are searched with ~0.56 mHz spacing and limits presented separately for 0.25 Hz bands.

A publication is planned based on the present PowerFlux search over the first 8 months of S5 data. Preliminary results have been presented publicly for a search over 50-1000 Hz with no spindown, and results are now in production over the same frequency range with spindown magnitude as large as 5×10^{-9} Hz/s. In the meantime, additional improvements have been added to the PowerFlux program that permit deeper searches for coincident candidates among multiple interferometers and that make better use of the strain data available in each 30-minute SFT. In addition, work is underway to add a coherent IFO-sum option for each SFT to gain further SNR. We expect to exploit these new improvements in a final PowerFlux search over the entire S5 data set.

In the meantime, the Hough analysis is also being developed further. The multi-IFO Hough analysis has already been used in the S4 analysis and we will investigate the feasibility of performing a multi-IFO analysis for S5 data. For these data volumes, computational efficiency becomes an important factor which can limit our sensitivity. We will explore better candidate selection methods and veto strategies for improving the sensitivity of the Hough search. When the pipeline has been tuned, and if the sensitivity is found to be sufficiently good, we would like to perform a fast all-sky search.

As indicated above, searching for unknown pulsars in unknown binary systems is a formidable computing challenge. Exploratory work has begun on semi-coherent methods based on SFT's much shorter than 30 minutes. Reducing the lengths of the SFT's sacrifices attainable further sensitivity (relative to a perfect targeted search), but gives the promise that a search at some sensitivity can be carried out. It is unlikely such a search will yield a discovery, but it would be imprudent not to search at all for unknown binaries.

4.3.2 Hierarchical Searches and `Einstein@Home`

`Einstein@Home` is a public distributed computing project in which users contribute the spare CPU cycles on their computers for gravitational wave searches. Thus far, it has been used in the blind wide parameter space searches for CW sources. It was launched in February 2005 and since then it has built up a user-base of 160,000 active users and currently it delivers $\sim$ 80Tflops of computing power round-the-clock. This is by far the largest computational platform available to the LSC and it is also one of the largest public distributed projects of its kind in the world. The project is targeted towards making a detection and not on setting precise upper-limits, and so far it has analysed S3, S4 and S5 data.

The S3 analysis is complete, and the final results are posted on the `Einstein@Home` webpage. This analysis used 60 segments of 10 hours duration. Each host machine searched over a small portion of the parameter space using two such segments and returned the best candidates following a coincidence analysis. A further coincidence analysis between the 60 segments was performed as a post-processing step. The S4 analysis was very similar. It looked at 17 segments of 30h each. Each host machine returned the best 10,000 candidates from a single data segment. The coincidence analysis for candidates from the different segments was performed only in the post-processing phase. The post-processing of the S4 results is complete and is currently undergoing LSC review. A publication is planned based on these results. Similarly, the first S5 analysis used 28×30h segments and the post-processing is expected to be completed in the near future. The sensitivity of all these analyses is limited by one bottleneck: the amount of data that can be returned by the host machines. This limits the number of candidates that can be returned and therefore it implies a very high threshold, much higher than the optimal value calculated in [74].

The second S5 analysis is currently underway and it constitutes a significant improvement over the previous analyses. This run uses a Hierarchical search in which each host machine analysis analyses data from 84 segments of data. Each of these segments contains at least 40h of data from H1 and L1 (this multi-IFO coherent analysis is another significant improvement). The different segments are then combined using the Hough transform and the 10,000 best candidates surviving the Hough analysis are returned. The biggest advantage of this procedure is that since the Hough transform step takes place on the host machines themselves, we are free to set the thresholds to their optimal values. The current run is designed to last for about 3 months, which will be used to improve the reliability and stability of the software. This will be followed by a long 1-yr run.

The hierarchical search is meant not just for running on `Einstein@Home`; it should be useful whenever computational cost becomes an issue. In particular, it can be used in the "semi-targeted" searches which target, say, a small patch around the galactic center or other interesting regions which could harbor young pulsars emitting gravitational waves. This will be investigated in the near future. In addition, we will investigate better ways of selecting candidates from the semi-coherent stage and the trade-offs between computational cost and sensitivity in comparing the Hough and StackSlide algorithms. Finally, in the longer term, we will study the feasibility of implementing a multi-stage hierarchical search as described in [58, 59] (the present design can be viewed as a single stage search). In this scheme, the candidates from each stage are followed-up using longer and longer coherent integrations and, in principle, this should allow us to maximize the sensitivity for a given computational cost.

4.3.3 Virgo hierarchical searches

This hierarchical pipeline consists of a series of steps [67, 68, 69]. First, calibrated data at 4kHz are cleaned in time domain; then the "short" FFT database is built. From it, time-frequency peak maps are produced. The peak maps are the input of the Hough transform stage, which produces a set of candidates. Coincidences among candidates obtained from the analysis of different data sets, belonging to the same or different detectors, are done in order to reduce the false alarm probability. On the surviving candidates the coherent follow-up is applied. The Hough transform step, which is the heaviest from a computational point of view, is performed on the *INFN Production Grid*, which allows us to access to a large set of geographically distributed resources.

We have applied the procedure, apart from the final coherent step, to data of both commissioning runs (C6 and C7) and WSR runs (WSR8,9,10). We have also tested the detection efficiency, and accuracy in source parameter estimation, through software injections [70]. The analysis of a small portion of LIGO S5 data has also been started, already providing some interesting information on the data itself and hints on how to improve the analysis procedure. We are now starting the analysis of VSR1 Virgo data.

An adaptive version of the Hough transform stage, which allows to take into account detector radiation pattern and noise non-stationarities, has been developed and implemented [69] and will be used in the next analyses.

A publication is planned with a full description of the hierarchical method.

We will also try to improve the computational efficiency of the procedure by an efficient parameter space coverage.

4.4 Accreting neutron stars

For this class of source the gravitational radiation is thought to be powered by accretion onto the neutron star and not, as is the case for isolated neutron starts, by its own rotation. In this scenario, first proposed by [**?**], the neutron star achieves an equilibrium state whereby the angular momentum fed to it through accretion is balanced with the angular momentum radiated away through gravitational waves. This argument and its history is summarized in [49]. The resulting indirect limit on can be put in terms of x-ray flux F_x and spin frequency ν as

$$h_{\rm IL} = 5 \times 10^{-27} \left(\frac{300\ \rm Hz}{\nu}\right)^{1/2} \left(\frac{F_x}{10^{-8}\ \rm erg\ cm^{-2}\ s^{-1}}\right)^{1/2}. \quad (4)$$

At present we divide the accreting neutron stars into two groups: the low-mass X-ray binaries (LMXBs) and the accreting millisecond X-ray pulsars (AMXPs). Sources from both groups consist of a neutron star in orbit around a lower mass companion object from which it is accreting matter. From a data analysis perspective the key difference is that for the majority of the $\sim$85 known LMXBs the spin frequency of the neutron star is unknown but though to lie in the range $\sim$200 Hz – 1 KHz and for the 7 known AMXPs the spin frequency (equal to the pulsar frequency) is known to high accuracy. This difference makes searches for the LMXBs a far more challenging task that of the AMXPs. Note that there are 10 LMXBs for which type-I thermonuclear bursts are seen from which the spin frequency can be constrained to within $\sim$1 Hz.

Another important difference are the indirectly measured time averaged accretion rates which are typically at, or within a factor of a few of, the Eddington limit for the LMXBs. The AMXPs exhibit accretion rates lower by a factor of 10 – 100 in comparison. This, via Wagoners arguments, make the LMXBs likely to be stronger gravitational wave emitters than the AMXPs.

To date we have completed a single coherent analysis on the accreting neutron star in the LMXB Sco X-1 using S2 data [49]. This was an exercise in wide multi-dimensional parameter space matched filtering and due to the rapid increase of search templates with observation time the search was computationally limited to an observation time of only 6 hours. Sco X-1, although the brightest X-ray source in the sky and consequently, also likely to also be the brightest continuous gravitational wave source, is typical of the LMXBs. As such it is clear that incoherent hierarchical search strategies need to be developed in order to maximise the search sensitivity given the volume of parameter space we need to search and the computational resources. In this spirit, an incoherent search approach, based on the "radiometer" technique developed within the stochastic background group was applied to S4 data to set an upper-limit on radiation from Sco X-1 [79].

A Hierarchical search pipeline is currently in development to address the LMXB problem (and in addition, the AMXP search). We have taken an approach initially adopted by [**?**] for the detection of pulsars from radio observations, and adapted it accordingly. Signals from sources in binary systems are Doppler modulated due to the motion within the binary orbit. The power spectrum of such a frequency modulated (FM) signal, taken over a number of orbital cycles, resembles a finite set of FM sidebands each separated by $1/P$ Hz where P is the orbital period. The number of sidebands is $\sim 4\pi f_0 a$ where f_0 is the gravitational wave frequency and a is the orbital semi-major axis projected along the line of sight and normalised by the speed of light. We then construct an approximate power spectrum template consisting of a finite set of unit amplitude spikes each separated by $1/P$ Hz and convolve this with the power spectrum. This, in effect, performs an incoherent summation of FM sideband power for all frequencies.

This procedure allows us to target individual sources and identify candidate frequencies on which to follow up with more powerful coherent techniques. One such technique that is also being developed is a Markov chain Monte Carlo (MCMC) which, once given a candidate frequency, explores the associated signal parameter space and outputs marginalised posterior probability distributions on all unknown source parameters including signal amplitude. This procedure alone is suitable for the AMXPs due to the fact that the signal frequency is known a priori.

In parallel a hierarchical search pipeline based on the coherent $\mathcal{F}-$statistic code used for the S2 analysis and the StackSlide technique is being investigated. It is not yet clear whether this approach achieves a sensitivity comparable to the one reached with the pipeline described above. Once the pipeline is completed and the search parameters have been tuned, we will consider whether it is advantageous to carry out a search on (a subset of) LMBXs using this scheme.

4.4.1 Virgo searches for neutron stars in binary systems

We are starting to work on a procedure for the search of signals emitted by neutron stars in binary systems, which can be also applied to accreting systems, like LMXBs.The basic idea is that of spectral filtering, i.e. of matched filtering on the power spectrum. It was first applied in resonant detectors [71]; more recently it has been proposed as part of the procedure for coherent searches of isolated neutron stars, see [66] and Sec.4.1.3.

5 Searches for stochastic backgrounds

5.1 Sources of Stochastic Gravitational-wave Background

The stochastic background searches target a broadband and continuous background of gravitational waves, that could be produced by a large collection of incoherent sources. Sources of stochastic gravitational-wave background could be cosmological (such as inflationary models, cosmic strings models etc) or astrophysical (such as rotating neutron stars, low-mass X-ray binaries (LMXBs) etc) in nature.

One of the searches performed by the Stochastic Background Working Group targets an isotropic gravitational-wave background. The isotropic background is predicted by different models, and it can be completely described in terms of dimensionless $\Omega_{\rm GW}(f)$, the gravitational-wave energy density per unit logarithmic frequency (in units of the closure density of the Universe). Different models predict different spectral shapes in the LIGO frequency band (roughly $50-150$ Hz), although they typically follow a power-law form. Hence, the group performs the stochastic background search for different power-law forms of $\Omega_{\rm GW}(f)$. The increasing sensitivity of LIGO interferometers has allowed the group to start exploring the implications of the stochastic background searches for various models. In particular, the most recent result of the isotropic background search, based on the LIGO S4 science run, has started to explore cosmic strings and pre-big-bang models. In the case of cosmic strings models, a population of models has been ruled out, that was not accessible to other measurements and observations. The group is also performing isotropic searches at the free-spectral range frequency (37.5 kHz), at which the strain sensitivity of the 4-km interferometers is similar to that at 100 Hz.

Another search performed by the group is non-isotropic in nature, and it is designed to be sensitive to possible localized foreground (astrophysical) sources of stochastic gravitational waves. Analogous to the CMB, such sources would be localized with a distribution that follows the local matter distribution in our galactic neighborhood. Potential sources that could fall into this category are the low-mass X-ray binaries, rotating neutron stars etc. In addition to this search, which focusses on localized sources, the group is also investigating ways of searching for other patterns of stochastic gravitational-wave background across the sky, and potentially for correlations between different directions on the sky.

5.2 Stochastic Search Method

5.2.1 All-Sky Search

A stochastic background of gravitational waves (GWs) is expected to arise as a superposition of a large number of unresolved sources, from different directions in the sky, and with different polarizations. It is usually described in terms of the logarithmic spectrum:

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\,\frac{d\rho_{\rm GW}}{d\ln f}\,, \tag{5}$$

where $\rho_{\rm GW}$ is the energy density of gravitational waves, ρ_c is the critical density of the Universe, and f is frequency. The effect of a SGWB is to generate correlations in the outputs s_A, s_B of a pair of GW detectors, which can be described for an isotropic background in the Fourier domain by

$$\langle \widetilde{s}_A^*(f)\, \widetilde{s}_B(f') \rangle = \frac{1}{2}\delta(f-f')\, \gamma_{AB}(f)\, S_{\rm gw}(f) \tag{6}$$

where $\tilde{s}_A$ and $\tilde{s}_B$ are the Fourier transforms of the strain time-series of two interferometers ($A \neq B$).

The raw correlation depends on the (one-sided) power spectral density $S_{\rm gw}(f)$ the SGWB would generate in an IFO with perpendicular arms, as well as the observing geometry. The geometrical dependence manifests itself via the overlap reduction function (ORF)[80], which can be written as

$$\gamma_{AB}(f) = d_{Aab}\, d_B^{cd}\, \frac{5}{4\pi} \iint d^2\Omega_{\hat{n}}\, P^{{\rm TT}\hat{n}ab}{}_{cd}\, e^{i2\pi f \hat{n}\cdot(\vec{r}_2-\vec{r}_1)/c} \tag{7}$$

where each IFO's geometry is described by a response tensor constructed from unit vectors $\hat{x}$ and $\hat{y}$ down the two arms

$$d^{ab} = \frac{1}{2}(\hat{x}^a\hat{x}^b - \hat{y}^a\hat{y}^b)\,, \tag{8}$$

$\vec{r}_{1,2}$ is the respective interferometer's location and $P^{{\rm TT}\hat{n}ab}{}_{cd}$ is a projector onto traceless symmetric tensors transverse to the unit vector $\hat{n}$.

We deploy a cross-correlation method to search for the stochastic GW background, following [81]. In particular, we define the following cross-correlation estimator:

$$Y_{AB} = \int_{-\infty}^{+\infty} df \int_{-\infty}^{+\infty} df'\ \delta_T(f-f')\ \tilde{s}_A(f)^*\ \tilde{s}_B(f')\ \tilde{Q}_{AB}(f')\,, \tag{9}$$

where δ_T is a finite-time approximation to the Dirac delta function, and $\tilde{Q}_{AB}$ is a filter function. Assuming that the detector noise is Gaussian, stationary, uncorrelated between the two interferometers, and uncorrelated with and much larger than the GW signal, the variance of the estimator Y_{AB} is given by:

$$\sigma^2_{Y_{AB}} = \frac{T}{2}\int_0^{+\infty} df\ P_A(f)P_B(f) \mid \tilde{Q}(f) \mid^2, \tag{10}$$

where $P_i(f)$ are the one-sided power spectral densities (PSDs) of the two interferometers, and T is the measurement time. Optimization of the signal-to-noise ratio leads to the following form of the optimal filter [81]:

$$\tilde{Q}_{AB}(f) = N_{AB}\ \frac{\gamma_{AB}(f)S_{GW}(f)}{P_A(f)P_B(f)}\ ,\ \text{where}\ S_{GW}(f) = \frac{3H_0^2}{10\pi^2}\ \frac{\Omega_{GW}(f)}{f^3}\ . \tag{11}$$

$S_{GW}(f)$ is the strain power spectrum of the stochastic GW background to be searched. Assuming a power-law template spectrum with index α, $\Omega_{GW}(f) = \Omega_\alpha(f/100\ \text{Hz})^\alpha$, the normalization constant N_{AB} is chosen such that $< Y_{AB} >= \Omega_\alpha T$.

In order to handle gaps in the data, data non-stationarity, and for purposes of computational feasibility, the data for an interferometer pair are divided into many intervals of equal duration (typically 1-3 minutes), and Y_I and σ_{Y_I} are calculated for each interval I. The loss in duty-cycle due to the finite interval size is of order 1 minute for each analyzable data segment (which is typically several hours). The data in each interval are decimated from 16384 Hz to 1024 Hz and high-passed filtered with a 40 Hz cut-off. They are also Hann-windowed to avoid spectral leakage from strong lines present in the data. Since Hann-windowing effectively reduces the interval length by 50%, the data intervals are overlapped by 50% to recover the original signal-to-noise ratio. The effects of windowing are taken into account as discussed in [83].

The PSDs for each interval (needed for the calculation of $Q_I(f)$ and of σ_{Y_I}) are calculated using the two neighboring intervals. This approach avoids a bias that would otherwise exist due to a non-zero covariance between the cross-power and the power spectra estimated from the same data. Furthermore, by comparing σ_I calculated using the neighboring intervals with σ'_I calculated using the interval I, we identify intervals containing large noise transients and reject them from the analysis. In addition to this stationarity cut, we impose some data-quality flags (such as 30-sec before lock-loss), a large-σ cut (rejecting particularly noisy time-periods), and we ignore frequency bins which are determined to contain instrumental correlations. The intervals that pass all the data-quality cuts are averaged with $1/\sigma_I^2$ as weights, yielding the final estimates of Y and σ_Y.

5.2.2 Directional Search

The analysis described above is designed to search for the signal integrated over the whole sky. It is also possible to search for anisotropies in the GW background. One way to approach the problem is to define a sky-position dependent optimal filter. As discussed in [84], one can write:

$$Q(t, f, \hat{\Omega}) = N(t, \hat{\Omega}) \, \frac{\int d\hat{\Omega}' \, \gamma(t, f, \hat{\Omega}') \, A(\hat{\Omega}, \hat{\Omega}') \, H(f)}{P_1(f) \, P_2(f)}, \tag{12}$$

where $A(\hat{\Omega}, \hat{\Omega}')$ reflects the anisotropy in the GW spectrum across the sky. For point sources, one chooses $A(\hat{\Omega}, \hat{\Omega}') = \delta^2(\hat{\Omega}, \hat{\Omega}')$. Note, also, that the overlap reduction function γ is now dependent on the sky-position, as well as on the sidereal time t. Following the procedure analogous to the one outlined in the previous Section leads to an estimate of Y and σ_Y for every direction on the sky - i.e. a map of the GW background. However, this map is “blurred” by the antenna patterns of the interferometers. The problem of deconvolving the antenna pattern from this map is non-trivial and is being actively pursued.

5.2.3 H1H2 All-Sky Search

The all-sky search outlined above is usually applied to the non-collocated interferometers (such as the two 4-km interferometers at Hanford and Livingston), in order to minimize the instrumental correlations. However, the overlap reduction for this interferometer pair is significant above 50 Hz. Hence, the collocated pair of Hanford interferometers could potentially lead to a $\sim 10\times$ more sensitive all-sky stochastic result, but it is also more susceptible to instrumental correlations. We are pursuing several analysis methods to handle this problem.

One approach relies on the coherence, defined as

$$\Gamma_{XY}(f) = \frac{|P_{XY}(f)|^2}{P_{XX}(f) P_{YY}(f)} \tag{13}$$

where P_{XY} is the cross-power spectrum between channels X and Y, and P_{XX} and P_{YY} are the two power spectra. As discussed in [85], it is possible to estimate the instrumental correlations between interferometers 1 and 2 by

$$\Gamma_{instr,12} \approx \max_i(\Gamma_{1Z_i} \times \Gamma_{2Z_i}) \tag{14}$$

where Z_i are the numerous environmental channels, including microphones, seismometers, accelerometers, power-line monitors etc. As discussed in [85], this method can be used to identify frequency bands in which the instrumental correlations between two interferometers are large. These bands could then be removed from the all-sky stochastic search.

Alternative approaches rely on regressing the GW channels against the environmental channels, or on time-shifting one GW channel with respect to the other (with the idea that after a sufficiently long shift the GW correlations would disappear, but the instrumental correlations may survive). These approaches are in the early phases of development.

5.2.4 LSC/VIRGO joint search

As shown in [81], the optimal method for combining correlation measurements from different detector pairs is the same as that for combining measurements from different times: average the point estimates Y with a relative weighting of σ^{-2}. As discussed in [82] the inclusion of the LIGO-Virgo pairs can enhance the sensitivity of the global GW detector network to an isotropic background of gravitational waves, particularly at frequencies above 200 Hz.

Virgo is also expected to make a valuable contribution to searches for directionally localised sources. In such a search the lack of an all-sky integral in the counterpart to 7 means that correlations between widely-separated detectors are not suppressed at high frequencies. On the contrary, a longer baseline can lead to better sky resolution in a directional search.

5.2.5 Stochastic background simulation

The problem of simulation of the signal for a network of N GW detectors can be formulated in the following way. We need to satisfy (6) for each pair of detectors; treating the signals $\widetilde{h}_A(f)$ as the elements of a column vector $\widetilde{\mathbf{h}}(f)$ and $\gamma_{AB}(f)$ as the elements of a real, symmetric matrix[1] $\boldsymbol{\gamma}(f)$, we can write this as a matrix equation

$$\langle\widetilde{\mathbf{h}}(f)\,\widetilde{\mathbf{h}}(f')^{\dagger}\rangle = \frac{1}{2}S_{\rm gw}(f)\boldsymbol{\gamma}(f)\delta(f-f') \tag{15}$$

If we can define a matrix $\boldsymbol{\beta}(f)$ which factors $\boldsymbol{\gamma}(f)$:

$$\boldsymbol{\gamma}(f) = \boldsymbol{\beta}(f)\boldsymbol{\beta}(f)^{\dagger} \;, \tag{16}$$

then we can generate N independent white noise data streams $\widetilde{\eta}_A(f)$ which satisfy

$$\langle\widetilde{\boldsymbol{\eta}}(f)\,\widetilde{\boldsymbol{\eta}}(f')^{\dagger}\rangle = \mathbf{1}\delta(f-f') \tag{17}$$

and then convert them into the desired coloured correlated data streams via

$$\widetilde{\mathbf{h}}(f) = \sqrt{\frac{S_{\rm gw}(f)}{2}}\boldsymbol{\beta}(f)\widetilde{\boldsymbol{\eta}}(f) \tag{18}$$

For a given $\boldsymbol{\gamma}(f)$, there are different choices of $\widetilde{\boldsymbol{\eta}}(f)$ which achieve the factorisation (16), for example the standard Cholesky algorithm. See for further discussion.

The continuous frequency-domain idealisation (18) needs to be applied with care to finite stretches of real detector data. In the time domain, the multiplication (18) amounts to a convolution

$$\mathbf{h}(t) = \int_{-\infty}^{\infty}\mathbf{K}(t-t')\,\boldsymbol{\eta}(t')\,dt' \tag{19}$$

with a kernel which is the inverse Fourier transform of

$$\widetilde{\mathbf{K}}(f) = \sqrt{\frac{S_{\rm gw}(f)}{2}}\boldsymbol{\beta}(f)\;. \tag{20}$$

If the time-domain kernel $\mathbf{K}(\tau)$ is negligible outside the interval $-\tau_- < \tau < \tau_+$, we can use the standard overlap-and-add strategy to generate a continuous stream of time-series data. This strategy was implemented in code based on Virgo's "Noise Analysis Package" (NAP) [86].

The generalization of the method to a non isotropic stochastic background model is in progress. The issue of the simulation of a non gaussian stochastic background, which is relevant for some astrophysical models, is very different and is also under investigation.

[1] For non-isotropic backgrounds, the ORF is complex rather than real, and more care must be taken with the definition of the Hermitian matrix $\boldsymbol{\gamma_{AB}}(f)$.

5.3 Results and Plans

5.3.1 Recent and Pending Publications

The stochastic group has developed several searches, targeting different sources of stochastic gravitational-wave radiation: all-sky search, radiometer search, and search at the free-spectral-range (FSR) frequencies.

The all-sky analysis is optimized to search for the stochastic signal averaged over the whole sky by cross-correlating two GW detectors. It can be applied to pairs of interferometers, or to an interferometer-resonant bar pair. Usually, the two 4-km interferometers at LHO and LLO are the best choice because of their good strain sensitivity over a large frequency range, and because their large geographic separation minimizes instrumental and environmental correlations. This analysis was performed using the S4 data, producing 13$\times$ more sensitive measurement of the stochastic GW background than the previous published result (based on the S3 data). This result is beginning to explore the parameter space of some models of stochastic GW background, such as cosmic strings and pre-big-bang models. A paper on this result has been published in The Astrophysical Journal [77].

Similarly, the all-sky analysis was performed using the S4 data of the LLO 4-km interferometer and of the ALLEGRO resonant bar experiment. The strain sensitivity of ALLEGRO around 915 Hz is similar to that of the LLO interferometer. Moreover, the geographic proximity of ALLEGRO and LLO makes this pair about 50$\times$ more sensitive to stochastic GW signal at 915 Hz than the LLO-LHO 4-km interferometer pair. A paper describing this result has passed the internal LSC review, and has been submitted to Physical Review D [78].

The radiometer search also deploys the cross-correlation technique, but it is optimized to search for point-like sources of stochastic GW radiation on the sky. This method has been applied to the S4 data of the LLO-LHO 4-km interferometer pair, and has yielded first upper limit maps of the GW sky. A paper describing this result has passed the internal LSC review and has been submitted to Physical Review D [79].

The FSR search also relies on the cross-correlation method. It is very similar to the all-sky pipeline, but it is tuned to search at the free-spectral range frequencies of the interferometers (for 4-km LHO interferometer, this is 37.5 kHz), where the strain sensitivity is similar to that at $\sim$ 100 Hz. This method has been applied to the S4 data of the two LHO interferometers. A mature draft of the paper discussing this analysis is under internal LSC review.

5.3.2 Status of S5 Searches

Pipeline Upgrade The stochastic group is in the process of modifying the analysis pipeline. In particular, since several searches rely on similar quantities (such as strain cross and power spectral densities of different interferometers), the group will produce Stochastic Intermediate Data (SID). This data will be stored in the frame format, and it will contain the commonly used quantities calculated for segments throughout the S5 run. The segment duration will be of order 60 sec. These files will then be used by different stochastic searches, but could also be used for detector characterization by studying the behavior of the instrumentally correlated noise over time.

The group is also intending to appropriately average the intermediate data, producing the cross and power spectral densities for segments of one sidereal day. The advantage of this approach is that the resulting data set is small enough that it could be stored on a personal computer, consequently simplifying different stochastic searches.

Isotropic Search The new pipeline will be used to perform the isotropic search with LHO-LLO interferometer pairs. This search is expected to be about 10 times more sensitive than the published S4 upper limit [77]. The current estimates of the sensitivity of the 4-km interferometer pair, made using the old pipeline and based on the first half of the S5 run, indicate that this search will be more sensitive than the Big-Bang Nucleosynthesis bound in the LIGO frequency band.

Radiometer Search The stochastic group is planning to repeat the radiometer search using the S5 data of the LHO-LLO 4-km interferometer pair (and using the new pipeline). This analysis is expected to produce $\sim 10\times$ more sensitive maps of the GW sky than those produced using the S4 data, and it will apply an algorithm for deconvolution of the antenna pattern from the maps. This search will also produce a second isotropic measurement, with similar sensitivity improvement over the S4 all-sky result.

Spherical Harmonics Search In addition to the radiometer analysis, the stochastic group is pursuing a directional search based on spherical harmonics. The goal of the search is to estimate the spherical-harmonic decomposition of the gravitational-wave sky, similarly to what is done in the field of Cosmic Microwave Background. This method would allow searches for complex source distributions on the sky. The expected sensitivities and correlations between different spherical-harmonic components are currently being examined. Much of the formalism for this search has been developed, and the group is beginning to implement the formalism in a Matlab-based code. This search will also rely on the new pipeline.

Isotropic Search using Collocated Hanford Interferometers The isotropic searches performed up to date have prefered using the LLO-LHO 4-km interferometer pair because of the negligible instrumental correlations between the two sites. The LHO interferometer pair, however, could potentially be $\sim 10\times$ more sensitive to stochastic GW background, because the antenna pattern overlap of collocated interferometers is optimal. However, the collocated interferometer pair also suffers from the instrumental correlations, because the two interferometers share the same environment and the same sources of instrumental noise.

The stochastic group is developing two methods to estimate and suppress the instrumental correlations, as discussed above in more detail. The group has applied these methods to the first 5 months of the S5 run, and the preliminary results indicate that the PEM-coherence and the time-shift approaches identify well the instrumentally contaminated frequency bands. More effort is needed to understand the estimates of the broadband instrumental correlations, and the systematic errors of the applied techniques. The group plans to apply these methods using the rest of the S5 H1H2 data and produce an isotropic measurement of the stochastic GW background.

All-sky Search at Free-Spectral-Range Frequencies Another goal of the stochastic group is to repeat the FSR search using the S5 data of the collocated LHO interferometers. This analysis is expected to produce a measurement of the stochastic GW background at 37.5 kHz, $\sim 10\times$ more sensitive than the analysis based on the S4 data.

The group is also considering the FSR analysis using the LHO-LLO 4-km interferometer pairs. The overlap reduction due to the different antenna patterns would be significant for this analysis. However, using the non-collocated interferometer pair offers the possibility of a directional search at the FSR frequencies.

LIGO-VIRGO Searches The stochastic group is also planning joint LIGO-VIRGO stochastic searches, using the shared S5 data (data acquired after May 18, 2007). Sensitivity studies have shown that the LIGO-VIRGO interferometer pairs are less sensitive than the LIGO 4-km interferometer pair to the isotropic stochastic background at frequencies below 800 Hz. However, above 800 Hz the LIGO-VIRGO pairs are similar or even more sensitive than the LIGO-LIGO pairs. Moreover, the LIGO-VIRGO pairs have different zeroes in the overlap reduction function, which could improve the overall network sensitivity even at lower frequencies. Finally, the group is considering the possibility of performing directional searches with the LIGO-VIRGO pairs. Although currently less sensitive than LIGO-LIGO pairs, in the long run such directional searches could lead to a better angular resolution of the estimates of the stochastic gravitational-wave sky.

6 The characterization of the data

6.1 LIGO Detector Characterization

6.1.1 Introduction

Analysis of LIGO data requires a systematic understanding and characterization of the detector: its response function, timing stability, noise behavior and sensitivity to the environment, including correlated noise between interferometers. The confidence associated with source detection or upper limits for detection depends on detector performance characteristics, including: power spectra, the probability distribution of the detector output, stationarity of the noise, line noise sources, and the statistics of transients.

Commissioning too depends, of course, upon detector characterization. In particular, understanding which instrumental or environmental sources define the current noise floor at any given frequency is critical to eliminating or ameliorating those sources.

In practice, detector characterization is carried out at several different levels within the LSC and by a variety of scientists focused on different problems. Commissioners operate at the cutting edge of detector characterization, evaluating and updating interferometer noise budgets, as improvements are made between data runs. By the nature of commissioning, long-term stability is difficult to evaluate when such work is most intense. In the past, data runs have served as testing grounds for that stability, and there have been some unpleasant surprises. As experience has accumulated, as background monitoring tools have improved, and as more data have been collected in science mode, the rapidity of diagnostic feedback has improved dramatically. Feedback useful for mitigation and commissioning is now routine. Some investigations focus on interferometer-based detector characterization, such as investigation of line artifacts or environmental disturbances, while others focus on astrophysics-search-targeted artifacts, such as coherent glitches in H1 & H2 that could pollute inspiral and burst searches, or wandering line features that could mimic a pulsar.

As new artifacts are found and new characterization methods developed offline, there is a steady effort to migrate those improvements to the real-time online monitoring for more rapid detection of problems. This online monitoring includes programs run under the Data Monitoring Tool (DMT) environment[92], controls system software (EPICS), and a variety of customized tools written in C++ and Matlab. It also includes a human element, namely the attentiveness and active data exploration by interferometer operators and scientific monitors (scimons).

Commissioning work is carried out primarily by LIGO Laboratory scientists, but with significant contributions from other LSC scientists in residence near the Observatories *More such on-site investigations by LSC scientists would be highly useful; stationing of more graduate students and postdocs at observatories would help greatly.*

The LSC Detector Characterization (DetChar) community has a broad membership, including full-time commissioners, full-time data analysts, and many in between. In practice, the DetChar working groups have concentrated most on providing online characterization tools, e.g., DMT monitors and on providing characterization of interferometer data in science runs for astrophysical analysis. Every search working group has active DetChar members, and information flows in both directions, to mutual benefit.

In the next several years the DetChar efforts will include completing characterization of the S5 data already taken, support for the H2 Astrowatch running, development and implementation of improved diagnostics for the S6 run (with "Enhanced LIGO") that starts in 2009, and planning for Advanced LIGO diagnostics.

In the following subsections, the software infrastructure used for detector characterization is summarized and the array of investigations using that software is described.

6.1.2 Software Infrastructure

The interferometer controls system based on EPICS (Experimental Physics and Industrial Control Sytesm) software[93] is essential to operations. That software includes simple automated monitoring (e.g., alarms for values out of range) and the capability via customized microprocessor programs to carry out more sophisticated monitoring of interferometer state. This real-time controls system provides the first line of defense against wandering detector conditions and records literally thousands of data channels that permit later reconstruction of conditions, if needed. An online Data Viewer program permits engineers and scientists to view selected data channels in the style of an oscilloscope in either real-time or playback.

Closely coupled to the detector controls system is the Global Diagnostics System (GDS) software that includes both the interactive Diagnostic Test Tool (DTT)[94] and the background monitoring of the DMT. The DTT allows rapid exploration of data in the time and Fourier domains and includes user-selected filtering and extensive choice of data sources, real-time or stored in LIGO's distributed archives. The DTT also permits stimulation of detector channels for measuring transfer functions. The same underlying driver is used to inject sinusoidal "calibration lines" and simulated GW signals of various types into the interferometer hardware.

The DMT[94] offers an interactive ROOT-driven[95] environment for exploration and algorithm development and a background-process environment for continuous monitoring. Most DMT detector characterization is carried out via the 24/7 background monitors, which have been written by scientists from well over a dozen LSC institutions. As for the EPICS system, the DMT programs permanently record trended data channels, derived from the original interferometer and environmental data channels, in addition to providing real-time feedback to operators and scientists. That feedback comes in several forms: graphical displays on control room workstations (the most important of which are projected onto the walls), alarms (the most important of which are audible), and status web pages.

Offline detector characterization investigations are carried out using a variety of tools, ranging from offline DMT programs to Matlab, to LAL programs, to TCL scripts examining DMT trends, to simple interactive data viewing with the Data Viewer or ligo_viewer[96]. Many of these offline studies typically work with data products (e.g., trends or triggers) produced by programs upstream in a pipeline. The S5 science run has seen the development and widespread use of the Q-transform-based QScan tool[97] for examining interesting transient phenomenal, along with the use of an event display program, both using spectrograms and whitened time series.

These studies also benefit from the production of reduced data sets in which only selected raw data channels are included, some of which are downsampled for further reduction[98].

There is also ongoing work in interferometer modeling, using the End-to-End model infrastructure, with the goals of assisting commissioners and of giving better understanding of detector performance.

There are several areas where S5 experience suggests improvement is needed in control room diagnostics: 1) easier interactive mathematical manipulation and graphical display of real-time or near-real-time data; 2) more systematic (and robust) archiving and retrieval of figures of merit, including spectral snapshots; 3) faster real-time graphical display of ordinary or generalized spectrograms; and 4) standardized and simple interfacing of the real-time data streams to commonly used external interactive graphical programs, most notably Matlab. Refining and upgrading these software tools require attention in the next few years. DMT program improvements will be discussed below.

6.1.3 Calibrations

Calibration of the LIGO interferometers is a task critical to the success of the data analysis algorithms, and the confidence associated with their results. A correct detector calibration is a complex task that involves instrumental hardware measurements, detector modeling, computer programs, and extensive validation. The

Calibration Committee responsible for this essential work includes LIGO Laboratory and other LSC scientists. A dedicated Calibration Review Committee provides advice and vetting of this work.The Calibration Committee's results are posted and documented on a web page[99] available to the Collaboration, as well as recorded in the electronic logs, software repositories, and LIGO documents[100].

The calibration procedure has evolved in sophistication since the S1 run, most notably in automation, modeling, and redundant validation methods, with calibration provided both in the frequency domain (a frequency-indexed response function to be applied to the Fourier transform of the gravitational wave channel) and in the time-domain (a derived digital time series, "h(t)", representing strain as a function of time)[101]. There also ongoing efforts to calibrate the detector data at higher frequencies, near the 4-km cavities' free spectral range at 37 kHz, where the detectors are, in principle, comparable in sensitivity to gravitational waves as in the baseband near 100 Hz.

An alternative method of calibration using auxiliary laser pressure actuation ("photon calibrator") and interferometer laser frequency modulation have been developed and implemented in the S5 run. The various methods agree to within 15%. Understanding the residual discrepancies is an important ongoing study. It is strongly desired that by the time of the S6 run, we will have routine calibrations by several different methods based on different physical principles with agreement at the 5% level or better. More generally, estimation and reduction of the errors in the calibration data products has been a major effort in recent years, and these investigations will continue.

There has been a very fruitful exchange of ideas and methods with the scientists performing the calibration of the GEO detector, and a similar exchange is now under way with Virgo collaborators. *The Calibration Committee's membership has been augmented in recent years by graduate students from several LSC institutions. It would be highly desirable to sustain this broad participation, in part to provide more manpower for a critical function and in part to provide valuable instrumental training for the students.*

6.1.4 Timing

Verifiable and closely monitored timing performance of the LIGO detectors is mission critical for reliable interferometer operation and astrophysical data analysis. For example (a) Timing jitter of digitization of the GW signal directly contributes to the noise level, i.e., the astrophysical reach of the LIGO interferometers, (b) Coincident and coherent observation using the network of GW detectors is only possible if the absolute timing of the data streams agree with a high degree of accuracy, (c) A network of interferometric GW detectors can only recover both the polarization and sky direction information for a detected event to a high accuracy if the absolute timing of their data-streams are well known and verified, (d) In case of a coincident detection of GWs and astrophysical events, such as GRBs or supernovae, it is absolutely necessary to have trustworthy timing information on hand.

Based on our S5 experience, continuation and enhancement of timing verification studies and development of timing performance diagnostics tools are essential for Enhanced LIGO and Advanced LIGO. It is important to have a robust and tested primary system and a fully independent verification system that both deliver beyond the required accuracy. For reference, to detect a 2 kHz coincidence signal with a phase mismatch between detectors no worse than 1° requires a timing precision better than $\pm 1.4\mu$s.

In the past LIGO timing was based on a network of independent Global Positioning System (GPS) based clocks. These provide the timing signals used in the controls and data acquisitions system. The interferometer length sensing and control software also incorporates several internal consistency and synchronization checks. Since 2003 a second independent timing system, based on a Caesium clock, was incorporated and installed to complement the existing GPS-based system[103].

Timing monitoring has proven critical, as it identified various faults ranging from hardware failures through firmware bugs to software errors/glitches. As the LIGO detectors reached their design sensitivity the aged original timing/diagnostic system part/methods were no longer viable as they became unreliable and also disturbed the GW data at high sensitivities. We switched to a new prototype system in late 2005 in critical places and monitored timing with them throughout the S5 run. The new system relies on highly stable hardware components directly locked to a single modern GPS clock and/or atomic clock, redundant optical fiber based timing distribution systems and novel timing diagnostic methods. As expected, the system provides the same functionality, higher level of timing accuracy and notably a negligible effect on the GW channel. This is the present baseline method in LIGO. Based on the S5 experience both the new timing distribution and diagnostic systems has to be enhanced, standardized, implemented, tested and commissioned throughout the observatory sites and for the subsystems of Enhanced LIGO. It is desired to maximize the role of precision and commercial hardware components, accuracy and reliability while minimizing complexity. The new system can also provide a NIST-traceable calibration of the absolute timing of the LIGO detectors, which is essential when timing is compared to triggers received from independent observatories (e.g. GRB satellites or radio telescopes).

Building on our accumulated practical experience, it is important to develop the Advanced LIGO timing distribution and diagnostics system design soon, to be able to conduct in situ prototype tests with Enhanced LIGO.

It is desirable to continue to survey/consider alternative time-sources to GPS and atomic clocks as technologies become commercially enabled. Prototyping and testing of injections of precise timing signals directly through direct test mass excitations must also be pursued.

The Timing Stability Working Group responsible for ensuring timing accuracy includes LIGO Laboratory and LSC scientists [102]. The construction, testing and diagnostics tasks provided fertile ground for students and their involvement is strongly encouraged for the future.

6.1.5 Glitch Investigations

The largest DetChar working group[104] carries out studies of interferometer noise transients, or "glitches". Composed of experimentalists and analysts, the working group has broad expertise, with its work closely coupled to the burst and inspiral searches.

The short-term goal of the Glitch Working Group is to characterize the non-stationarity and non-Gaussianity of the interferometer data taken during engineering and science runs. Its long-term goal is to provide the information needed to achieve interferometer noise that *is* stationary and Gaussian.

To serve both of these goals, the working group is charged with the following tasks & priorities:

- Classification and statistical description of transients in the gravitational wave channel and in relevant auxiliary data channels.
- Identification of possible correlations between transients in the auxiliry channels and in the gravitational wave channel, collaborating with the detector commissioners in the search for their cause.
- Participation in the data quality assessment efforts (identification of data quality flags; study of correlations between data quality flags and burst/inspiral event candidates).
- Identification of veto strategies for the burst and the inspiral searches;

These goals are pursued both online and offline:

1. During science runs, the Glitch Working Group reports regularly on recently found anomalies and investigations of them[105]. This rapid-feedback analysis is based on transients found in the gravitational wave channel and in auxiliary channels (e.g. KleineWelle and BlockNormal triggers) and of the output of DMT monitors such as BurstMon. This was accomplished, during S5 via multi-day shifts of volunteers, weekly teleconferences, and through participation in scimon shifts at the observatories.

2. In the offline analysis, as new data quality flags and event candidates are produced, the working group explores their correlation in order to establish which data quality flags and veto strategies are appropriate for burst and inspiral searches, taking into account the different needs of each search, but aiming at a consistent usage of vetos and data quality flags.

More specifically, working group studies include:

- Identification of time intervals to be flagged as having uncertain or poor data quality.
- Comparison between data quality flags and event candidates for burst and inspiral searches.
- Production & analysis of KleineWelle[107] (offline DMT glitch-finding program) triggers.
- Detailed scans of loudest events from the online inspiral and burst searches.
- Statistical and event-by-event (e.g., with QScan displays) exploration of vetoes for inspiral and burst trigger candidates, including evaluation of veto safety via hardware signal injections.
- An independent burst veto search, using the time-domain BlockNormal event trigger generator, with the same frequency band is explored in the gravitational wave and in the auxiliary channels[108]
- Special investigation of H1-H2 coincidences to understand better common Hanford environmental disturbances.
- Determining when key auxiliary channels are disconnected or malfunctioning.

Where more work is needed:

- Contribution of upconversion (see environmental disturbances subsection below) to glitches, *e.g.*, implementation of an interactive tool based on the Hilbert-Huang Tranform algorithm[109].
- Transient classification using multi-variate analysis for better automation of identification.

6.1.6 Environmental Disturbances

Major environmental disturbances of the interferometers include seismicity, high wind, acoustic noise, and electromagnetic interference. Some sources are natural, but many are anthropogenic, including sources from observatory infrastructure, e.g., nearby motors and HVAC systems. A wide variety of environmental channels have been commissioned and are monitored, but unusual artifacts typically require detailed on-site investigations and eventually mitigation, work carried out by scientists from the Observatories and from several LSC institutions, as part of commissioning. Acoustic mitigation has played an especially critical role in lowering interferometer noise floors[110]. The retrofitting of LLO vacuum chambers with feed-forward, hydraulic pre-actuators led to dramatic improvement in L1 duty cycle, allowing the interferometer to ride out the passage of trains without lock loss. Nonetheless, significant increase in gravitational wave channel noise is seen during such a passage.

Understanding the mechanisms by which low-frequency seismic noise is upconverted to higher-frequency noise in the GW channel has received serious attention in S5 running from the Upconversion Working Group[111], with some notable successes in mitigation, but more subtle effects remain which merit further investigation. Barkhausen noise in actuation magnets appears to contribute significantly, for example, where the strength of the effect depends on the RMS motion of the mirrors w.r.t. the fixed actuation coils. There also remain sidebands and shoulders on the 60 Hz harmonics (especially 180 Hz on H1) which indicate residual upconversion.

Environmental disturbances may also, of course, be manifested through linear couplings to the interferometer as direct glitches or lines, for sources with characteristic frequencies in the LIGO band of sensitivity. There have been extensive studies during S5 to understand better the sources of steady-state environmental couplings, particularly lines. The Spectral Lines Catalog Working Group[112] has taken responsibility for finding spectral lines in the gravitational wave data channel, compiling a web-based catalog of known sources, using the results of many studies, including from other DetChar working group. Understanding sources of lines is important for their eventual removal via commissioning, for vetoing pulsar candidates, and for regression in data analysis. Systematic and automated scanning for and reporting on correlations between the gravitational wave channel and a large number of auxiliary channels has been implemented by the Interchannel Correlations Working Group[106].

Ambient environmental noise that affects both the H1 and H2 interferometers is of particular interest to the Stochastic Analysis Group because any correlation between the noise of the two detectors degrades the precision of their stochastic gravitational wave background measurement. The group now devotes significant effort to quantifying frequencies and time intervals for which H1-H2 correlations are strongest Simlarly, some effort has gone into studying possible inter-observatory correlated environmental noise, both steady-state and transient, but more effort here would be desirable.

Looking ahead, systematic survey of the coverage, quality and reliability of the environmental monitoring from both the hardware and monitoring software side is warranted between S5 and S6, given gaps that have arisen or been appreciated during S5 running.

6.1.7 Thermal Noise Investigations

Interferometer performance is limited at high frequencies by shot noise and at low frequencies by seismic noise, but at the sweet spot (~ 150 Hz), the ultimate noise floor is expected to be defined by thermal noise in the suspension wires. As other, non-fundamental noise sources are reduced in commissioning, it becomes more important to understand the thermal noise limitations, in part to assess priorities in commissioning and in part to determine whether amelioration is possible.

Initial LIGO suspension thermal noise is being characterized using violin mode Q measurements, both time domain ringdowns and frequency domain peak fitting. Both techniques show similar results, with Q's that are up to an order of magnitude worse than expected from the wire material and can change for a given mode at different times. Together, these two effects are thought to be evidence of rubbing friction. Laboratory experiments at MIT and HWS have shown that the rubbing is most likely occurring between the wires and the silica standoffs connected to the optics on its side.

Recent results with standoffs made from BK7 glass in prism geometry show improved violin mode Q's that are limited by the wire material losses at high frequencies. Further experiments are in progress, to try additional prism materials (sapphire, silica) and adding a machined notch to the prism. Tests to see if the clamping at the top of the suspension may play a role once friction at the standoff is improved is also crucial. Additional experiments replacing the cylindrical wires with metal ribbons, to improve the dissipation dilution factor, are in their earliest stages.

6.1.8 DMT Monitor Development

After many years of development, the suite of online DMT monitors is quite mature. Existing programs monitor the controls state of the interferometers, servo unity-gain frequency, environmental noise (including seismic bands, overflying aircraft and liquid nitrogen dewar shifts), non-Gaussianity, spectral line contamination, glitchiness and non-stationarity, hardware/software overflows, faulty ADC's, timing stability, and spectral stability. In addition, several monitors produce astrophysically motivated figures of merit (FOM's) for display and archiving: sensitivity to inspiral mergers, sensitivity to bursts, sensitivity to stochastic background, and sensitivity to pulsars. For the inspiral search there is also a near-real-time display of results in the control room from template banks run on the observatory computing clusters.

Nonetheless, there is need for additional online monitoring. Displaying results of other cluster-based searches would be desirable, as would diagnostics on additional interferometer servo channels. More information on calibration stability (and sources of instability) could also be derived. As noted earlier, running spectrograms are CPU-intensive but quite valuable. The new era of networked interferometer operations will make it desirable to develop on-line monitors, which will use datastreams from multiple observatories, with low latency. Online transient classification based on offline studies needs substantial attention. The extensive environmental monitoring system in place offers the potential for real-time identification of many transients, but exploitation of that potential is now limited to a handful of sources, such as earthquakes, aircraft, or liquid nitrogen dewar creaks. Much more work can and should be done in this area. More generally, it will be important in the next few years to build real-time monitors based on lessons learned in S5 off-line analysis.

6.1.9 Data Quality

A small working group[113] of LIGO Laboratory and LSC scientists compiles information from DMT monitors, from the other DetChar working groups, and from electronic logbooks to create a repository of data quality (DQ) information for each engineering and science run. Software tools are provided for viewing and saving of DQ information in the form of “segments”. For the S5 run an SQL database was created to store the DQ information. Upgrading the interfaces to that database for higher speed of insertion and extraction of information is a near-term task. In addition, automation of interval identification and DQ flag insertion for a broader category of artifacts than the present handful would improve near-real-time astrophysical searches, mitigating the human bottleneck of manual DQ flag insertion. A related task that needs attention before the S6 run is flagging more systematically when auxiliary channels, especially environmental channels, are disconnected or malfunctioning.

6.1.10 Data Run Support

For most of the engineering runs and all of the science runs, LSC policy has been to staff the control rooms around the clock with one operator per interferometer and at least one scientist (scimon) per observatory. The scimons have been responsible for monitoring the quality of the data, carrying out investigations (including the causes of lock loss), and making decisions on when to take science data *vs.* when to make adjustments / repairs, in consultation with the operator on duty and the local run coordinator, when appropriate.

There is a significant travel burden associated with LSC scientists taking scimon shifts, but it is the judgement of the collaboration that ensuring close monitoring of data quality outweighs the cost. That said, there is a potential cost benefit in stationing more LSC graduate students and postdocs longterm at the observatories which can naturally ensure more seasoned expertise among the scimons.

Another important aspect of data run support is injection of simulated astrophysical signals into the detector hardware [114], to validate data analysis pipelines with high confidence. LIGO Laboratory and LSC scientists have provided the manpower to set up the injection infrastructure and carry out the injections during data runs. In addition, environmental signal injections of a wide variety have been carried out by Lab and LSC scientists. The sophistication and automation of signal and environmental injections has increased with each data run, and that steady improvement based on experience is expected to continue. In particular, the software should be enhanced so that it is able to inject distinct signals at the the sites which are consistent with an astrophysical signal arriving from a specified direction with specified polarization components. The system should also be made more robust against a few failure modes encountered during the S5 run. At the moment, only a handful of LSC scientists are expert in signal or environmental injections; increasing those numbers would be helpful and prudent.

6.1.11 LSC Presence at the Observatories

A recurring theme in detector characterization is the value of stationing LSC members for long periods at the LIGO Observatories. Many investigations are more efficiently and effectively carried out on-site, where invasive studies are feasibile, *e.g.*, disconnecting a cable, moving a magnetometer, tapping a vacuum chamber, *etc.*. A graduate student or postdoc who is stationed for six months, a year, or more, at an Observatory can become quite expert in detector characterization and can contribute to expediting commissioning.

The high energy physics community learned long ago the value of stationing junior physicists at accelerator laboratories, both for the health of their experiments and for the good career-rounding such experience gives to young scientists. LSC groups, even those with a traditionally phenomenological research focus, are strongly encouraged to learn from this model. In particular, the upcoming Astrowatch period at LIGO Hanford Observatory offers in-residence physicists the opportunity not only to participate in active data-taking and H2 maintenance, but also the chance to assist in Enhanced LIGO commissioning. As the gravitational wave community looks ahead to routine astrophysical detections in the Advanced LIGO era, we need to ensure that our community members understand their detectors, not just waveforms and analysis.

6.2 GEO Detector Characterization

6.2.1 Introduction

The GEO 600 detector is a significantly different design to the 3 LIGO detectors. As such, it has separate commissioning and characterisation teams. The vast majority of the characterisation work is carried out by the commissioning team with additional help by other scientists within the GEO collaboration. The characterisation work at GEO 600 can be considered as two threads of work with some overlap: characterisation of the detector for the purposes of guiding and informing the commissioning plan; and characterisation of the resulting data in order to prepare it for input into the various LSC search groups.

The characterisation of the detector focusses mainly on the areas of calibration, tracking of the detector sensitivity, studying the long-term stability of the detector, identification of limiting noise sources, and on studying the couplings of the many sub-systems that make up the entire instrument.

As GEO 600 approaches its predicted design sensitivity, the commissioning work depends more and more on an accurate understanding of the noise present in the main output channels. In the case of GEO 600, this requires two things: a reliable on-line calibrated strain sensitivity, and a detailed understanding of the limiting noise sources. With these two requirements satisfied, it is possible to track small changes in the sensitivity of the instrument which arise from any particular experiment or hardware change that takes place. In this way, the commissioning team can quickly and accurately evaluate the impact of their work.

Part of this sensitivity-tracking is achieved through the use of Summary Reports. For every 8 hours of data collected at GEO 600, every second of the calibrated output data stream is analysed in various ways, together with data from many other channels. The results from these various analyses are presented as web pages in the form of summary reports [115]. In addition, many on-line monitors are run to present the commissioners with an up-to-date view of the current detector sensitivity. These on-line monitors typically include:

- Continuously updating, low-latency spectrum of the calibrated $h(t)$ signal, with a background reference trace.
- Continuously updating, low-latency spectra of many interferometer and enviromental monitor signals, with background reference traces.

- Time-frequency map of detected glitches for the last N hours (typically 24 hours). The glitch detection algorithm used at GEO 600 is a modified version of the HACR algorithm [116, 117] and the monitor is called `hacrMon`.
- Range to 3 different optimally oriented binary systems which would produce an snr of 8 in the current $h(t)$ data stream. This monitor is called `inspiralMon`.
- The `burstMon` monitor determines the h_{rss} needed to detect 6 different sine-gaussian signals ($Q = 9$, central frequencies between 200 Hz and 2 kHz) at an snr of 8.

A lot of the software that carries out the on-line analysis is dedicated C-code. Such codes include the calibration code (that produces the on-line $h(t)$ data-stream), and four on-line monitors which analyse a large fraction of the recorded data (`hacrMon`, `inspiralSensMon`, `burstMon`, `saturationMon`). The output of these monitors is captured in a database where it is subsequently mined and presented in the summary reports. In addition, the contents of the database are routinely mined by scientists carrying out characterisation investigations.

Most of the daily on-site data analysis carried out by the commissioning team is performed in MATLAB using a suite of dedicated tools (`geomatapps`) designed to easily interact with the GEO 600 data servers and to allow easy access to typical signal processing routines.

6.2.2 Data Acquisition and timing

The data acquisition system used at GEO 600 uses the same analog-to-digital converter (ADC) cards as those used at the LIGO detectors. However, the infrastructure in which these cards are placed is somewhat different. There are three data-collecting units (DCUs) at GEO 600: one in each building. The main DCU, located in the central-building, contains one 32-channel ADC card sampling at 16384 Hz, and one 64-channel ADC card sampling at 512 Hz. The other two DCUS contain only a single 16-channel ADC board sampling at 16384 Hz. All cards are clocked by timing signals locked to a GPS reference clock. In addition, to ensure good time-stamping accuracy, the clock signals sent to the ADC cards are read-back by a dedicated circuit which counts the number of pulses in a defined period of time to ensure that the sample rate remains constant at 16384 Hz. More details of the GEO 600 data acquisition system can be found in [118] and [119].

To determine that the GPS references used to clock the ADC are performing properly, a second Rubidium atomic clock (locked to a GPS receiver for long term stability), is used to generate a periodic ramp signal. This ramp signal is recorded in the DAQ system and used to check that the ramp originates close to the beginning of each second of data. The measured offset of the ramp from the second boundary of the data-stream is monitored and an alarm is raised should this value exceed a certain threshold. Typically, this offset is measured to be around 6 μs with a standard deviation around 500 ns. This measured timing offset is also the basis for one the data quality flags generated at GEO 600 (see Section 6.2.5 for more details).

The measurement of the relative timing accuracy between GEO 600 and other LSC detectors is an ongoing area of research and discussion within the LSC.

6.2.3 Strain calibration

GEO 600 is the first long-baseline GW detector to use Signal-Recycling. This, together with the heterodyne readout employed, results in GW signal being spread between the two demodulated quadratures of the main output photodiode signal. In other words, there is no demodulation phase that can be chosen that puts all the GW signal in one quadrature for all frequencies. These two output signals are typically referred to as P and Q, and both must be properly calibrated and then combined to recover the best estimate of the detected strain with the optimal snr. Because of this, estimating the sensitivity of the detector from the uncalibrated output signals is difficult, and as such an on-line time-domain calibration scheme was developed at GEO in order to give the commissioning team a single data-stream that properly reflects the strain sensitivity of the detector. This on-line calibration scheme is detailed in [120, 121, 122].

The calibration process is a complex one, relying on very detailed knowledge of the detector and supporting sub-systems. The accuracy of the calibration is paramount to the success of much of the data analysis that is performed within the LSC, particularly when more than one detector is used in a network.

The calibration accuracy can be thought of as two measures: the absolute calibration accuracy, how the voltage recorded at the two main output signals is scaled to be in units of GW strain; and the relative calibration accuracy, how the calibration accuracy varies as a function of frequency relative to some idealised, perfect calibration system. The relative calibration accuracy is reasonably easy to determine in GEO. The main actuators used to hold the Michelson interferometer at its dark-fringe condition follow a simple pendulum response: $1/f^2$ for $f \gg 0.6\,\text{Hz}$ (main longitudinal pendulum resonance) and $f \ll 10\,\text{kHz}$ (the first internal mode of the main test-masses). As such, we can induce known differential length changes and measure the predicted response to that given by the calibrated $h(t)$ signal. This typically gives results within 10% and 10 degrees across the detection band (50 Hz to 2 kHz).

The absolute calibration of GEO 600 is based ultimately on the length of the first Mode-cleaner (which is known to $<1\%$). By driving only one of the end-mirrors of the Michelson interferometer we induce some differential arm-length change, but also some (common-mode) length change of the Power-Recycling (PR) cavity. Since the laser frequency in GEO is stabilised to the length of the PR cavity, this length change ultimately results in a feedback signal which is applied to the control piezo of the master laser. The calibration of the master laser control piezo is then done by sweeping the frequency of the master laser across Free-Spectral-Ranges of the first mode-cleaner. We then relate the FSR of the mode-cleaner to its length. This measurement process is a difficult one, requiring many (careful) steps. Overall, the accuracy of this method is believed to be of the order 5%.

GEO 600 also recently started experimenting with a photon-pressure actuator. The first aim was to confirm the absolute calibration achieved using the method described above. Until recently, the model used to convert photon-pressure (through momentum transfer) into displacement of the test-mass was thought to be simple, yielding a reliable alternative calibration method. The results of the experiments carried out at GEO and LIGO have shown that this is not the case. For example, it has become clear that the test-masses can not be considered as rigid bodies when applying localised forces. The effect of this on the simple model is particularly strong at high ($> 2\,\text{kHz}$) frequencies, where it begins to dominate the simple pendulum response. Nevertheless, the initial calibrations derived using the photon-pressure actuator were within 30% of the calibration achieved using the routine method described above. The use of photon-pressure actuators is an active area of research within the LSC and VIRGO, and comparison of results between the different calibration teams is an essential step in properly characterising this method.

Clearly it is highly desirable to have multiple methods for determining the absolute calibration accuracy. Within the LSC, various methods are employed at different detectors, and very important and fruitful exchanges of information and methods are carried out by members of the LSC Calibration Committee and the VIRGO calibration experts. It is essential that this collaboration continues in order to maximise the chances of finding more and better ways of calibrating these highly complex instruments.

6.2.4 Glitch studies

Due to the difference in sensitivity of the GEO detector compared to the LIGO detectors at low-frequency, data from GEO can have maximum scientific impact in the search for transient (burst) GW signals, particularly above 500 Hz where the sensitivity of GEO comes close to that of the LIGO detectors. As such, a significant amount of the detector and data characterisation at GEO 600 centers around the measurement, removal and characterisation of transient signals. As stated above, the HACR glitch detection algorithm is run continuously on many signals recorded at GEO. HACR characterises detected glitches (events) by a few parameters. For example, central frequency, central time, bandwidth, and duration.

Coincidence analysis is routinely performed between many instrumental/environmental signals and the $h(t)$ signal. Any signal that shows a significant population of coincident glitches is either targeted for repair, or (if repair is not possible), is studied further in the hope of creating a robust veto signal that can be used to reduce the final set of $h(t)$ events that will be considered as candidate GW bursts in subsequent (multi-detector) analysis.

To date, 3 veto methods are typically used to reduce the list of candidate GW events. These are:

Null-stream veto The calibration method described above in Section 6.2.3 stated that two output signals of GEO are calibrated and then optimally combined to produce the final estimate of the strain sensitivity of GEO. In addition to this optimal combination, one can take the difference of these two calibrated outputs to produce a null-stream: a signal that contains (to within the relative calibration accuracy of the two output signals), no GW information. This signal, while (by definition), being insensitive to GWs, remains sensitive to various classes of instrumental glitches. As such, it can be used as a powerful veto method. See [123] for more details.

Noise-projection veto The characterisation of the GEO instrument includes the determination of the limiting noise sources through a process termed *noise-projections* [124]. One result of this is that the transfer function from various points in various subsystems to the main detector output is routinely measured and tracked. Having knowledge of how these various subsystems couple to the $h(t)$ datastream means that, should these subsytems exhibit glitchy behaviour, the glitches that appear in $h(t)$ as a result can be acurately predicted. This provides a very robust and efficient veto method [125, 126]. The characterisation and study of more veto channels which use this method is a source of continuing research.

Statistical veto with additional amplitude cut During S5, one population of glitches was identified as coming from dust particles moving through the main output beam in the path to the main photodiode. After some investigation, it turned out that the dc power detected on that photodiode was also sensitive to those glitches (since they affect the light power falling on the diode). Unfortunately, the dc light power at the detector output is also sensitive at some extent to GWs (about 10 times less than the main $h(t)$ channel). In order to use the dc light power as a veto, we had to add an amplitude consistency check to the standard time and frequency coincidence windows. Having properly determined the sensitivity ratio of the two channels ($h(t)$ and dc light power) to GWs, we were able to veto these dust glitches with reasonable efficiency. The veto was checked for safety by some GW-like hardware injections; none of the hardware injections was vetoed by this method. This work is on-going and needs a more comprehensive set of hardware injections to adequately check the safety of the veto. When the characterisation of this veto is completed, the veto can be applied to the full S5 data set.

The continuing development of novel veto methods is a strong area of research at GEO 600.

6.2.5 Data quality

A number of data quality flags are used at GEO in order to decide whether the produced $h(t)$ signal is considered to be science quality data. These data quality flags are automatically produced and checked during the calibration process so that a final Data Quality channel is produced which, for any value other than zero in the first 6 bits, indicates non-science data. For S5, this data quality channel is encoded in the bits of a 16-bit integer as described in Table 1. There are additional data quality flags encoded in bits 6 though 11. These represent a measure of the calibration quality. For S5, we build an additional data quality flag if bit 6 is 1 for more than 10 consecutive seconds.

Bit	Description	Science condition
0	Detector lock status.	0
1	Hardware maintenance on.	0
2	Software maintenance on.	0
3	Calibration lines missing.	0
4	Configuration re-read.	0
5	DAQ time-stamping not valid.	0
6	Calibration quality, $\chi^2 > 5$.	-
7	Calibration quality, $\chi^2 > 6$.	-
8	Calibration quality, $\chi^2 > 7$.	-
9	Calibration quality, $\chi^2 > 8$.	-
10	Calibration quality, $\chi^2 > 9$.	-
11	Calibration quality, $\chi^2 > 10$.	-
12-15	Not used.	-

Table 1: Data quality flags encoded in calibration data quality channel.

6.2.6 GEO detector and data characterisation post-S5

Since the GEO 600 commissioning plan post-S5 involves fairly invasive procedures, a full characterisation and veto study will need to be carried out prior to GEO entering a further science run. The three veto methods described above must be re-evaluated and tested, and possibly extended to additional subsystems and channels.

To help characterise and study existing and new veto methods, a burst hardware-injection pipeline is under development. A system will be put in place that allows various waveforms, both astrophysical and ad-hoc, to be injected into various subsystems of the interferometer, as well as into frame files to allow software injections.

GEO 600 is currently exploring different read-out schemes and operating points, for example, dc read-out and different tunings of the Signal-Recycling cavity. This may necessitate modifications to the existing calibration scheme. In addition, the commissioning team continues to investigate new absolute calibration methods, including continued study and characterisation of the photon-pressure actuator. The discovery from the photon-pressure work that test-masses can not be considered as rigid bodies under certain circumstances motivates further characterisation of the electro-static actuators (ESDs) used as the reference for the on-line calibration scheme. Although the uniform force of the ESDs is not expected to induce any significant test-mass defomation in the detection band, this is worth checking.

Recent investigations into time-domain noise-subtraction methods have yielded encouraging results for systems whose coupling to $h(t)$ is well understood (for example, Michelson differential alignment). Attempts will be made to expand these subtraction methods to include subsystems with more complicated, or even, unknown, couplings to $h(t)$.

6.3 Virgo Detector Characterization

6.3.1 Introduction

The characterization of the Virgo data is performed at several levels, reflecting the different needs which this activity is meant to address.

The *Commissioning* of the detector, which includes the improvements and tunings performed during the short commissioning breaks during the Science Run, require a quick analysis which can provide easy to interpret, robust figures of merit about the detector performance.

The *Noise Hunting* goes more in depth to characterize statistically the noise properties and to search for correlations/coherences with environmental channels.

The *h-Reconstruction* implements part of the noise cancellation strategies, for instance for further mitigation of the control noise or the 50Hz noise, and as a byproduct monitors some figures of merit of the detector performance.

The *Search Groups* run specialized tools for assessing the quality of the data, specifically for each kind of search and in some cases online. This tools mostly consist of highly representative subsets of a full search pipeline, and therefore provide results very informative.

The outputs of these activities are not yet organized in a unique, coherent way, but are for the most part accessible over the web.

In the following we provide a list of the activities/tools being used, a minimal information about their purpose and scope, and web references for people more interested.

6.3.2 Detector status monitors

We list here the basic information which allows to know and track the status of the detector.

Logbook "If it is not in the logbook, it didn't happen" is true also for Virgo. The logbook is available at
https://pub3.ego-gw.it/logbook/
and is searchable.

Locking monitor The first very basic information about the status of the detector at a specific epoch is available in the online locking monitor at
http://wwwcascina.virgo.infn.it/locking/lockmoni.htm.
It may also be of interest the monitor of the power injected in the interferometer, available at
http://wwwcascina.virgo.infn.it/commissioning/FastUnlock/
which indirectly serves as a lock monitor for the injection system.

General ITF status A first look at the detector status can be obtained at
http://wwwcascina.virgo.infn.it/MonitoringWeb/General/
which groups several informations, including the current sensitivity, compared to a reference one, the history of the detector status, the BNS horizon, the duty cycle, as well as a few important signals like the power in the carrier and in the sidebands.

Data quality The basic quality of Virgo data is reported in the frames using the data quality words, whose interpretation is available here
http://wwwcascina.virgo.infn.it/DataAnalysis/Quality/.

This is a flag which results from a number of other conditions being fulfilled, in particular that a number of ITF signals are within the nominal ranges. A list of ITF signals, operating conditions and current status is available at

https://olserver13.virgo.infn.it/itf/qcmoni/V5/index.php.

Albeit rather cryptic for non experts, it may be useful once one knows the name of an interesting channels and just uses the fact that "green" means "good state".

Mirror temperature monitor This monitor uses the frequency of mirror internal resonances to gauge the temperature of the bulk, and provides the history, as well as the current status, at

http://wwwcascina.virgo.infn.it/commissioning/MirrorT/

Spectrograms Time-frequency plots of various channels, including the dark fringe (Pr_B1_ACp) as well as the dark fringe whitened, the power circulating in the FP cavities (proportional to Pr_B7_DC and Pr_B8_DC), are available under

http://wwwcascina.virgo.infn.it/MonitoringWeb/Spectro/index.html

It is worth mentioning that all the plots displayed under `../MonitoringWeb/...` directories are saved and available in the page history.

Reconstruction The status of the h-Reconstruction is monitored under

http://wwwcascina.virgo.infn.it/MonitoringWeb/Reconstruction/index.html

and provides also some figures of merit specific for the CBC searches, namely the detection range for 1.4 - 1.4 BNS and 10.0 - 10.0 BBH, in various flavors (time trace, histogram, spectral distribution).

6.3.3 Calibration and Hardware Injections

The detector calibration is performed at regular intervals by injecting noise in the coils of one of the end mirrors. The techniques employed, as well as the transfer functions measured and the resulting sensitivities, are all available at

http://wwwcascina.virgo.infn.it/DataAnalysis/Calibration/home.html

Another sort of calibration is performed by simulating the occurrence of GW events. This is done by injecting properly shaped signals in the coils of one of the input mirrors of the FP cavities. Two kind of injections are performed: **loud injections** are performed as one of the activities during the weekly maintenance breaks of the detector, with the purpose to check the safety of veto procedures. On the other hand **moderate injections** are performed for about 5 minutes every shift, alternating burst and inspiral injections, to check the performance and effectiveness of the actuation-detection-reconstruction-search pipeline.

6.3.4 Noise studies

These are performed both online and offline, using a variety of tools. Their goal is both to systematically assess the status of the detector and to investigate the sources of noise, in some cases performing ad-hoc actions on the detector. A non-exhaustive list of the activities follows:

Environmental monitoring Information about various environmental channels, like temperatures in the building, different sorts of seismic activities, planes passing by, etc. are available on recent data at

http://wwwcascina.virgo.infn.it/MonitoringWeb/Environment/index.html

Further information about the seismic noise in different bands (which can be associated to different sources, like wind and sea) is available at

http://wwwcascina.virgo.infn.it/commissioning/Monitoring_50Hz/
Other information, resulting from follow-ups of various noise sources, is available at
http://wwwcascina.virgo.infn.it/DataAnalysis/Noise/EnvStudies/

Line characterization Virgo has classified a large part of the narrow spectral features present in the noise and maintains a database at the address
https://pub3.ego-gw.it/linesdb/
which can be interrogated in various ways, including by frequency range, by epoch or by kind of line. The database is regularly updated at each run. An online line monitor is also being developed, to track the most important spectral features and their evolution: it is under testing at
http://wwwcascina.virgo.infn.it/commissioning/Test/

Outlier monitor This searches for events in the tails of the distribution of the whitened dark fringe, which should be gaussian noise. It provides a running histogram of the whitened noise distribution, as well as a list of the loudest events, at
http://wwwcascina.virgo.infn.it/MonitoringWeb/Noise/outlierMoni/index.html.

Non stationary monitor This simple tool computes the RMS in various frequency bands, and searches also for non-stationarities in the narrow spectral features: more information and results at
http://wwwcascina.virgo.infn.it/MonitoringWeb/Noise/NonStatMoni/.

Glitch monitor This algorithm searches for sudden jumps in the dark fringe data, and in correspondence of an event displays also the simultaneous traces of several other channels; this can be useful to quickly gauge the source of the event. More information at
http://wwwcascina.virgo.infn.it/MonitoringWeb/Noise/glitchMoni/

Noise budget The Virgo noise budget, that is the breakdown of the measured noise in terms of modeled noises, which include the coherences with control noises, is regularly computed and displayed at
http://wwwcascina.virgo.infn.it/MonitoringWeb/Noise/NoiseBudget/.

6.3.5 DC resulting from the searches for impulsive events

Both the CBC and Burst group run online, and routinely offline, portions of search pipelines specialized to gauge the quality of the data.

CBC analysis The search for BNS is run online over the range 0.9 - 3 $M_\odot$ for the components, and is rather sensitive to the status of the detector (during VSR1, from about 60Hz upwards). Condensed information is made available at
http://wwwcascina.virgo.infn.it/MonitoringWeb/Inspirals/index.html
by the two pipelines:

MBTA provides history of max and mean SNR detected, as well as SNR histogram and the SNR-χ^2 (two bands) scatter plot. The spectrum of max SNR fluctuation is also very useful to detect autocorrelations in the events.

Merlino provides also the SNR-χ^2 (seven bands) scatter plot, as well as histogram of full and χ^2 selected events. The `Horizon Distance vs Chirp Mass` plot can also be useful to detect noise more relevant in certain bands, while the density (or 3D) plot of the candidates as a function of the individual masses can also be informative.

Burst analysis The Burst group runs on Virgo online the Q-pipeline, which allows to monitor the trigger rate and strength of unmodelled pulses in the dark fringe, and to keep note for further analysis of the loudest events. All the results, as well as links to further information, are available at

http://wwwcascina.virgo.infn.it/MonitoringWeb/Bursts/index.html

In addition to the online analysis, the Burst group routinely runs algorithms like the Peak Correlator and the Exponential Gaussian Correlator on recent data segments; all the results are regularly reported in

https://workarea.ego-gw.it/ego2/virgo/data-analysis/burst/burst-working-area/

and discussed at the Burst telecons.

7 Computing and Software

The LIGO instruments deliver about 1TB/day of data. Even with only about 1% of this data in the gravitational-wave strain channel (the rest consists of detector and environment monitoring information) LIGO data analysis is a formidable computing challenge. Binary inspiral, burst and stochastic searches can utilize many Tflops of computing power to analyze the data at the rate it is acquired. *LIGO's scientific pay-off is therefore bounded by the ability to perform computations on this data.*

The LSC has converged on commodity computer clusters as the solution that meets its computational needs most cost effectively. LIGO has super-computer class requirements and data that can be handled efficiently in the simple parallel environment of clusters. In recent years the LSC has migrated to the grid concept of geographically distributed computing with clusters located at several sites. This approach has the advantage that it puts resources close to the university researchers who are analyzing the data. Grid middleware allows for relatively easy access to data and computing power. If local resources are inadequate or a poor match, a researcher can access additional resources on the grid.

The LSC also developed the Einstein@Home project to leverage an alternative distributed computing paradigm for its most formidable computing challenge, the search for gravitational waves from isolated pulsars. The pulsar analysis puts reduced demand on quick turn-around and has low data flow, but requires PFlops of computing power. The analysis engine that underlies Einstein@Home utilizes much of the standard LSC software infrastructure described below; BOINC [2] is used to distribute work to thousands of volunteered personal computers world-wide.

7.1 Current status

The LIGO Data Grid (LDG) is the combination of computational resources, data storage, grid computing middleware and LSC services which, together, create a coherent data analysis environment for gravitational-wave science. With resources located at LIGO Laboratory centers (Caltech, MIT, LHO and LLO) and LSC institutions (PSU, UWM, and 3 sites in the EU managed by the GEO-600 collaboration), the LDG is a true distributed facility.

The LIGO Data Grid currently offers the minimal services required on a fully functional data grid. LIGO is in continuous science operation at unprecedented sensitivity, and the LDG continues to see growth in the number of users, higher demand for the resources, and construction of more sophisticated workflows.

[2] `http://boinc.berkeley.edu`

It is essential, therefore, to provide support of the LDG infrastructure, to provide user support and documentation, and to create the new services that gravitational-wave scientists will require. These services include: improved resource monitoring service and a resource brokering service to ensure that optimal use is made of LDG resources at all times; a metadata service to provide collation, distribution and access to the scientific results of searches; and a virtual organization management service to facilitate access control of LDG resources.

We anticipate evolution of the usage model as the community gains experience, and so we are committed to a modular approach which allows us to remain light on our feet and implement solutions to enable the best gravitational-wave science. A detailed description of the program of work on the LIGO Data Grid follows.

7.2 Activities in support of LDG Operations

1. **Hardware and Operating System Maintenance** The LDG clusters are all commodity Linux beowulf clusters as this offers the most GFLOPs/dollar of capital investment. Using Linux requires an investment to track, and in some cases work around, such a rapidly developing operating system. Furthermore, the next generation LDG clusters are likely to use 64-bit versions of Linux which will require some system administration effort to ensure a smooth transition. These are the traditional system-administration roles independent of grid activities.

2. **Grid Middleware Administration** Each local cluster must maintain a rapidly evolving set of middleware in as stable a fashion as possible. The primary means to do this is the LDG Server software, discussed in Section **??**. This software is rapidly evolving and requires effort to configure, support and maintain, independent of the effort required to create and maintain the LDG Server package itself.

3. **Data Distribution and Storage** The LDG currently uses the commercial SAM-QFS mass storage software from Sun Microsystems, commodity storage in the compute nodes, Linux based RAID servers, and the LIGO Data Replicator (LDR, Section **??**) to store and distribute data. Input data is common to the majority of analysis pipelines, and so is distributed to all LDG centers in advance of job scheduling.

4. **Certificate Authority and User Accounts** LIGO uses X.509 certificates for authentication and authorization of users. LIGO use the DOEGrids CA to provide certificates for authentication. RA agents are required to verify certificate requests and then approve them. User accounts are requested by a centralized web site; approvals are sent to each site where local admins add the accounts.

5. **LIGO Data Grid Client/Server Bundles** LSC staff leveraged experience with the VDT and built upon the VDT to create the LIGO Data Grid Client and Server packages. The server bundle enables LSC administrators to easily deploy standard grid services and middleware such as Globus GRAM and GridFTP across the LDG. The client bundle provides quick one-stop installation of all the software needed to gain access to the LDG resources by users in the LSC. Moreover, the LDG Client bundle provides scripts specific to the LDG to simplify certificate requests and other activities that users perform. This bundle is maintained and released on a cycle similar to the VDT.

6. **User Support** The LDG predominantly uses Condor for job queue management. As the analysis workflows for this new branch of astronomy are evolving rapidly, significant effort is required to work closely with the Condor development team to ensure effecient use of the LDG clusters. This feedback has been productive, with many timely bug fixes and feature enhancements being provided, however this requires significant effort from LDG administrators to isolate and troubleshoot issues that are particular to gravitational-wave data analysis. Compared with our High Energy Physics colleagues, the workflows that are being developed on the LDG are not yet as mature or stable, causing a significant

burden on cluster administrative staff. Since the LDG users are generally scientists and not grid experts, staff are required to offer performance tuning in terms of GFLOP/s, job scheduling efficiencies, memory utilization, file management, and general debugging support for intermittent job failures.

7.3 Data Analysis Software Development Activities

A suite of software tools are supported, developed and released by the LSC for the purpose of analyzing data from gravitational-wave experiments. These data analysis software projects are developed under the umbrella of the *Data Analysis Software Working Groups* (DASWG). Many of these projects have evolved into full scale software projects which enable most of the large scale analysis efforts within the LSC, thus requiring substantial effort to maintain them. Moreover, the LSC and the international community of gravitational-wave astronomers have embraced the grid-computing model and its associated technologies placing further demands on the software tools developed by DASWG.

1. **Data Monitoring Tools** The Data Monitoring Toolbox or DMT is a C++ software environment designed for use in developing instrumental and data quality monitors. About 50 such monitor programs have already been developed by members of the LIGO Scientific Community. DMT monitors are run continuously while LIGO is in operation, and displays produced by these monitors are relied on to give the operators immediate quantitative feedback on the data quality and interferometer state. In addition to their on-line use, the monitors and the software infrastructure they are based on have many offline applications including detector characterization, data quality determination and gravitational wave analysis. To facilitate the use of the DMT environment and monitors offline, the majority of the DMT package has been ported to the LSC offline processing clusters. Porting and packaging the DMT for offline use will continue to be supported. Further development of the tools needed to enable grid-based process submission and data access is also in progress.

2. **GLUE** The Grid LSC User Environment (GLUE) provides workflow creation tools and metadata services, written in Python, which allow LSC scientists to efficiently use grid computing resources within and external to the LIGO Data Grid. GLUE leverages grid middleware to provide secure authentication mechanisms (Globus), job submission and control on clusters (Condor) and workflow planning for grids (Pegasus). Analysis of data from gravitational-wave detectors is a complicated process typically involving many steps: filtering of the data from each individual detector, moving trigger data to a central location to apply multiple instrument coincidence tests, investigating auxiliary channels, and coherent combination of data from all detectors in the network. The description of these complicated workflows requires a flexible and easy to use toolkit to construct a virtual representation of the workflow and then execute it on a single cluster, across the entire LIGO Data Grid, or across the OSG. The pipeline module of GLUE provides this facility and is used in all large-scale inspiral and burst searches, and is being adopted by the pulsar and stochastic groups.

3. **OnASys**

   The Online Analysis System (OnASys) is a software package designed to submit and monitor analysis jobs as data is collected by the gravitational-wave detectors. It is built around Condor and a MySQL job status database, and is being enhanced to utilize the Pegasus planner. This daemon was first deployed during the 4th LIGO science run (S4) when it was used to run several searches for gravitational-waves, including bursts from supernovae, black holes, and neutron star binary inspirals. Future development work will focus on automated error recovery and enhancements to the job status database, to the user tools, and also to the web-based status monitoring tools.

4. **LSC Algorithm Library**

The LSC Algorithm Library (LAL) is a library of C language routines that form the engine of the computationally-intensive data analysis programs. LAL routines are used in LAL Applications (collected in the LALApps package) which are programs that perform specific data analysis searches, and the LAL-Python interface (PyLAL) that provides access to LAL routines within the Python scripting environment. LAL contains (i) general purpose data analysis routines that provide common data analysis tools (e.g., routines to perform time-domain filtering, Fourier and spectral analysis, differential equation integrators), astrometric tools (e.g., routines for converting between sky coordinate systems and time systems), and gravitational-wave specific tools for signal simulation and data calibration; (ii) routines for reading and writing data in standard LIGO data formats; and (iii) implementations of search-specific gravitational data analysis algorithms. Enhancements are planned to improve the I/O routines to interface with LDR data catalogs directly and to leverage Grid tools to directly access data stored remotely. Also planned are significant improvements to the interface of the core analysis routines to make these routines easier to integrate into other software.

C language applications for performing specific searches are contained in the LALApps package which is freely available under the GPL. This package provides a set of stand-alone programs that use LAL routines to perform specific pieces of a search pipeline. The programs can be strung together to form a data analysis workflow: a sequence of steps that transform the raw interferometer output into a set of candidate events. These applications continue to be enhanced and new ones developed.

PyLAL is a Python module that includes extension modules that link against LAL, thereby making LAL routines available within the Python scripting environment. PyLAL thus provides a mechanism for rapid data analysis application development, for data exploration and graphing, and for performing quick follow-up analyses. As PyLAL matures, many more LAL routines will be incorporated so that significant aspects of the data analysis pipelines will be written in Python.

5. **MATLAB Applications** The MATLAB software suite is a commercial product which is widely used within the LIGO

   Scientific Collaboration (and the broader gravitational wave detection

   community beyond) for on-line and off-line data analysis,

   detector characterization, and operations. The MATLAB Applications package (MatApps) is a collection of gravitational-wave

   data analysis tools for use within the MATLAB environment that were written

   by the LSC members in support the analysis of LIGO and GEO data.

   This software is now maintained as part of the LSC MATLAB Applications

   (MatApps) project. Many of the contributions to MatApps are complete

   analysis tools developed by individual scientists. As a result, there

   is considerable duplication within the current repository. The next

   step is to develop a set of atomic functions, together with associated

   documentation and automated test suites, that address the most common

   functions and evolve the existing analysis tools to use these new

   functions. Candidates for this factorization include a single MATLAB

   Application Programming Interfaces (API) for I/O to the several

   gravitational wave data file storage

formats; data calibration functions; and higher level functions that are identified as commonly used and useful. By developing and migrating the existing code base to use these APIs and atomic functions the collaboration will significantly increase the verifiability and maintainability of this analysis software, while simultaneously reducing the barrier to the development of analysis software by individual researchers, educators and students.

7.4 Intermediate-term development activities

The distributed LDG relies on a number of grid services to allow robust, efficient operations. A minimal subset are currently deployed on the LDG. The full set is outlined here along with estimated personnel requirements to support, enhance and deploy them where appropriate.

1. **Problem Tracking and Security** Robust operation of the LDG requires detailed problem tracking to insure that services are maintained and that security issues are quickly and efficiently addressed. There is already web based problem tracking facilities. This service needs to be extended and integrated with the LDG monitoring services.

2. **Virtual Organization Management Service** The LSC relies on the Grid Security Infrastructure (GSI) from the Globus toolkit as part of its public key infrastructure. There is currently no centralized, fine grained authorization control within GSI; system administrators at each site map use gridmap files to map credentials to standard unix accounts. This approach will not scale sufficiently for the LDG. The OSG is using the VOMS-GUMS-PRIMA model for this purpose. The LSC has deployed these tools to share resources with OSG, but needs to explore all technologies that meet the collaboration's needs. In the near term, a personnel database system is under development and a sub-committee is exploring design requirements for its integration with Virtual Organization Management.

3. **Metadata Services** The LDG relies on the LIGO Data Replicator (LDR) to manage bulk data transfers and to maintain the metadata associated with the large archives of files and resources. Other metadata are also needed for gravitational wave data analysis, such as time intervals during which the interferometers are in operation, metadata associated with analysis pipelines, and metadata associated with event candidates. It is evident that metadata management is an important requirement for LIGO. Considerable effort is needed to examine metadata management requirements, design and develop necessary services, and deploy and operate the services. The LIGO Metadata Service will be built using industry standard technologies and will be compliant with current frameworks to ensure smooth integration with the wider international gravitational-wave community.

4. **Monitoring Services** Another type of metadata inherent to grid computing models describes the status of clusters and their processes and services, the status of jobs on the cluster, and the status of connectivity between clusters. In order to maximize the harvest of cluster cycle time, users and job submitting agents need to be aware of these metadata. The LDG currently uses Ganglia to obtain snapshots of the status of clusters at different locations and then reports them to a central Ganglia metadata server. Enhancing monitoring services by including one or more available tools and collating the information collected by these to provide a consolidated Grid friendly interface is an essential step to improve efficiency.

5. **Enhancing LDAS for the LDG** The Globus Toolkit provides Application Programming Interfaces (API) to several popular computer languages such as C and Java. But Tcl/Tk is not one of the available API interfaces. LDAS software technology is based on the principle of extending the Tcl/Tk scripting language with highly efficient C++ Tcl packages (software libraries). Since the LDAS control level is in Tcl, LDAS requires an extension to the Tcl language to bring Grid technologies into its infrastructure. This is achieved using the TclGlobus package being developed at Caltech. The TclGlobus project is using SWIG to expose Globus Toolkit functions to the Tcl/Tk scripting language. The continued use of the Tcl/Tk scripting language within LIGO along with the evolutionary migration towards Grid based computational technologies by LIGO make TclGlobus a critical component for continued support and maintenance. LIGO is in the midst of enhancing LDAS to incorporate several of the Grid components found in the Globus Toolkit.

   In addition to the LDAS system, many of LIGO's client side tools, collectively called LIGOtools, are based on the Tcl/Tk scripting language. These client side tools are also slated to be upgraded with Grid technologies using the TclGlobus package, providing a common Grid enabled interface for users of LIGOtools.

6. **LIGO Data Replicator** The LIGO Data Replicator (LDR) replicates in bulk interferometer data files to LSC computing sites. LDR also provides a metadata catalog for LSC files that in conjunction with other tools allows LSC scientists and their codes to discover data and other files within the LIGO Data Grid. Replication begins when data is *published* into the LDR network at a site. Publishing implies that relevant metadata about a file is entered into the local metadata catalog that is part of LDR and that a mapping from the logical filename (LFN) to an access path (typically a URL) or physical filename (PFN) is created in the local replica catalog (LRC). By the end of the LIGO S5 science run the LDR metadata catalog is expected to contain metadata information on more then 25 million files and each RLS replica catalog is expected to hold between 1 and 50 million mappings, depending on the data sets replicated to each site. With at least seven LDR installations in the LIGO Data Grid the RLS network is expected to serve between 100 and 350 million mappings, making the LDR deployment in the LIGO Data Grid the single largest deployment of the Globus RLS. Intense investigations and testing are needed to insure that this solution continues to scale through the operation of initial and enhanced LIGO. Moreover the LDR metadata catalogs will need to be integrated into the LIGO Data Grid metadata service to provide a unified look-and-feel to the user community.

7. **LDG Service Software** The lightweight database daemon (LDBD) provides a client and server framework for scientific metadata services. LDBD is built on top of Globus (which provides authentication and data location services) and a relational database (MySQL). This framework is designed to be extensible; the first application using it is the interferometer data quality service which requires further enhancement and continued maintenance. Scientists and applications need to efficiently discover and access data across the LIGO Data Grid. The LSCdataFind client uses the Globus toolkit to interface to the LDRdataFind server. Scientists at remote sites can use this client to easily locate data at any of the LIGO Data Grid centers.

8. **Multi-Site Scheduling and Brokering** The ability to plan, schedule, and monitor large workflows simultaneously across multiple LDG sites is becoming increasingly necessary in order to load balance across the computational resources distributed throughout the LDG and to support ever larger workflows which cannot easily or always be serviced within time constraints at a single LDG site. A number of intermediate-term development activities are focused on supporting LIGO data analysis workflows across multiple LDG sites as well as other "grid" sites external to LDG.

   One such activity focues on leveraging the "Grid Universe" available with the Condor High Throughput Computing system and in particular "Condor-C", the Condor Grid type. Currently Condor manages most LDG computational resources (Linux clusters) at a site level. That is, each Linux cluster resource is its own Condor pool and jobs submitted to be run and managed at any single site only run within that same Condor pool. When properly configured, however, the jobs submitted at one site and into one Condor pool may migrate and be run and managed by a remote Condor pool, with the results and output being staged back to the original submission site as if the jobs had ran at the submitting site. An earlier attempt by Condor to support this type of migration of jobs was the Condor "flocking" mechanism. This newer approach known as Condor-C promises to scale better. LDG staff are evaluating Condor-C throughput and scaling behavior and providing feedback to the Condor team, as well as working to understand how best to abstract the details of Condor-C job submission and management away so that LDG users do not have to manage the details themselves.

A second and complimentary approach being investigated for planning and scheduling LIGO workflows across multiple sites leverages the Pegasus workflow mapping engine. LIGO workflows described using abstract directed acyclic graphs (DAX) are planned by Pegasus across both LDG and non-LDG sites and during the planning phase the abstract DAX representation of the workflow is converted to a concrete graph (DAG) with instructions for running parts of the workflow across specific (multiple) sites. The actual management of the workflow is handled by Condor DAGMan. Pegasus can plan workflows for execution across sites that do not run Condor pools as well as into sites that do run Condor pools. LDG staff are evaluating Pegasus and working to understand how to tune Pegasus to schedule LIGO workflows across sites most efficiently.

7.5 Long-term goals

In the long term, the LIGO Data Grid must evolve into a robust system for processing gravitational-wave data in real-time, delivering easy access to compute resources and catalogs of gravitational-wave observations. Here are some of the points that must be addressed to reach this goal:

- **Hardware** The current LDG infrastructure is the best value for money solution available at the present time. Hardware is evolving rapidly and it is important that plans for the LIGO Data Grid in the era of advanced detectors and gravitational-wave astronomy should take account of this. During the initial LIGO era, institutions (other than Caltech and MIT) from the LIGO Scientific Collaboration provided approximately half of the computing resources needed for the analysis of LIGO data. The computing hardware plan for the next few years and continuing into the Advanced LIGO era remains the same, i.e. half of the computing hardware will be provided by LIGO Lab and the other half will be provided by other institutions in the LIGO Scientific Collaboration.

- **Software** The evolution of software technology continues to play an important role in developing tools for scientific data analysis. The open-source software development effort has been of great benefit to the LSC. The LSC will continue to assess its policies and procedures for software development in a manner that allows rapid response to new developments without compromising the quality of the scientific products delivered by the Collaboration.

- **Services** The nature of the services which the collaboration will deliver to members and to the broader community will continue to evolve. In the future, reduced data products will have more value to some scientists than the raw data. Nevertheless, the spectrum of scientific investigations will require a similar spectrum of services to deliver data and compute cycles, and to allow easy sharing of information with the whole scientific community.

- **International partners** The ultimate vision of gravitationalwave astronomy involves a world network of gravitational-wave detectors. The software and computing models of individual collaborations are likely to be quite different. The development of protocols and tools for collaboration will be critical to the rapid success of these efforts in gravitational-wave astronomy.

It is also important to continuously evaluate emerging technologies, having the potential to enable increased efficiency in data analysis.

7.6 Virgo computing and software

This section does not aim at providing a full overview of the Virgo computing and software, but only to provide a few entry points for further information. While in fact Virgo and the LSC keep independent computing resources, and their software developments are partially independent, still in the long term it can be expected an higher degree of interoperability and integration, hence it is important to start providing some more information in this document.

7.6.1 Computing at the EGO/Virgo site

At EGO, the Virgo collaboration runs not only the Data AcQuisition, but also a relevant computing center. Several tasks are run here:

DAQ Virgo acquires about 6 MByte/s of raw data, which are stored on a hierarchy of circular buffers, ultimately allowing to keep about 3 months of data at the site. A separation is in place, at network and disk level, between the computers and applications critical for Virgo operation and monitoring, and the rest of the computing/user environment.

Detector control and monitoring A number of real time machines and workstations are dedicated to run the control and data monitoring algorithms, with an high level of automation and web reporting. Most of the actions are either automatic or run via an interface which also takes care of tracking and reporting the actions in logfiles.

Online processing A number of real time processes take care of formatting the acquired data and of performing a first processing, including the production of online hrec and the basic data quality assessment. More information about this and the previous activities is available at
http://wwwcascina.virgo.infn.it/WebGUI.htm

Data logging and transfer Data are automatically indexed, producing Frame File Lists, and transferred at the computing centers of CNAF (Bologna) and CCIN2P3 (Lyon) for permanent storage, saturating about half of the 100 MBit/s link to the GARR network.

Online/offline analysis A cluster of about 100 nodes of the latest generation, including 32 dual processors and 64 dual-core dual processor machines, is available for online analysis as well as for offline studies on recent data. These machines receive either data from the online processing, thus with a very small latency (a few seconds), or read data from the raw data buffer, with a larger latency (a few minutes).

General purpose workstation A small farm of workstations is available for general purposes; both these machines and the user's workstations access all the recent interferometer data.

7.6.2 Computing at CNAF (Bologna, Italy)

It is worth underlining that both at Bologna and at Lyon the Virgo Collaboration uses resources which are shared with the High Energy Physics community: this means on one hand that the actual resources are negotiated year by year, on the other hand it means that Virgo leverages on the experience in user support and middleware development developed by the more mature HEP community.

The CNAF

http://www.cnaf.infn.it/joomla/index.php?lang=en

is the main computing center of the *Istituto Nazionale di Fisica Nucleare* and serves as repository of two year's worth of the most recent Virgo data. It also provides a large computing facility, consisting of a collection of Linux workstations (about 10^3 bi-processor nodes) accessing about 430 TByte of disk space and 1000 TByte of tape space.

Jobs can be launched either via GRID or via a standard batch scheduler system.

The CNAF is linked at 10 Gbit/s with CERN, and at 1 GBit/s with various other locations in Italy and Europe.

At CNAF recent Virgo data are stored on spinning media, on large, data contiguous GPFS file systems. Less recent data are stored on CASTOR, a mass-storage system.

Virgo runs at CNAF mostly pulsar searches, and up to now has used only a small fraction of the total CNAF power. It plans to run in Bologna also the other offline searches, most notably the CBC searches.

7.6.3 Computing at CCIN2P3 (Lyon, France)

The CCIN2P3

http://cc.in2p3.fr/

is the computing center of the *Institut National de Physique Nucleaire et des Particules*, and serves as official repository of the Virgo data. It provides large computing facilities as well, based on about 700 Linux workstations (bi-processors), as well as a large mass-storage system, with a tape capacity of more than 7000 TByte and equipped with a large spinning media cache.

Also at CCIN2P3 the jobs can be launched either via a batch queue system or via GRID.

The CCIN2P3 is linked at high speed with CERN and with the US.

Virgo runs at CCIN2P3 both burst and pulsar searches, and up to now typically uses 4% of the total computing energy available.

7.6.4 Virgo software

The Virgo data analysis software is organized in a hierarchy of libraries, from the very basic ones which allow to format and to access frame data, to very specialized ones for the searches.

While referring to

http://wwwcascina.virgo.infn.it/sDoc/

for more information, we give here just a brief overview, which should not be taken as complete.

Basic software Data are formatted and accessed with the `Frame` library. Data visualization is possible using the `dataDisplay` software, which is capable of reading data from the online and offline, also from geographically distance places. Simulation of the detector and the sources is possible with the `siesta` software, which can be programmed with "cards" which describe objects and their relation, and outputs data in frame format. Interactive work with frame data is possible with the `vega` software, which is `ROOT` linked with various Virgo libraries.

Data transfer and GRID Virgo transfers data at the Computing Centers using the BBFTP software (a multi-threaded FTP client/server system) complemented with a set of PERL scripts and a DB database. While satisfactory for point-to-point data transfer, this solution is not optimal for distributing data on request, hence Virgo is developing a GRID-compatible solution based on the FTS architecture, and plans to exploit more fully the range of middleware available by the GRID development.

In the medium-long term, every effort has to be devoted to make this GRID architecture compatible with the one adopted by the LSC, also operating towards a greater interoperability of the EU and US grids.

The Virgo pulsar group is routinely running jobs over the GRID, inside the VIRGO Virtual Organization, both at the two TIER1 computing centers of CNAF and CCIN2P3, and at several TIER2 sites, fully belonging to Virgo or not.

Noise analysis software A C++ package called `NAP` is dedicated to the noise analysis, from the computation of basic statistics to more sophisticated approaches, like AR and ARMA modeling, as well as multi-coherence and non-linear analysis. More information is available at

http://wwwcascina.virgo.infn.it/DataAnalysis/Noise/nap_index.html

Search software The Burst group has developed a comprehensive `BuL` library which hosts most of the search algorithms, as well as utilities and service routines which allow to build pipelines running on real or simulated data.

The Coalescing Binaries group uses the `inspiral` library for templates, signals and template grids. It uses `MBTA` and `Merlino` for running the searches on real or simulated data.

Both Burst and CBC software is available in the standard Virgo Common Software distribution, available at

http://wwwcascina.virgo.infn.it/sDoc/VirgoReleases/current.html

The Pulsar group has developed a comprehensive package, mostly based on Matlab or Matlab compiled routines. More information is available at

http://grwavsf.roma1.infn.it/pss/

The Stochastic Background Group has developed a specific search and simulation library `SB`, documented at

http://wwwcascina.virgo.infn.it/DataAnalysis/Stochastic/software/SB/index.html

which leverages also on the noise library `NAP`

8 Astrowatch

9 S6 Run

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