# 1 Detector Characterization

## Introduction

Data analysis 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 commissioning work is most intense. In the past, long 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 has been collected in AstroWatch mode, the prospects of such surprises have been greatly reduced. In addition, the growing experience of dedicated engineering & science run investigation teams has led recently to early identification of artifacts limiting astrophysical sensitivity, just prior to science running. As discussed below, some of these investigations are focused on interferometer-based detector characterization, such as investigation of line artifacts or environmental disturbancs, while others are focused on analysis-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, controls system software (EPICS), 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).

The commissioning of the LIGO interferometers is described in section **??** and includes invasive stimulus-response detector characterization, in addition to the use of a variety of passive characterization software also used in data running. That work is carried out primarily by LIGO Laboratory scientists, but with significant contributions from other LSC scientists in residence near the Observatories, primarily Columbia, Florida, LSU, Michigan & Oregon. In addition, there is considerable End-to-End interferometer simulation work carried out by LIGO Laboratory scientists, with assistance from other LSC institutions (Penn State, Southeastern Louisiana, Florida, Columbia?). These simulations have provided insight to commissioners on servo control design and on sources of non-linear noise, as discussed in section **??**.

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

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

## 1.1 Software Infrastructure

The interferometer controls system based on EPICS software[**?**] 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 literally thousands of recorded data channels that permit later reconstruction of conditions, if needed. An online Data Viewer[**?**] 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)[?] 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 driver is used for calibration line and artificial hardware signal injection.

The DMT[?] offers an interactive ROOT-driven[?] environment for exploration and algorithm development and a background-process environment for 24/7 monitoring. Most DMT detector characterization is carried out via the 24/7 background monitors, which have been written or are being written by scientists from the LIGO Lab, Columbia, Dominguez Hills, Florida, Hobart / William Smith, La. State, La. Tech, Loyola, Michigan, McNeese, Oregon, Penn. State, and Wash. State. 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 wide 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[?]. Many of these offline studies typically work data products (e.g., trends or triggers) produced by programs upstream in a pipeline.

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. The data reduction is carried out by LIGO Lab scientists, with channel and decimation selections coordinated by the Oregon group.

## 1.2 Calibrations

The 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 Team responsible for this essential work includes LIGO Laboratory scientists at Hanford, Livingston, MIT and Caltech, as well as scientists from LSU and Milwaukee. A dedicated Calibration Review Committee provides advice and vetting of this work.The Calibration Review Committee's results are posted and documented on a web page[**?**] available to the Collaboration, as well as recorded in the electronic logs, software repositories, LIGO documents[**?**], and journal publications[**?**].

The calibration procedure has evolved in sophistication since the S1 run, mostly in automation, modeling, and redundant validation methods. The ultimate goal is to provide a calibration 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 representing strain as a function of time). The first has been the traditional method used in S1-S4, but recent progress in applying the frequency-domain models to a time-domain calibration "h(t)" (Milwaukee)[**?**] gives strong promise that at least some LIGO S5 analysis efforts can be carried out in the time domain, allowing some streamlining of analyses and reducing the chance of error from multiple calibration implementations.

Estimation and reduction of the errors in the calibration data products has been a major part of the effort in recent years. An important objective yet to be achieved is to obtain calibrations with a $\sim$1% error in magnitude and $\sim$1 degree in phase (for the response function in the frequency domain); new methods and better measurement techniques are being developed to achieve this goal. The error estimation for and validation of the time-domain calibration remains one of the critical tasks to be finished in the next year.

When the detector reaches a stable hardware configuration for S5 and beyond, a secondary but also very important goal is to calibrate the "other" detector data streams that can be interpreted as changes in relative distances between the mirrors. These channels are often used to diagnose transients in the detector, which can then be used to "veto" gravitational wave candidates arising from the data analysis. However, this can only rule out a false dismissal if these channels are calibrated in meters and shown to be inconsistent with the presence of true gravitational waves.

There has been a very fruitful exchange of ideas and methods with the people performing the calibration of the GEO detector, and a similar exchange is now starting with the TAMA detector; we expect the same to happen with the VIRGO detector when it reaches a more mature state.

## 1.3 Timing

Verifiable and closely monitored timing performance of the detectors, at the $\mu$s level, is essential for reliable data analysis, as results are based on coincidence between gravitational wave detectors. Continuation of timing verification studies and development of timing performance diagnostics tools are therefore mission critical for both LIGO and Advanced LIGO. It is important to have a primary system and an independent verification system that both deliver the required accuracy. For reference, to detect a 2-kHz coincidence signal (well within the LIGO band) with a phase mismatch between detectors no worse than $5^\circ$ requires a timing precision better than $\pm 7\mu$s. The Timing Stability Team responsible for ensuring timing accuracy includes scientists from Columbia and the LIGO Observatories.

Current LIGO timing is based on a network of independent Global Positioning System (GPS) based clocks. These provide all necessary timing signals for data taking. A quartz oscillator running at 224Hz is phase locked to the GPS's 1 pulse per second (1PPS) signal and serves as the main clock signal for the analog to digital converter (ADC) and digital to analog converter (DAC) boards. The end-to-end accuracy of the sampling process on the $\sim$ 100 ns level. To ensure perfect timing performance, sharp ramp and IRIG-B signals, that are precisely aligned with the GPS second, are read in and evaluated by a DMT monitor (Caltech, Columbia) in near real time. The interferometer length sensing and control software also incorporates several internal consistency and synchronization checks.

Timing monitoring has proven critical in the past, in catching various faults ranging from hardware failures through firmware bugs to software errors/glitches. It has also become apparent, from the built-in limitations and fault history of the GPS based timing system, that one cannot simply rely solely on a single timing solution/system to achieve the desired redundancy in detector timing. Therefore, in 2003 a second independent timing system, based on a caesium clock, was incorporated and installed to complement the existing GPS-based system. It can also provide a NIST traceable calibration of the absolute timing of the LIGO detectors.

At the moment, the most important detector subsystems are monitored and their timing accuracy verified in redundant ways. There are other subsystems, however, including parts of the angular sensing and control (ASC) and physical environmental monitoring (PEM) system, that are not monitored with the same margin of safety. Equipping and monitoring the timing accuracy of all subsystems is highly desirable, a responsibily the Columbia group has taken on. Lesson learned will be applied to the design of the Advanced LIGO timing system.

## 1.4 Glitch Investigations

The largest detector characterization investigation team (led by MIT) carries out studies of interferometer “glitches”. Composed of experimentalists and analysts, the team has broad expertise; its work is closely coupled to the burst and inspiral searches.

The short-term goal of the Glitch Investigation Team 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 team 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 auxiliary 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;
- Study of environmental couplings at all sites.

These goals are pursued both online and offline:

1. During science runs, the Glitch Team is committed to a quasi-online (through daily reports) analysis of transients identified in the gravitational wave channel and on auxiliary channels (e.g. KleineWelle triggers) and of the output of monitors such as BurstMon. This was accomplished, during S4, through participation in scimon shifts at the site, active work off-site and frequent teleconferences.

2. In the offline analysis, as new data quality flags and event candidates are produced, the team explores their correlation in order to establish which data quality flags and veto strategies are appropriate for burst and inspiral searches.

The group's activities, based on S4 investigations and projected for S5 are listed below.

- Definition of data quality flags (typically contributed by experimentalists, primarily scientists from LIGO Lab, LSU, Oregon, and Carleton).
- Comparison between data quality flags and event candidates for burst and inspiral (LIGO Lab, Syracuse, LSU, Carleton).
- Online and offline production & analysis of triggers produced by KleineWelle (offline DMT program - MIT).
- Event-by-event and statistical exploration of vetoes for inspiral candidates (LSU & Carleton).
- Evaluation of glitch veto safety by studying hardware signal injections (Syracuse).
- Independent burst veto search, using the BlockNormal event trigger generator, with the same frequency band is explored in the gravitational wave and in the auxiliary channels[**?**] (Penn State).
- Identification of stationary intervals of data (Penn State).
- Exhamination of H1-H2 coincidences for a better understanding of some of the common Hanford environmental disturbances (MIT, Syracuse)

Where more work is needed:

- Understanding of the coupling between a larger (more exhaustive) number of channels than the current set.
- Improvements in the automation of the analysis, for a faster turnaround during longer data runs.
- Improved tools for hand-scanning of loudest events.

- Transient classification (work is starting, in this direction, with a proposal for a multivariate classification of triggers, using parameters like bandwidth and shape to relate burst event candidates and auxiliary channel triggers and define potential veto strategies).

## 1.5 Environmental Disturbances

Environmental disturbances of the interferometers include primarily 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 Oregon, LSU, Michigan, Columbia, and Florida, as part of commissioning. Acoustic mitigation has played an especially critical role in lowering interferometer noise floors, an effort led by Oregon.

Environmental disturbances may be manifested as direct "glitches" or "lines" through linear couplings to the interferometer, for sources with characteristic frequencies in the LIGO band of sensitivity. Or strong lower-frequency sources may enter the LIGO band indirectly through non-linear upconversion, e.g., sidebands / shoulders on 60 Hz harmonics. Scientists from the Observatories, Oregon, LSU, Carleton and Syracuse have investigated sources of environmental glitches, with scientists from the Observatories, Oregon, Carleton, and Michigan focused on understanding the sources of steady-state environmental couplings, particularly lines. A team led by Penn State has taken responsibility for finding spectral lines in the gravitational wave data channel and compiling a web-based catalog of known sources, using the results of many studies. 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 Carleton group. The Penn State group is exploring a data mining method for finding hidden correlations.

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 (Caltech) to quantifying frequencies and time intervals for which H1-H2 correlations are strongest (see section **??**). Simlarly, the Oregon group has examined closely possible inter-observatory correlated environmental noise, both steady-state and transient. As interferometer sensitivities continue to improve, these correlation studies will become increasingly important.

Non-linear noise upconversion is a pervasive problem, especially in the 50-100 Hz range and requires more attention. A set of DMT interactive and background monitoring bispectrum tools for their study has been developed by the Hobart / William Smith and LSU groups, but help in applying those those to understanding data artifacts is needed. The Penn State group is exploring an alternative, computationally cheap algorithm for detecting evidence of non-linear couplings.

## 1.6 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 ($\sim$ 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. This effort includes scientists from MIT, Embry-Riddle, Hanford, and Florida.

Initial LIGO suspension thermal noise is being characterized using violin mode Q measurements (MIT & Embry-Riddle). In the process of collecting data on all optics, it became apparent that the Q's were changing on the same mode of the same optic over time. This called seriously into question whether the measured Q's were providing information on the mechanical loss relevant to thermal noise calculations. There are a number of theories about why this could be (influence from feedback loops, physical changes in the wire and/or clamps, recoil damping with the suspension cage) which are being investigated. Unresponsiveness of the Q's to changes in interferometer power make the feedback explanation unlikely, but not completely ruled out. The replacement of ITMx in LHO 4k is allowing some tests of the clamping theory. The most likely explanation currently, however, is recoil damping with the suspension cage. Modeling suggests this is possible, with laboratory research on this subject to begin soon (Embry-Riddle).

A duplicate suspension cage from LLO will be measured in air for both modal frequencies and Q's. This will allow more realistic parameters to be put into the model. Depending on the results of this, experiments changing the mass distribution and/or stiffness of various elements of the cage will be tried to see if the recoil effect can be reduced or eliminated. If this effect can be eliminated, each optic will have its violin modes remeasured to determine the true thermodynamic loss that predicts thermal noise. Further experiments on the test cage can also be done on the wires and clamping, to see if the loss can be improved. If feedback proves to be a contributor to the violin mode Q's, further measurements at the sites will be necessary. Measurements of Q vs loop gain will allow the loss at zero gain to be extrapolated.

Long-term tracking of violin mode strengths and drifts via a DMT monitor has been provided by the Florida group, which has also examined modelling of higher-order violin harmonics.

## 1.7 DMT Monitor Development

After many years of development, the suite of online DMT monitors is approaching maturity. Existing programs monitor the controls state of the interferometers (Michigan, Caltech), environmental noise (LSU, Caltech, Hanford, Oregon, Dominguez Hills), non-Gaussianity (Caltech, Hobart / William Smith), line contamination (Florida, Michigan), glitchiness and non-stationarity (Oregon, Florida, Caltech, Louisiana Tech., Michigan), overflows and faulty ADC's (Caltech, Columbia), timing stability (Caltech, Columbia, Hanford), spectral color (Caltech). In addition, several monitors produces astrophysically motivated figures of merit (FOM's) for display and archiving: sensitivity to inspiral mergers (Penn State, Caltech), sensitivity to bursts (Florida), sensitivity to stochastic background (Loyola, Livingston), and sensitivity to pulsars (McNeese). Caltech scientists have also implemented an interface to online astrophysical search engines for near real-time display of search results in the control room.

Nonetheless, there is need for additional online monitoring. Enhancement of the burst, stochastic, and pulsar sensitivity monitors above is underway for S5. A non-stationarity monitor based on median baseline tracking is under development (Brownsville, AEI), along with monitors of servo instability (Washington State, Michigan). Dedicated online monitors are also in development for monitoring glitches from liquid nitrogen dewar creaks (Oregon), acoustic noise from aircraft (Michigan), and signals from cosmic-ray scintillators (Oregon).

Most of the underlying DMT infrastructure has been developed at Caltech, with assistance from Hanford in graphical support, from Oregon in histogramming support, from Michigan in channel state conditions, and from MIT in filters and Grid support. Columbia is now active in enhancing web support and developing more sophisticated general-purpose spectral monitoring tools. Michigan and Milwaukee are developing a general-purpose h(t) interface for DMT monitors, to facilitate development of new astrophysical FOM monitors.

## 1.8 Data Quality

A team led by Caltech and Michigan scientists compiles information from DMT monitors, from the other various investigation teams, 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". An important ongoing effort led by Caltech and Milwaukee is the incorporation of DQ information into a database and the provision of filling and querying tools, to eliminate present human bottlenecks (see section **??**).

## 1.9 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, and making decisions on when to take science data vs make adjustments / repairs. Although many scimons have carried out their duties admirably, catching detector problems early on and diagnosing them, others have been less effective. In many cases, scimons have taken expert shifts with little training experience. As we enter the S5 run, it is more important than ever that scimons be alert to troubles and be prepared to carry out on-the-fly investigations, supported by scientists in search groups scanning the data on a daily basis. Given the enormous financial and human investment in the LIGO interferometers, there is an obligation to ensure we record the highest quality data possible on any given day.

It is planned for S5 and beyond that scimons take substantially longer blocks of shifts, both to reduce travel cost overhead from multiple trips, and to become thoroughly acquainted with known detector pathologies and with investigation tools during those blocks. Hence it is likely that postdocs and graduate students will take a disproportionate number of the scimon shifts. It is hoped that a number of LSC groups will choose to station young scientists at the Observatories for long periods, not only to provide scientific monitoring, but also to ensure good training of successive generations of gravitational wave scientists.

Another important aspect of data run support is injection of simulated astrophysical signals into the detector hardware, to validate data analysis pipelines with high confidence. Caltech and Observatory scientists have provided the manpower to set up the injection infrastructure and carry out the injections during data runs. That effort has been supported by signal injection software creation by scientists at Milwaukee, Washington State, AEI, and Glasgow. In addition, environmental signal injections of a wide variety have been carried out by Oregon and Observatory scientists, with recent assistance from Syracuse. 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.

*(There is more one can say about data run support; there is the work of the operators, the stationing of experts on call, the recording and archiving of full and reduced data, observatory operations infrastructure, data access support, shift organization, web documentation, etc. Do these items belong in the White Paper? Should there be one or more extra sections / subsections on some of these topics?)*