0.1 LIGO Detector Characterization

0.1.1 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[1], 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.

0.1.2 Software Infrastructure

The interferometer controls system based on EPICS (Experimental Physics and Industrial Control Systesm) software[2] 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)[3] and the background monitoring of the DMT. The DTT allows rapid exploration of data in the time and Fourier domains and includes userselected 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[3] offers an interactive ROOT-driven[4] 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[5]. 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[6] 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[7].

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.

0.1.3 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[8] available to the Collaboration, as well as recorded in the electronic logs, software repositories, and LIGO documents[9].

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)[10]. 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.*

0.1.4 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[12].

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 [11]. The construction, testing and diagnostics tasks provided fertile ground for students and their involvement is strongly encouraged for the future.

0.1.5 Glitch Investigations

The largest DetChar working group[13] 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[14]. 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[16] (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[17]

- 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[18].

- Transient classification using multi-variate analysis for better automation of identification.

0.1.6 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[19].

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[20], 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[21] 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[15].

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.

0.1.7 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.

0.1.8 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.

0.1.9 Data Quality

A small working group[22] 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.

0.1.10 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 [23], 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.

0.1.11 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.

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