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LIGO Laboratory / LIGO Scientific Collaboration

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LIGO Laboratory Activities for LSC MOU Planning

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LIGO Laboratory Report on Data Analysis Activities in FY2008 and Plans for FY2009

S. Anderson, S. Ballmer, E. Katsavounidis, M. Landry, and A. Weinstein for the LIGO Laboratory

1 Introduction

We report on the participation and accomplishments of LIGO Laboratory personnel in the LSC-Virgo Burst, CBC, Stochastic, CW, Detector Characterization, and Computing groups during FY 2008 (September 1, 2007 – August 31, 2008). We also outline the plans for such participation and work to be carried out during the upcoming FY 2009 (September 1, 2008 – August 31, 2009).

In what follows, Laboratory members *in italic* indicate FY2008 employees that will no longer be with the Laboratory on September 1, 2008. Laboratory members **in bold** indicate employees who will be assuming a Laboratory position some time in FY2009.

2 Burst Searches

LIGO Laboratory members who have been active in the LSC burst working group in FY2008 include:
L. Blackburn, *G. Brunet*, K. Cannon, S. Chatterji [1], J. Garofoli, D. Hoak, B. Hughey, E. Katsavounidis, J. Markowitz, B. O'Reilly, F. Raab, N. Robertson, A. Searle, *Y. Shi*, L. Stein, A. Stuver, C. Torres, S. Whitcomb, I. Yakushin, and J. Zweizig.

[1] joint appointment with INFN-Rome-1

Katsavounidis is one of the group's co-chair (with P. Shawhan, U Maryland and Patrice Hello, Orsay). O'Reilly and Robertson are members of the group's analysis review committee. Cannon is a member of the focused review committee on the S5 SGR search. Raab serves on the LSC detection committee as a burst group representative. Blackburn, Chatterji and Zweizig served in 2 software review committees (KleineWelle and Q-pipeline.)

The broad areas of burst group activities where LIGO Laboratory members have contributed during FY2008 are:

- all-sky searches for unmodelled bursts,
- externally triggered searches,
- astrophysically and cosmologically motivated searches,
- detector characterization, data quality and veto investigations,
- algorithmic development for hierarchical and fully-coherent searches,
- LSC-Virgo joint analysis activities.

More specifically:

- Blackburn, Chatterji, Hughey, Katsavounidis, Yakushin and Zweizig contributed in the S4 and S5 all-sky searches for unmodelled bursts by providing triggers, post-processing analysis, data quality and vetoes. They also contributed in bringing the S5-year-1 untriggered search to closure. Chatterji is leading the S5 publication covering the first year of the S5 run.
- Hughey led the search for high-frequency bursts with data from the S5-year1 run.
- Blackburn, Cannon, Chatterji, Katsavounidis and Yakushin maintained a near real-time search for transients during S5 using the KleineWelle, Q-pipeline and WaveBurst algorithms.
- Blackburn, Chatterji and Katsavounidis maintained an online analysis of data from Astrowatch run using the KleineWelle and Q-pipeline algorithms.

- Chatterji co-led the S5 glitch investigations within the burst group; Blackburn, Garofoli, Hoak, Katsavounidis, O'Reilly, Raab, Stein and Zweizig also contributed to this by developing infrastructure as well as pursuing investigations on a day-by-day basis. Work emphasized in study of outlier events (coincident among instruments as well as on a single-detector basis), correlations with auxiliary interferometric and environmental channels and the study of overall data quality and vetoes.

- Cannon developed a direction-sensitive burst search looking for evidence of gravitational-wave bursts originating from the direction of the galactic core.

- Cannon, with collaborators, worked for a search for gravitational-wave bursts originating from cosmic strings in the LIGO S4 data set. This search and its results are currently undergoing review by the LSC.

- Markowitz and Katsavounidis in collaboration with former Lab members Cadonati and Zanolin, developed stand-alone source reconstruction algorithms and experimented with its application to sample data for pointed-searches and gravitational-wave sky maps production.

- Yeming Shi and Katsavounidis in collaboration with former Lab member Zanolin, developed a distributional analysis for gravitational wave bursts and compared its performance to counting-based experiments.

- Brunet completed his Master's thesis on a study of the LIGO instrument sensitivity using S5 hardware injections.

- Chatterji, with help from Stein, developed Q-Pipeline data analysis infrastructure for the S5 searches.

- Chatterji, Searle and Stein are core contributors to the Ω pipeline development.

- Searle developed standard likelihood coherent analysis and Bayesian analysis modules within the Ω pipeline.

- Yakushin analyzed LSC-Virgo data on the Joint-Week-1 project.

- Blackburn led the detection checklist project.

The following LIGO laboratory personnel are expected to be active in the burst group during FY2009: **P. Ajith**, L. Blackburn, K. Cannon, S. Chatterji [2], F. Grimaldi, D. Hoak, B. Hughey, E. Katsavounidis, *J. Markowitz*, B. O'Reilly, F. Raab, N. Robertson, A. Searle, L. Stein, A. Stuver, C. Torres, S. Whitcomb, I. Yakushin, and J. Zweizig.

Their intended contributions to burst search group work will be as follows:

- Blackburn, Cannon, Chatterji, Hughey, Katsavounidis, Stuver, Yakushin and Zweizig will continue to contribute to the S5 searches for untriggered bursts by providing triggers, post-processing analysis, data quality and vetoes. They will also contribute in bringing the full S5-VSR1 untriggered search to closure and publication.

- Cannon will pursue directional searches for gravitational wave bursts.

- Hughey and Katsavounidis in collaboration with former Lab member Zanolin will contribute to the search for high-frequency bursts; will also bring the S5-year-1 search to closure and publication.

- Blackburn, Chatterji, Katsavounidis will continue maintaining through the remaining of Astrowatch run an online analysis, detchar and search for transients using the KleineWelle and Q-pipeline algorithms.

- Searle will complete the testing and validation of the fast Bayesian coherent bursts analysis. Potentially use in the S5Y2 search as a follow-up to incoherent Omega search. Will also introduce glitch models that will improve robustness.

- Ajith will pursue Binary Black Hole searches using burst detection methods. Will lead developing of pipelines for injecting phenomenological inspiral, merger and ringdown waveforms fromm non-spinning binaries as well as leading harmonics waveforms from spinning binaries with no precession.

- Chatterji will co-lead the glitch investigations within the burst group.

- Stuver will be point of contact for GravEn maintenance.

[2] joint appointment with INFN-Rome-1

- Markowitz, with Katsavounidis, will complete the search for coincidence glitches from Sco-X1 as well as other LMXBs and Black Hole candidates observed in coincidence by the Rossi X-ray Transient Explorer (RXTE).

- Blackburn, Cannon, Chatterji, Grimaldi, Hughey, Katsavounidis, Searle, Stein, Stuver, Yakushin, and Zweizig will contribute in the implementation and carry out the S6-VSR2 near real time burst searches.

- Hughey, Katsavounidis and Stein, will develop Target-of-Opportunity proposals to follow up electromagnetically outstanding burst events during S6/VSR2 as well as carrying out collaborative analysis with data from non-electromagnetic detectors and relevant external collaborators.

3 CBC Searches

The following LIGO laboratory personnel were active in the CBC group during FY2008: B. Daudert, D. Fazi, *L. Goggin*, K. Hodge, D. Keppel, A. Sengupta, and A. Weinstein. Their specific contributions to CBC search group work are as follows:

- S5 1st-year low-mass CBC search [Keppel]:
  Keppel led the S5 1st-year low-mass CBC search, focusing on the post-pipeline processing and upper limit generation. This work is nearing completion. Keppel and Weinstein have a maturing draft of the S5 1st year low mass paper.

- S5 high-mass CBC search [Sengupta]:
  Sengupta continued his work on the S5 high-mass CBC search, including the development and tuning of chisq, rsq, e-thinca and trigscan, and running the search on playground and injections.

- e-thinca and trigscan [Sengupta]:
  Sengupta continued the development of this code, submitted the e-thinca paper and is writing the trigscan paper.

- S4 ringdown search [Goggin, Weinstein]:
  Goggin brought the S4 ringdown search to conclusion, completed the review process (for the most part), completed her thesis, and has now

moved on to UWM, where she will prepare the publication and contribute to the S5 ringdown search.

- Improved detection statistic [Hodge]:
  Hodge continued development of an improved detection statistic for inspiral searches, making use of multivariate classification algorithms. She is preparing to make it accessible to all inspiral analyses as part of the follow-up pipeline.

- PTF spin template search [Fazi]:
  Fazi (in collaboration with Syracuse and Caltech TAPIR) continued development of the PTF code and has developed a spinning-CBC search applied to S5 data. He began focusing on regions of parameter space where spin templates perform better than non-spin templates.

- Committees [Weinstein, Cannon]:
  Weinstein served as chair of the Inspiral Review Committee through Nov 2007, and has served as co-chair of the CBC group since Dec 2007. Cannon served on the S4 ringdown search review. Weinstein contributed (as reviewer) to the preparation of the S3/S4 joint search paper, the GRB070201 paper and the S3 SBBH paper.

- Grid development [Daudert]:
  Daudert continued development of OSG infrastructure in support of inspiral group analyses and began testing the ihope pipeline on OSG. She reports to DASWG and at the CBC code call.

The following LIGO laboratory personnel are expected to be active in the CBC group during FY2009: B. Daudert, K. Cannon, D. Fazi, C. Hanna, K. Hodge, D. Keppel, **A. Parameswaran**, A. Sengupta, B. Tucker, and A. Weinstein. Their intended contributions to CBC search group work will be as follows:

- S5 1st-year low-mass CBC search [Keppel, Weinstein]:
  Keppel will continue to lead, and bring to conclusion and publication, t he S5 low-mass CBC search. Weinstein will help with preparing the paper, and contribute to the S5 2nd-year search.

- S5 high-mass CBC search [Sengupta, Hanna, Tucker, Parameswaran]:
  Complete the full-S5 high-mass search, using ihope, contribute to the

follow up of detection candidates, set upper limits, write and publish paper (in collaboration with the rest of the CBC group).

- IMR waveform and search development [Hanna, Parameswaran]:
  Work on the IMR effort, joint with the burst group. Test current pipeline's efficiency to IMR waveforms. Continue development of AEI hybrid waveforms within LAL for use in CBC and burst searches. Keep the high mass search up-to-date with developments in NR.

- S6 low-latency pipeline [Cannon, Hanna]:
  Hanna will develop "online" low-latency CBC pipeline, and online h(t) generation, in collaboration with CBC group and DASWG. Cannon will continue to maintain and develop the Onasys online data analysis system, assuming it plays a major role in S6 online analysis.

- e-thinca and trigscan [Sengupta]:
  Sengupta will develop and implement SNR dependent e-thinca, to improve our sensitivity. Submit the trigscan paper ASAP.

- Improved detection statistic [Hodge]:
  Hodge will complete development of an improved detection statistic for inspiral searches, making use of multivariate classification algorithms. Fully implement it within the common pipeline infrastructure. Learn how to use it to improve our signal/background separation and sensitivity. We expect this work to be ongoing as we learn how to incorporate more of the available information.

- Signal-based vetoes [Hanna, Sengupta]:
  Hanna will assist in adoption of template-bank veto and other signal-based vetoes that he has developed and implemented in LAL. Sengupta will develop a new chi-square shape veto to see if this helps our multi-dimensional classification schemes to distinguish signal from background. Sengupta will develop the fast chisq calculation for use in low-latency online search.

- PTF spin template search [Fazi]:
  Fazi (in collaboration with Syracuse and Caltech TAPIR) will continue development of the PTF code and search, identify regions of parameter space where spin templates perform better than non-spin templates, and apply the search algorithm to S5 data.

- Parameter estimation [Cannon]:
  Cannon will work on determining the accuracy of the GW detector network to identify the sky location of an inspiral event.

- h(t) validation [Sengupta, Hanna, Stuver, Betzwieser]:
  Continue work on validating and quantifying the accuracy of the h(t) data.

- Pipeline and Grid development [Daudert, Hanna, Cannon]:
  Daudert and Hanna will continue development of the ihope pipeline, as well as the OSG infrastructure and testing of the ihope pipeline on OSG, in collaboration with DASWG and the LIGO Grid R&D group (Blackburn and new hire). Cannon will continue as librarian for the pyLAL software package, and also continue to provide significant contributions to other LSC software projects such as LAL, LALApps, Glue, and libmetaio.

- Service [Weinstein, Cannon]:
  Weinstein will continue to serve as co-chair of the CBC group. Cannon will continue to serve as chair of the S4 ringdown search review till completion.

4 Searches for Stochastic Background

LIGO Laboratory members who have been active in the LSC stochastic working group in FY2008 include: S. Ballmer, P. Fritschel, V. Frolov, A. Lazzarini, R. Ward, and R. Weiss.

- Ballmer is one of the group co-chairs.
- Ward continued to work on the S5 radiometer search.
- Ballmer led the code development for a multipole analysis of the stochastic background. A methods paper is in preparation.
- Ballmer helped in the L1-H1 S5 all-sky stochastic search.

Laboratory members who expect to be active in the stochastic search during FY2009 are: S. Ballmer, A. Lazzarini, S. Mitra, R. Ward, and R. Weiss.

- Ballmer will help finish and publish the baseline L1-H1 plus L1-H2 S5 all-sky stochastic search.
- Ward will finish the stochastic radiometer search for S5.
- Ballmer will lead the multipole analysis of the S5 data set and its publication.
- Mitra will develop code for collapsing all data on to one sidereal day, which will allow running any stochastic analysis in much shorter time.

5 Searches for Continuous Wave sources

LIGO Laboratory members who have been active in the LSC continuous wave working group in FY2008 include: J. Betzweizer, M. Landry, G. Mendell, P. Patel, F. Raab, and P. Willems.

- Landry co-chaired the LSC Continuous Wave group, first with M. Papa (AEI), then later with G. Woan (Glasgow). Landry's term as co-chair ended in June 08. Landry also serves on the detection committee.
- Raab and Willems are part of the Continuous Wave group review committee.
- Mendell helped write and see the S4 PSH (Powerflux-Stackslide-Hough) paper through to publication in Phys. Rev. D.
- Mendell completed the implementation of the Stackslide code under the Einstein@home platform.
- Betzwieser completed the S5 coherent F-statistic analysis to search for gravitational waves from the Crab pulsar. The null-result and upper limits were written up and accepted for publication in Ap. J. Letters.
- Patel is working on his Ph.D. thesis research within the Continuous Waves group. He has completed the coding of the new re-sampling analysis that more directly implements the method detailed in seminal F-statistic paper (Physics Review D 58 (1998) 063001). Validation of the code is essentially complete. Patel has assessed targets for an S5 wide-parameter search.

- Mendell continued work on Fscan spectra of S5 data.

Laboratory members who expect to be active in the continuous wave search during FY2009 are: J. Betzweizer, M. Landry, G. Mendell, P. Patel, F. Raab and P. Willems. Contributions to the group in the following year will include:

- Betzweizer will expand the parameter space of the S5 Crab analysis, and begin a new search employing the Patel resampling code.
- Landry will work on line identification and mitigation.
- Mendell will resume S5 analyses with the Stackslide algorithm, debugging the implementation under the Einstein@home platform, and begin analyzing S5 data.
- Mendell will prepare SFTs for the CW group once V4 calibrated data are available.
- Patel will complete a search of nearby globular clusters with the resampling code.
- Willems and Raab will continue to serve on the CW review committee.

6 Collaboration software infrastructure

LIGO Laboratory members who have been active in Collaboration software infrastructure development work in FY2008 include: S. Anderson, M. Araya, K. Blackburn, C. Cepeda, K. Cannon, B. Daudert, F. Donovan, P. Ehrens, C. Hanna, *B. Johnson*, V. Kondrashov, D. Kozak, E. Maros, G. Mendell, M. Pedraza, L. Wallace, I. Yakushin, J. Zweizig.

- Cannon continued as one of the two maintainers of the Onasys online data analysis system used throughout S4 and S5 for online h(t) production, kleineWelle veto trigger production, SFT production, and online BNS trigger production among other things.
- Cannon operated as project library for the pyLAL software project, and provided significant contributions to several other LSC software projects including Glue, LAL, LALApps, and libmetaio.

- Zweizig continued to develop and support the DMT infrastructure
- Zweizig started developing the next generation Network Data Server tool for distributing real-time IFO data.
- Maros continued to provide LDAS software support, including updates to the FrameCPP I/O library to support our collaboration with Virgo.
- Blackburn and Daudert continues to offer support for the Open Science Grid and establishing collaborative work between LSC analysis efforts and this external Grid resource.
- Anderson provided leadership in establishing the Condor-LIGO working group to provide functional enhancements to Condor to support large scale LSC analysis pipelines.
- Mendell managed the LIGO Data Grid client and server software bundle, which is used by all LSC data analysts to access computing resources.
- Hanna investigated production running of the CBC analysis using pegasus to enable leveraging resources beyond the LDG.
- Kozak managed the PByte frame archive and distributing data.
- Ehrens operated as grid manager and providing web application and version control systems support.
- Yakushin managed the segment database and replication.
- Araya developing new document control system.
- Kondrashov supporting ligo.org web site.
- Yakushin, Mendell, Johnson, Donovan, Ehrens managed LDAS-MIT, -LHO, -LLO, and -CIT clusters for the LIGO Data Grid.
- Wallace, Pedraza and Cepeda provided computing support for LIGO Caltech group and both computing and communications support for numerous LSC meetings.

LIGO Laboratory members who intend to be active in Collaboration software infrastructure development work in FY2009 include: S. Anderson, M. Araya, K. Blackburn, C. Cepeda, K. Cannon, B. Daudert, F. Donovan, P. Ehrens, C. Hanna, V. Kondrashov, D. Kozak, E. Maros, G. Mendell, M. Pedraza, L. Wallace, I. Yakushin, J. Zweizig.

- Cannon will continue to maintain the Onasys online data analysis system, given my expectation that it will be a key component in the online data analysis efforts of the CBC working group during S6.
- Cannon will continue as the librarian for the pyLAL software package, and also continue to provide significant contributions to other LSC software projects such as LAL, LALApps, Glue, and libmetaio.
- Zweizig will continue to support the DMT infrastructure for Enhanced LIGO control room monitors.
- Zweizig will complete and support the development of the next generation Network Data Server tool for distributing real-time IFO data.
- Maros will continue to provide LDAS software support, including another Frame Specification update for VSR2/S6, packaging of the diskcacheAPI methods for use in other data discovery tools, e.g., LDR, and providing additional language interfaces to the frame I/O library frameCPP.
- Mendell will support the generation and distribution of h(t) data during S6 and continue to manage the LIGO Data Grid client and server software bundle, which is used by all LSC data analysts to access computing resources.
- TBD person will support the provisioning of cluster resources during S6 to give guaranteed numbers of compute cycles to individual searches as determined by the collaboration Science priorities.
- Blackburn and Daudert will continue to provide leadership to the Open Science Grid and porting of LSC analysis code to this Grid resource.
- Anderson will continue to lead the Condor-LIGO working group to identify and work on technical solutions for LSC analysis issues with the Condor job management system.

- Hanna will continue developing and supporting running of the CBC analysis using more advanced grid tools that allow LSC access to resources beyond our own internally managed LDG clusters.
- Kozak will continue to manage the PByte frame archive and distributing data.
- Ehrens will continue to operate as gird manager and providing web application and version control systems support.
- Yakushin will continue to manage the segment database and replication.
- Araya will continue to deploy and support new document control system.
- Kondrashov will continue to support ligo.org web site.
- Yakushin, Mendell, Donovan, TBD will continue to operate LDAS-MIT, -LHO, -LLO, and -CIT clusters for the LIGO Data Grid.
- Wallace, Pedraza and Cepeda will continue to provide computing support for LIGO Caltech group and both computing and communications support for numerous LSC meetings.

7 Detector Characterization

LIGO Laboratory members who have been active in the LSC detector characterization group in FY2008 include: L. Blackburn, S. Chatterji, J. Garofoli, D. Hoak, E. Katsavounidis, B. O'Reilly, F. Raab, L. Stein, A. Stuver, C. Torres, and J. Zweizig.

More specifically:

- Zweizig led the LIGO Laboratory Detector Characterization work. He developed and maintained the Data Monitor Tool (DMT) software infrastructure. DMT provides the software basis on which most of the detector characterization tools rely on. Zweizig provided coordination (including system integration, release, online monitor configuration management and helpdesk) of DMT software all across the LSC.

He also began development of the NDS2 server will will enable remote use of control room tools (and other tools) on real-time and archived data.

- Blackburn, Chatterji and Stein provided software infrastructure complimentary to the DMT one for the purpose of detector characterization. This included the KleineWelle and Q-Pipeline algorithmic library.
- Chatterji co-led the glitches working group of the Detector Characterization group.
- Blackburn, Chatterji, Garofoli, Hoak, Katsavounidis, O'Reilly, Raab, Stuver, Torres, and J. Zweizig contributed in the day-by-day investigations for the purpose of establishing the quality of data and vetoes. Defined data quality flags and vetoes.

In FY2009, L. Blackburn, S. Chatterji, D. Hoak, E. Katsavounidis, B. O'Reilly, F. Raab, L. Stein, A. Stuver, C. Torres and J. Zweizig expect to be active in Detector Characterization work along the same line of activities perfomed in FY2008. Particular emphasis will be given in providing support to the near real-time S6 searches including exploitation of the NDS2 and early production of data quality segments and an online h(t) stream. Torres will install the tracksearch pipeline software at lab sites (LLO first then LHO), with the intent to compliment existing tools such as DMT, QScan, KleineWelle, and etc. The tracksearch tool will aid in detector characterization, for the purposes of data quality flag creation and veto determination.

LIGO Laboratory Activities for LSC MOU Planning - July 2008

1. Simulation and Modeling

Accomplishments

Static Interferometer Simulations

There were two major developments in the past year. The first is the development of a new simulation tool, SIS, for advanced LIGO and the other is the updating of an existing simulation tool, MITFFT, for Enhanced LIGO.

SIS can now simulate a coupled cavity, FP arm with a short cavity and realistic optics characteristics. SIS was used to study the design of the advanced LIGO optical configuration and was used to demonstrate that the stable recycling cavity configuration is more robust than the marginally stable cavity against various imperfections, including curvature mismatches and wedge angles. For the stable cavity, in order to make the round trip loss acceptably small, it was shown that the beam size in the Michelson cavity needed to be smaller than the design value and an acceptable design of the arm cavity parameters were then calculated. MITFFT was updated, used to analyze the mode matching observed on the enhanced LLO interferometer, and has led to a possible interpretation of the observed large mode mismatch.

Optickle, Looptickle and Pickle

There has been continued development of the matlab based interferometer sensing and controls tools, Optickle, Looptickle, and Pickle. These tools are used for frequency-domain numerical analysis of, respectively, length sensing of all length and input light degrees-of-freedom; incorporation of feedback loops; alignment degrees-of-freedom. A unique feature of these tools is that they include the effects of radiation pressure/torque.

Parametric Instability

Recently there has been renewed emphasis on the Parametric Instability problem with respect to the final Advanced LIGO design. Several aspects of PI have been re-considered or expanded upon in response:

> A detailed study, continuing as a component of SURF 2008, to clarify the relationship between the three existent theoretical derivations of the threshold condition (**R** value). The first is the coupled equivalent oscillator eigen-solution method of ~Braginsky/Vyatchanin. The second is the linear filter equivalent model (e.g. Simulink) of the process as a feedback loop, where the minimum plant gain causing a loop instability is interpreted as a PI (and the Bode plot frequency at which this occurs being the eigen-frequency). The third is the physical power balance condition of Kells (LIGO-T060296) which arrives at the correct R value but without identifying any eigen-frequency.
>
> To date all analyses of the PI threshold (R value) have been static (exactly constant system parameters, such as the acoustic mode frequencies and cavity g factors). The consequence of slow parameter drift has been a question of interest. Typical PI exponentiation times are long (minutes-hour) while significant characterstic drift times might be short (e.g., time for acoustic frequency to drift

~line width). This makes it plausible that the PI "feedback" mechanism may be diluted by plant parameter drift/dither.

Double Cavity Eigenmodes
COC PDR preparation triggered intense discussion around the Caltech LIGO Lab during the winter of 2008 of the nature of modes in [distorted] partitioned cavities. Subsequent systematic analysis of the eigen-modes of both the Simple Michelson cavity (really a summary exposition of previous work by Kells and D'Ambrosio), and of the double coupled linear cavity (prototype of a single recycled arm cavity) was carried out. This has been completed in LIGO-T080046, where the importance of new possible degeneracies (due to the additional DOF brought into play via partition) is emphasized. Qualitatively new modal configurations become possible which cannot be extrapolated from single cavity concepts.

Planned Work
The LIGO Laboratory simulation and modeling development work will focus on specifying the main interferometer optical components including: surface figure, scatter, optical absorption and interferometer design in the frequency domain.

In particular the inclusion of alignment was a big step forward, and Pickle is now the favored tool for analyzing the problem of alignment control in the presence of radiation torque-induced instabilities. This problem is currently being studied in the context of Enhanced LIGO, and the effort will transition later this year to study of the Advanced LIGO situation.

The comprehensive PI studies of Bantilan and Kells (T060207) had been outdated by recent refinement in Advanced LIGO arm cavity design. We have begun a resurrection of the machinery used in that study, with the goal of obtaining updated results. Similar results (but not identically modeled) by S. Gras (UWA) have been obtained (S. Gras, D. Blair Elba talk, "Elba20083") which are remarkably consistent with expectation extrapolated from T060207).

2. Reaching the Standard Quantum Limit at Frequencies above 10 Hz

In the area of sensitivity improvement the goal of the research is to reach the Standard Quantum Limit (SQL) in a broad range of frequencies. While it has been shown that this "SQL" is not a real limit to sensitivity, this point at which the motion due to momentum transfer to the test object by the coherent-state sensing photons is equal to the precision of the shot-noise limited position measurement precision at a given frequency is a useful benchmark. To reach the SQL requires the reduction of technical noise sources in the Advanced LIGO interferometer at frequencies above 10 Hz to a level significantly below the SQL, given the Advanced LIGO basic parameters of laser power and optic mass. This will require work in five research areas in which we will work to reduce noise including reducing the coating Brownian. The coating noise dominates the most sensitive region of the interferometer performance and will dominate any decisions about enhancements to Advanced LIGO or any interferometer which might succeed Advanced LIGO. The understanding of these noise sources is our highest research priority over the next five years.

2.1 Coating Brownian Noise

Accomplishments

LIGO Staff and students who have contributed to this work
Caltech: Helena Armandula, Garilynn Billingsley, Eric Black, Tara Chelermsongsak, Riccardo DeSalvo, Bill Kells, Greg Ogin, Ilaria Taurasi, Akira Villar, Hiro Yamamoto, Liyuan Zhang
MIT: Matt Evans, Gregg Harry

Experimental coating thermal noise work in LIGO Lab has focused on issues that may be important for next generation optics with some effort on risk reduction in Advanced LIGO. Some follow-up work at MIT has been done on change in coating mechanical loss with temperature. Previous work had established that tantala does show a noticeable increase in mechanical loss as the temperature rises above room temperature, but it is not enough to cause significant thermal noise increase in Advanced LIGO. Preparatory work was done to study single layer tantala (as opposed to the silica/tantala multilayer coating studied before) and titania doped tantala in the same way.

Q measurements are being made on a sample coated on one side with carbon nanotubes. This is in response to a published report that carbon nanotubes can decrease mechanical loss when coated onto silica. It is also possible that a carbon nanotube coating, being conductive, could be part of a solution to optic charging in a future interferometer, as well.

An important theoretical development was also made in the Lab, headed by Matt Evans. This work more completely describes the expected noise from thermorefractive and thermoelastic effects in coatings, taking into account the correlations of the temperature fluctuations that drive these effects. One important result is that for most materials (likely including silica, tantala, and titania doped tantala, but to be confirmed) there is significant partial cancellation between these effects in the LIGO band, resulting in lower noise from the combined thermorefractive and thermoelastic effects than previously anticipated.

The Thermal Noise Interferometer (TNI) measured samples coated with a thickness optimized tantala/silica coating. This is a test (partially supported by Italian funding) of the noise optimization algorithm developed at Sannio. The results showed the expected reduction in thermal noise, although the comparison is being made between coatings made by different vendors. A planned follow-up with titania-doped tantala/silica coatings coated by the same vendor is expected in September 2008. The TNI also measured coating thermal noise across the face of an optic and saw no change in noise to within 5% and finalized the calibration process so that it is accurate to an estimated 7%. TNI team member Greg Ogin has also participated in taking and analyzing data on dn/dT in tantala, to better estimate thermorefractive noise.

Scatter in tantala/silica coatings has been investigated at Caltech experimentally and with modeling. The initial LIGO coatings have excess scatter caused by point defects which are likely in the coating and not on the surface (like dust). Investigating the cause of this (coating chamber contamination, microcrystals in tantala from annealing, defects in polish, etc) is a high priority for immediate follow-up.

Planned Work

There is a consensus that coating thermal noise will be a limiting source of noise in the frequency region of maximum sensitivity in most future interferometers. Improvement to the detector sensitivity in any foreseeable enhancements to Advanced LIGO and more advanced future detectors will require a decrease in coating noise. The work on thermal noise in coatings is led by the LIGO Laboratory and is deeply embedded within the LIGO Scientific Collaboration (LSC): research directions will be determined by discussions between members of the collaboration. The LSC coating plan is to pursue ways to improve coating thermal noises while maintaining needed optical performance. Better understanding of the causes of mechanical loss and other properties important for sensitivity (Young's modulus, dn/dT, thermoelastic properties, optical absorption, etc) will be pursued to give more guidance to the search for new materials and processes than was possible on the shorter time scale of Advanced LIGO.

Materials studied for Advanced LIGO, including silica, tantala, and titania-doped tantala will be priorities next year, based on familiarity and the theoretical understanding of mechanical loss in silica. This will also allow for risk reduction work on Advanced LIGO coatings, as research is done on less well understood coating properties (notably scatter and Young's modulus). Coated samples will be measured for all important properties in both the Lab (MIT, Caltech) and the LSC (Glasgow, Hobart and William Smith College, Embry-Riddle Aeronautical University, Syracuse University, and Southern University). Where possible, Lab measurements will focus on more short term needs; proof of Advanced LIGO performance and risk reduction, while LSC labs will focus on longer term research for next generation detectors. Planned measurements include continuing work on Q, both at room temperature and cryogenic, dn/dT, Young's modulus, thermo-elastic properties, and material structure and makeup using X-ray and electron beam techniques. This final measurement, determining physical properties such as bond angle distribution and atomic separation as well as contaminant levels and oxidation states, will be combined with insights from modeling of materials to be done at Florida. Comparing these results with measurements of parameters important to LIGO (Q, dn/dT, etc) will allow for theoretical insights into the microscopic causes of noise. Research on optical properties, including scatter, absorption, and index, will still be pursued, but attempting improvement in thermal noise properties will drive the research.

The Thermal Noise Interferometer (TNI) at Caltech can make direct, broadband measurements of thermal noise in coatings. In its current incarnation, these measurements require specialized, relatively large samples (4"x4" optics), which are both expensive and time-consuming to fabricate. The TNI group has designed and is in the process of building a smaller interferometer that can measure coating noise in standard 1" optics, which is expected to substantially reduce the cost and accelerate the rate of sample evaluation and coating development. The existing (large) interferometer will be preserved but will play a secondary role once the sensitivity of the small interferometer surpasses it. The existing interferometer is currently the best testbed of thermal noise from other sources as well, such as silicate bonded attachments or barrel coatings to control parametric instabilities, and possibly other noise sources such as charge fluctuation or non-Gaussian events. Priorities will be set through discussions with the community and the TNI Advisory Board, but will likely be in favor of coating thermal noise work.

2.2 Suspensions and Suspension Thermal Noise

Accomplishments

LIGO Staff and students who contributed to suspensions work during the past year

Caltech: R. Abbott, H. Armandula, M. Barton (joined LIGO from Glasgow, July 2008) , A. Campos (SURF student), D. Coyne, C. Echols, J. Heefner, B. Kirsner, K. Mailand, C. Osthelder, N. Robertson, P Patel, G. Scarborough, C. Torrie (joined LIGO from Glasgow, June 2008), S. Waldman

MIT: M. Evans, P. Fritschel, A. Heptonstall, R. Mittleman, B. Shapiro, N. Smith, R. Weiss

LHO: B. Bland, D. Cook, G. Moreno

LLO: D. Bridges, T. Fricke, M. Meyer, J. Romie, D. Sellers, G. Traylor

The suspensions group is working on five major suspension designs for Advanced LIGO: ETM/ITM quadruple pendulum, beamsplitter/folding mirror (BS/FM) triple pendulum, input modecleaner triple pendulum (now known as the HAM Small Triple Suspension or HSTS), recycling mirror triple pendulum (now known as the HAM Large Triple Suspension or HLTS), output modecleaner (OMC) double pendulum and Enhanced LIGO Suspensions

Of these 5 designs, the Advanced LIGO UK (ALUK) suspension team has the primary responsibility for delivering the first two items, and for delivering the analog part of the electronics associated with damping and control of all the suspensions. The US LIGO team is supporting this work, and in particular is carrying out testing and characterization of the quad pendulum design at LASTI in collaboration with our UK colleagues. The suspension designs for the HSTS, HLTS and OMC are the responsibilities of the US SUS team, as is any redesign and development work required for the HAM auxiliary suspensions such as the small optics suspension (SOS). Work on the five major designs is considered in turn below.

ETM/ITM Quadruple Pendulum Suspension

During the last year much of the SUS team effort has focused on the noise prototype quad suspension which was assembled and is currently being tested at LASTI in conjunction with the BSC-ISI to which it is attached. LIGO staff members have carried out training trips to RAL in the UK and to LASTI and have supported the assembly work including bonding work in preparation for the first monolithic silica assembly. Early this year a hysteresis effect was identified in the quad pendulum and much work was carried out at RAL and LASTI to investigate what this was due to and what design changes might be needed. Currently the work at LASTI, in conjunction with UK colleagues, is focused on preparing the instrumentation and techniques for the pulling and characterization of the silica fibers and welding to the silica masses for the monolithic suspension. In parallel the US team has been supporting the development of the electronics for the quad which is underway at the University of Birmingham.

Beamsplitter/Folding Mirror Triple Pendulum Suspension
We have extensively revised the conceptual design during the last year to include updated size, wedge angle and orientation, reconsideration of the use of silica fiber suspensions and updated thermal noise estimates (see T040027-03-R, N Robertson and M Barton). The UK team has designed and is currently assembling a prototype suspension at RAL.

HAM Small Triple Suspension
One of the IMC prototypes was used at LASTI to carry out some cavity locking work in conjunction with the quad controls prototype. Preparation of documentation for an upcoming preliminary design review has been carried out, and initial work on electronics requirements has taken place.

HAM Large Triple Suspension
Work on fleshing out the design (which was first developed in 2003 but discontinued due to lack of resources) was restarted in mid-2007 with the employment of two engineers at Caltech. Significant work was carried out on producing a design of structure which meets the mass budget, can be easily welded without distortion and has a predicted first resonant frequency of ~150 Hz (to minimize its effect on the control system for the HAM-ISI). Drawings for building a prototype suspension are essentially completed, and some parts are in fabrication. The prototype will be constructed and tested at LLO.

OMC Suspension
The suspension supporting a metal dummy bench was constructed and characterized at Caltech over the summer 2007 with the help of our SURF student. Subsequently the metal bench was replaced with the silica bench carrying the OMC optics and associated electronics and further tests were carried out. Some redesign of the electronic cabling and routing was done to reduce coupling and DC alignment problems. After cleaning and baking, the first OMC was delivered to LLO in January 2008 for use in Enhanced LIGO. This is the first of the multiple pendulum suspension designs to be installed in LIGO. The second OMC is due to go to LHO in late July. The Enhanced LIGO OMCs serve as prototypes for Advanced LIGO.

Enhanced LIGO Suspensions
In the last year, the enhanced LIGO suspension thermal noise experiment was wrapped up. Previously it had been determined that there was likely excess loss and it was not coming from the clamps at the top of the suspension. This past year, it was confirmed that the loss was at the lower end of the wire, at the standoff where the wire leaves the barrel of the optic. The cylindrical shape of this standoff and the V shaped groove means that the boundary condition of the wire at this end is not very well defined; the position is constrained but the slope is not.

Several methods were tried to improve the mechanical loss at the standoff. Using two prisms in series, to define the wire slope, improved mechanical loss as did using a sapphire prism with a laser cut groove instead of the initial LIGO silica cylinder. A steel clamp with a pre-cut groove for the wire also improved the mechanical loss, but with more complexity. None of these methods reach the material limit of the wire, but they all are an overall improvement both in average reduced loss and in improved consistency over the installed initial LIGO suspensions.

Planned Work

Over the coming year R and D in suspensions will continue. However the effort will increasingly move over to direct project work for Advanced LIGO as we reach the final design stage of each of the suspensions.

ETM/ITM Quadruple Pendulum Suspension

The first monolithic assembly at LASTI is due in August 2008. A major program of work will follow. This includes testing installation and alignment procedures, carrying out characterization of the suspension in its monolithic form (transfer functions, mode frequencies, damping), testing of the electrostatic drive including investigation of optical mode damping, testing of violin mode dampers being developed in the UK, testing.

Beyond Advanced LIGO Suspensions Research

Once the coating noise is reduced to below the quantum noise, the suspension thermal noise will limit performance below 45 Hz. The suspension thermal noise is dominated above a few hertz by the thermal excitation of the final stage of the suspension, with contributions both from horizontal motion and vertical motion coupling into horizontal. The fundamental mechanism for that coupling arises from misalignment of the test masses with local vertical due to the curvature of the Earth over the 4 km arm length of the detector. Below approximately 15 Hz the noise is dominated by the vertical motion, with a peak at approximately 9 Hz due to the highest vertical mode of the suspension; see Figure 36 below. This peak corresponds to the “bounce mode” of the test mass on its four silica ribbon fibers. A lower resonant frequency, of order a few hertz, could be achieved by replacing the Maraging steel suspension blades with fused silica blades incorporated into the final stage suspension, which could be retrofitted into the existing Advanced LIGO quadruple suspensions. The use of such blades would have the added benefit of decreasing the residual seismic noise at the test masses arising from vertical seismic motion coupling into horizontal. If such blades can be developed, the suspension thermal noise becomes dominant from below 10 Hz and upwards via the direct horizontal contribution. Further development of silica ribbon suspensions to increase the dilution factor can be investigated to decrease this noise level. For example, the breaking stress of silica fibers of circular cross-section has been shown to exceed 5 GPa, a factor of two or so higher than current ribbon measurements. If ribbons can be similarly produced, thinner ribbons could be used. This, in combination with a more extreme aspect ratio (currently 10:1), could yield a factor of two to three in thermal noise performance. Achieving all the above will require research and development of blades and ribbons separately and in conjunction, and research on the attachment methods to the masses for such new suspension elements. This work will be carried out in collaboration with Glasgow University.

2.3 Detecting and Removing Gravity Gradient Noise

Accomplishments

LIGO Staff and students who have contributed to this work during the past year
Caltech: Rana Adhikari, Jane Driggers and Rob Ward
MIT: Matt Evans and Richard Mittleman
LLO: Brian O'Reilly and Valery Frolov

Adaptive noise cancellation uses auxiliary sensors to measure noise sources which can influence the main interferometer signal through subtle and not necessarily entirely understood (or even stationary) mechanisms. (These auxiliary signals will, of course, have no gravitational wave signal content or they could be used to detect gravitational waves in the first place.) The auxiliary signals are filtered by an adaptive FIR (finite impulse response) filter, the outputs of which are combined to make and estimate of the noise and the least mean squared (LMS) difference (the recursive least squares or RLS can also be used) between the main interferometer signal and the adaptive FIR filter output is used to iterate the FIR filter coefficients. These coefficients are continuously evolving to track changes to the system. At the Caltech 40-meter interferometer we have used a variant of the LMS algorithm to reduce the influence of seismic motion on the suspended mode cleaner by a factor of 10. We are setting up to extend this code to handle more channels and to include magnetic field couplings, acoustics, and control noise from auxiliary length and alignment feedback loops. This process of noise cancellation can be done in real time or on the data collected offline. As a result of this work, efforts have begun elsewhere to remove auxiliary noise signals from the S5 data.

Planned Work

Vibrations of the ground and density fluctuations in the air produce fluctuating Newtonian gravitational forces on the interferometer optics. Although we can reduce the direct vibrational coupling via improved seismic isolation, there is no way to shield the test mass from the gravitational forces. Current estimates predict that the motions of the test mass resulting from this Newtonian noise would be a limiting noise source somewhere between 10 and 20 Hz. Measurements of ground motions and other vibrating equipment using accelerometers and low frequency microphones will allow for estimation and some electronic cancellation of the fluctuating Newtonian forces. We plan to begin by modeling the ground, building, and vacuum system to estimate the level of the fluctuating Newtonian noise. We will complement this with vibration measurements of the vacuum system, support structures and buildings. To subtract the noise from our gravitational-wave channel we would need to form a feed-forward matrix, using Wiener or adaptive FIR filtering that would relate the environmental noise to the fluctuating gravitational forces being felt by the test mass. This method can be employed to an online feed-forward (directly driving the test mass) or by using linear regression on the gravitational-wave readout channel. This work will be coordinated with new efforts in the

LSC to pursue the same research direction, in particular with the University of Minnesota group.

2.4 Improved Seismic Isolation

Accomplishments

Significant effort was expended at all of the Lab sites to fabricate, assemble, install, and test the seismic isolation systems being developed for Advanced LIGO. Fully functional prototypes of the HAM isolators are installed at LHO and LLO for use in enhanced LIGO, and a prototype of the BSC isolator is installed at the MIT LASTI testbed. While all the systems are still in characterization, all signs at the close of the year are that the isolators will perform as required.

Planned Work

The work on Advanced LIGO isolation will be 'handed off' to the Advanced LIGO Project in the course of 2009. Continued risk-reduction work, and tests of novel approaches to servocontrols, will be performed at the MIT LASTI installation.

Work to go beyond the Advanced LIGO performance requirements will also be pursued. Low frequency (below a few Hz) motions of the test masses can corrupt our data by introducing excess noise couplings and by requiring the use of noisy, high dynamic range actuators. Our research will take two approaches for the reduction of low frequency seismic motions. The first approach involves the interferometric sensing of the distance between the two seismic isolation platforms in each arm and the feedback control of this distance below one Hz by actuating on the isolation platform and the intermediate stages of the multiple suspension system. While some version of this approach may be integrated in Advanced LIGO, more sophistication is likely to be helpful and could be employed as an Advanced LIGO enhancement. The reduction of low frequency motions can increase the stationarity of the noise, reduce upconversion, and also reduce the vulnerability to local wind, regional storms and global earthquakes. The second approach involves the development of ground tilt sensors. The seismometers used to provide the low frequency feed forward reduction in Advanced LIGO are dominated by tilt signals in the foundation slab below 50 mHz. The useful band of the seismometers can be extended to approximately ten mHz by measuring and electronically subtracting the tilt signals. We will explore the noise and stability of a few different types of tilt sensors (high stability, underground, optical levers, differential vertical seismometers, etc.). This work is complementary to the above techniques and both will be done in collaboration with researchers from Australian National University and Stanford University, as well as groups in the Virgo Collaboration. Adaptive noise cancellation techniques like those discussed above for the reduction of gravity gradient noise will be investigated as a means to improve seismic isolation.

2.5 Stochastic Electrostatic Forces

LIGO Staff and students who have contributed to this work
MIT: B. Gregg Harry

Planned Work
Charge buildup on interferometer optics can cause problems with (DC) mirror alignment and stochastic force noise in the gravitational-wave band. Understanding and reducing the fluctuating noise component will be the primary goal of research, although the most likely way to reduce noise is to remove charge and all charge-related problems will be mitigated. The power spectral density of Gaussian noise from charge is expected to depend on the fourth power of the amount of charge, inversely with the correlation time of the Markov process, and to fall as 1/f2 with frequency. Research will focus on measuring the correlation time for charge on silica and coating materials, on methods of reducing charge on optics, and possibly on ways of changing the correlation time. Charging research will continue to be coordinated by LIGO Lab personnel.

Preliminary measurements on correlation time on silica optics have given varying results, suggesting that the exact surface properties are crucial. Research on understanding this correlation time and getting the best estimate of the value for Advanced LIGO optics is centered at Trinity University and Moscow State University of the LSC. Depending on the results found, it may also be possible to increase this correlation time by surface treatments, which will also be pursued within the LSC.

UV light is a known way of removing charge buildup and has successfully been used on conducting optics by GP-B and LISA. Exploring how to use UV light to reduce charging on Advanced LIGO optics is underway in the LSC, centered at Stanford University. A prototype system for possible use in Advanced- or even potentially enhanced-LIGO is in development, and will possibly be tested with LIGO Laboratory support at the MIT LASTI facility, depending on need. Questions about detrimental effects of UV, primarily on the coatings but on other parts of the optics as well, need to be addressed before accepting a UV system in Advanced LIGO. Measurements of possible absorption and mechanical loss degradation with short term exposure to UV are ongoing at Stanford. The LIGO Laboratory has the capability at Caltech to monitor optical loss in a cavity over longer, month-like, timescales. It would be valuable to check for UV effects on optics using this technique to supplement the Stanford work.

Direct measurement of Gaussian (and non-Gaussian) noise from charged optics would be a valuable way of testing the noise model and determining the correlation time. A feasibility study will be done to determine which (if any) experimental setup in the LSC is appropriate for these studies and prioritization will be done through appropriate LIGO Lab and LSC committees. It may prove valuable to have an additional noise testing setup using a torsional pendulum, to better measure noise at the low frequencies where charge noise is most important.

3. Core Optics and Coating Absorption and Scattered Light

LIGO Laboratory Activities for LSC MOU Planning - July 2008

Accomplishments

LIGO Staff and students who contributed to core optics work during the past year

Caltech: Bill Kells, Hiro Yamamoto, Liyuan Zhang, H. Armandula, GariLynn Billingsley, Dan Fulton (Surf 2008), Hans Bantilan (Surf 2006), M. Smith, R. Desalvo
MIT: M. Zucker
LHO: C. Vorvick
LLO: V. Frolov

COC scatter/loss 1

Ongoing throughout this period has been detailed interpretation, updating and guiding of the OTF analysis of COC coated surfaces. A very large amount of comparative data has been collected, spanning many mirror types and pedigrees. The measurement technique has also matured, so that a convergent overall picture of our typical HR surface has emerged. The main features are that a fairly consistent [local, not including large scale "figure" aberrations] quasi-uniform background scatter (indicative of expected polish micro-roughness finish) and absorption exists. Then, superimposed is a randomly distributed "point defect" scattering component whose severity can vary markedly from sample to sample and which can typically contribute a large fraction to the total mirror loss. An overall modeling of these data (LIGO-G0700423-01 and G08003)48-01 shows consistency with LIGO I in-situ determined arm cavity losses.

COC scatter/loss 2

Large effort has gone into finalizing a scattering diffraction theory analysis of the expected appearance of micro-roughness lost light (as imaged at large angle through arm cavity VPs). The report on this (LIGO T070310) is in final draft (in abeyance pending completion of COC FDR). The analysis shows the close relationship between the angular distribution of scattered light we observe from LIGO COC and the existent theory of laser speckle scatter.

COC scatter/loss 3

New data were collected in situ at both LHO (Kells, Vorvick) and LLO (Frolov) on arm cavity light scattered (through accessible view ports) from TM HR surfaces. At LHO both high resolution images and photodiode integrated scatter were measured, while the LLO data was via photodiode only. These data update (addressing the vital question of HR surface degradation with time, since earlier studies from 2004 and earlier), and extend (higher resolution imaging at several view angles per optic, and sub-milliradian scatter angle integrated measurements) earlier in-situ light scatter studies. The overall corpus of data is consistent, and give a critical overview of the nature of arm cavity loss.
There is no indication that loss significantly increases long term say from cumulative contamination). A significant (perhaps dominant with respect to polish residual micro-roughness) scatter originates from a random density of "point" defects, largely responsible for the visual appearance of the beam spot images).

Identification of "bad" figure distortions

The general character of HR mirror distortions causing cavity loss (especially LIGO arm geometry regime) has been known since the design days of LIGO I. For distortion surface transverse scales small compared to the incident beam size (~Gaussian radius), a local (with respect to any incident intensity variation) rms amplitude for this distortion is well defined. In this regime the fractional loss is, locally, very closely $(4\pi \text{ rms}/\lambda)^2$. At the other extreme, the largest transverse scale distortions, e.g., the well known figure aberrations "power, astigmatism, coma, spherical", the cavity loss is little affected (exactly how much depending critically on the mirror/beam diameter ratio). Little intuition is found for distortions between these extremes. Extensive modeling (thanks to the fast, streamlined current Huygens propagation FFT-based numerical simulator) shows that certain intermediate distortion types can cause losses far in excess of the micro-roughness bound. One manifestation of this is that "randomly" distorted surfaces of the same rms scale may result in large (~factor 4 !) variation in cavity loss. Further we find cases of pathfinder mirror measurement distortion rich in these problematic components.

OTF lab R&D

Many mirrors have been characterized at OTF (Optical Test Facility) lab for the scatter, HR absorption, transmission, and AR reflection, for example, six spare mode cleaner mirrors for eLIGO, six witness samples from LHO and a steering mirror from LLO, which shows a uniform absorption and less point scatters in its HR coating, further investigation is underway.

The OTF lab was moved from West Bridge to Lauritsen. The new room is bigger and a portable clean room has been installed to provide a clean environment for the RTS test bench, which will be used to characterize COC mirrors of Advanced LIGO. The TIS (total integrated scattering) measurement has been improved. By replacing the commercial folding mirrors in the optical path with LIGO-I grade customized ones, the background optical noise is significantly decreased. Furthermore, a spatial filter is inserted just after the optical chopper to block the scattering of its blade and a quart wave plate and a polarized beam splitter are used to extract the reflected beam to make a better beam dump, which was suspected to introduce a big systematic uncertainty. With a beam size of about 180 μm in diameter on the sample surface, the noise level and the systematic uncertainty have been decreased to be about 1 ppm and 0.5 ppm respectively, comparing to 10 ppm and 1 ppm before the improvement.

A commercial scatterometer, SMS CASI system, has been installed at OTF. It can measure the scattering angular distribution of a small mirror in the reflection plane. With a mirror of 1" in diameter, the preliminary result is basically consistent with the TIS measured by the RTS bench, though the signal to noise ratio is not satisfied in small (0-4 degree) and large (30-90 degree) angle.

Planned Work

In addition to improvements in the thermal noise beyond that required for the initial Advanced LIGO installed optics, we wish to pursue further reductions in the coating optical absorption and scattering. The scattering loss due to the surface aberration in the short wave length region (< a few mm) is observed to be around 40 ppm in the initial LIGO and is required to be of the level of <20 ppm for Advanced LIGO. Absorption in Advanced LIGO coatings must meet a requirement of <0.5 ppm absorption per mirror.

Improvements beyond these requirements for both parameters would allow a better sensitivity and stability of an enhanced Advanced LIGO detector, and may allow higher laser powers to be employed successfully.

We have been investigating topographic scatter from micro-roughness, point scatter from defects in the coatings and from dust. In particular, simulation work on interferometer field propagation and spatial mode modeling, mirror figure error measurement, mirror micro-roughness and topographic scatter and coating bulk scatter and micro-roughness will continue to try to more exactly understand the problem. This work will be performed within the LIGO Laboratory, but with some LSC collaborators (in particular Syracuse University). In addition, experimental work on the Caltech 40-meter and the observatory interferometers will continue with improved measurements of the power recycling gain, the fringe visibility and measurements of the coating absorption inferred from the core optic internal mode frequency shifts as the mirrors heat up during and just after interferometer lock acquisition.

4. Evolution of the Interferometer Readout System

The development of quantum-limited sensing is critical for the performance of the Advanced LIGO interferometers. This can be achieved in a variety of ways that include modifying the interferometer's frequency response to GW by creating an optical spring to increase sensitivity in narrow frequency bands, or injecting squeezed light (vacuum) into the antisymmetric port of the beam splitter.

4.1 Prepared states of light

Accomplishments

LIGO Staff and students who have contributed to this work in the past year

Caltech: Stan Whitcomb, Alan Weinstein, Osamu Miyakawa, Steve Vass, Rob Ward, Rana Adhikari

MIT: T. Bodiya, T. Corbitt, Keisuke Goda, Eugeniy Mikhailov, Nergis Mavalvala, C. Wipf

LHO: Daniel Sigg

Since injection of squeezed vacuum into the antisymmetric port of the beam splitter was recognized as a promising method for reducing quantum noise in future GW detectors, an LSC collaboration comprising LIGO Lab, ANU and Hannover has developed squeezed state sources that meet the most important requirements needed for squeeze-enhanced GW detectors. These squeezed state sources using nonlinear optical materials (“crystal squeezing”) have realized coherently controlled squeezing at the low frequencies necessary in a GW detector (~100 Hz).

The Quantum Measurement group of the LIGO Lab produced an inferred 9 dB of squeezing at few kilohertz frequencies using a new family of nonlinear materials -- periodically poled potassium titanyl phosphate (PPKTP). This material has several advantages over our previous MgO-doped lithium niobate crystals, including lower optical losses, and hence larger squeeze factors, and also greater stability and ease of operation. This improved design was implemented at the 40m prototype at Caltech, and we observed about 3 dB (44%) broadband improvement in signal-to-noise in a squeeze-enhanced signal-recycled Michelson interferometer. This result appeared in Nature Physics and was covered by the scientific press of the Institute of Physics (physicsworld.com).

Planned Work

Following the success of the squeezing-enhancement test on the 40m prototype, LIGO Lab is actively evaluating a proposal to implement a squeeze source on a 4 km detector following the sixth science run (S6). We plan an experimental approach which is a continuation of the work carried out at the Caltech 40-meter interferometer by researchers from MIT and Caltech. It will incorporate a sub-threshold PPKTP parametric oscillator to generate squeezed vacuum for injection into the antisymmetric port of the full dual recycled configuration of Advanced LIGO. This entails fabricating a module that satisfies commercial reliability standards and can be integrated with LIGO control systems, is capable of producing squeezed vacuum in excess of 6dB, and includes actuators which make it possible to lock the squeezing angle (phase angle of the squeezed field relative to the gravitational-wave signal field). High reliability and availability is required, which sets certain restrictions on materials selection and optical configuration of the squeezing source. There will be additional work to improve the method of injecting the light into the interferometer and work to reduce the insertion loss of components such as Faraday isolators and output mode cleaners.

A program to address these issues in a post-S6 interferometer test would culminate in development and characterization of a robust squeezing source for Advanced LIGO that works across the approximately 10 to 10000 Hz frequency range, with full integration with the main interferometer's optical and control systems. This test will position LIGO Lab not only to reduce quantum noise in Advanced LIGO, but also serves as a risk management instrument for the possible challenge of handling high optical power. A team of LSC squeezers led by Daniel Sigg of LIGO Lab are preparing for a review in late summer 2008 that will evaluate the feasibility of the post-S6 squeezing test.

4.2 Frequency Response Tailoring inGravitational-Wave Interferometers

Planned Work

The current design of the Advanced LIGO interferometers allows for tuning of the frequency response by changing the signal cavity length (microscopically) and by changing the optical spring frequency (by adjusting the circulating laser power). By replacing the signal recycling mirror with a (triangular) resonant cavity the bandwidth and peak frequency of the interferometer's response curve can be tuned to tailor the sensitivity to match particular astrophysical sources.

4.3 Extending the Length of the Signal Recycling Cavity

Planned Work

The Advanced LIGO signal recycling cavity is contained within the corner station building and as such, the length is limited to tens of meters. Such a short cavity can be detuned to make a narrowband resonance to amplify the gravitational wave signal. However, it only amplifies one of the two gravitational-wave signal sidebands. Extending the length to kilometer scales allows resonating both signal sidebands to gain a factor of two in SNR. This configuration is also compatible with a compound, variable reflectivity signal recycling mirror. Modeling of the resulting frequency response and noise sources will be done in collaboration with the Australian National University (ANU) and Yanbei Chen's group at Caltech.

4.4 Squeezing and Radiation Pressure

Accomplishments

LIGO Staff and students who have contributed to this work in the past year
Caltech: Stan Whitcomb, Rolf Bork, Alex Ivanov, Jay Heefner
MIT: Thomas Corbitt, Christopher Wipf, Timothy Bodiya, Nicolas Smith, Sarah Ackley, Sheila Dwyer, Nergis Mavalvala
LHO: Daniel Sigg

An experimental program carried out at the LIGO LASTI facility at MIT seeks to generate and extract squeezing produced by the coupling of radiation pressure to mirror motion in suspended interferometers. This experiment operates in a regime where radiation pressure forces dominate the mirror dynamics. Several radiation pressure induced phenomena that are anticipated in Advanced LIGO, such as the optical spring effect, and parametrically driven optomechanical instability, have been observed (and controlled) in this experiment.

In addition to studying radiation pressure effects important to Advanced LIGO, this experiment is also an excellent testbed for observing quantum effects for macroscopic mechanical oscillators, such as achieving the quantum ground state of a 1 gram mirror, squeezing of light (vacuum), and entanglement of optical and mechanical degrees of freedom. Using a double optical spring allowed optical trapping of the gram-scale mirror, with a minimum temperature of 7 mk, a temperature well below the capabilities of bulk refrigeration for such a large object. The optical trapping work received wide coverage in the popular scientific press, including Science Magazine’s ScienceNow and AIP's Physics News. It was also selected as one of the top ten Physics stories of 2007 by the AIP.

Planned Work

This line of experiments has longer term goals of observing coherent and squeezed states of the mirror (in addition to the light, which is still planned as the first step), mirror-light entanglement, and eventually quantum information applications such as quantum memory storage. The present configuration has two identical cavities in the arms of a Michelson interferometer, with the goal of canceling laser noise. We have preliminary evidence that we are seeing thermal noise of the mini-mirror suspension, and are now in the process of making a monolithic all-glass suspension that should give a factor of 100 lower thermal noise. This new suspension uses the same technology used for the Advanced LIGO suspensions. This should be installed in summer 2008.

4.5 Photodetector Development

Accomplishments
We identified a good low-noise photodiode — a 3mm InGaAs Class A photodiode manufactured by Gtran. This photodiode has low dark current noise and a low thermal impedance between the photodiode substrate and the mounting case. This is important for the low-noise performance required by the in-vacuum intensity stabilisation photodetector and for the thermal management involved in operating at high photocurrent for long periods of time.

Other components for the photodetector design have been identified for low-noise performance; the bulk metal film resistor and a relay that has low contact noise. The current noise of the transimpedance resistor was found to be a major noise source that limited the performance of the intensity stabilisation electronics at low frequencies.

Two candidate designs for the intensity stabilisation exist with a fail-safe backup in hand just in case things don't go as expected. At this point in time it is not clear which of the two designs performs better at 10Hz. Further work on the candidate designs will be done over the next 12 months.

Planned Work
As a specific technical development needed to realize the changes above, we wish to pursue improvements in the performance of photodetectors beyond the requirements for Advanced LIGO. The highest sensitivity measurements of photodiodes to date at low frequencies show either an excess above shot noise, or an up-conversion mechanism, or both. By improving the noise performance of all of these sensors we hope to retire some of the risks of having unanticipated noise couplings. Increases in the dynamic range, quantum efficiency, linearity, optical backscatter, and power handling will be pursued. This work will be done in collaboration with the group at Stanford University where they will work to develop photodiodes in the Stanford Nano-Fabrication Facility (SNF) and make preliminary quantum efficiency measurements while the LIGO Lab will develop the specifications (through interferometer modeling) and measure the photodiode speed, spatial uniformity, large signal linearity, surface scatter, and quantum efficiency.

5. Interferometer Reliability and Up Time

5.1 Interferometer Lock Acquisition and Modern Control Techniques.
Accomplishments
The ISC design team completed the design requirements and conceptual design review, and moved into the preliminary design phase. A significant portion of the team's work went into the design, production and installation of the Enhanced LIGO readout hardware. In the coming year, the primary preliminary design work will be in the areas of alignment controls and photodetector development.

Planned Work

Once the Advanced LIGO controls have been designed and the interferometers accepted, the control system will be upgraded using the knowledge gained in early operation. Modern control techniques will be used to optimize the interferometer performance. Using dynamically adjustable filters and feedback matrices, the control systems can be trained to optimize various astrophysical figures of merit. This work will include both modeling and experimental work on the Caltech 40-meter interferometer and LASTI integrated isolation and suspension systems, but also directly on the Advanced LIGO system once operating (and under Laboratory Operation funding).

5.2 Interferometer Thermal Loading and Thermal Compensation.

Accomplishments

Much of the past year has been dedicated toward the upgrade of the thermal compensation system (TCS) in preparation for the Enhanced LIGO run to begin in 2009. The upgraded system will also serve as a prototype for the carbon dioxide laser projector in Advanced LIGO. The research for the upgrade has focused on two novel modifications. One is the use of axicon optics to more efficiently convert the CO2 laser beam profile from Gaussian to annular before delivery to the input test masses, thus delivering more compensating heat power in response to the PSL upgrade from 6 W to 30 W. The other is stabilization of the CO2 laser beam intensity to reduce the noise injected into the interferometer by TCS. We have proven both techniques in our lab. The axicon optics convert 85% of the incident Gaussian beam to annular, compared to only 30% for the transmissive mask design used in initial LIGO. Tests of intensity stabilization have reduced the laser intensity noise from the 1e-6/root(Hz) level to the 1e-7/root(Hz) level over most of LIGO's bandwidth.

Planned Work

One of the surprises uncovered during initial LIGO commissioning was that the thermal loading of the interferometer core optics was larger than expected in some components and smaller in others; additional measurements revealed coating absorption in excess of that expected. The thermal lensing distortions experienced by the mirrors when they absorbed some of the circulating light in the arm cavities led to difficulties in implementing the wavefront sensing angular control system and led, in addition, to a reduced level of power buildup in the optical cavities. This was overcome by building an optical phase camera and a CO2 laser projector which was able to heat the mirror in such a way as to compensate for the thermal lensing. As discussed in the Core Optics and Coating section above, we are working to discover the source of this additional absorption and will try to reduce it beyond the level needed for Advanced LIGO coatings. In addition we will work to improve the feedback control methods to minimize the amount of time required to bring the interferometer into lock.

Over the next year these projectors will be installed and commissioned on the 4 km interferometers at the LIGO sites. The intensity stabilization work begun at Caltech will be finished on projectors installed at the detectors, where it can focus on suppressing the noise sources specific to that environment. At the same time, an additional prototype table will be installed at LASTI to be tested on an Advanced LIGO input test mass prototype suspension in conjunction with a Hartmann sensor to monitor the induced wavefront distortion of the mirror in situ.

6. LASTI

Accomplishments

LIGO Staff and students who have contributed to this work during the past year
Caltech: Richard Abbott, Benjamin Abbott, Mark Barton, Rolf Bork, Riccardo DeSalvo, Jay Heefner, Alexander Ivanov, Ken Mailand, Norna Robertson, Virginio Sannibale, Alberto Stochino
MIT: Natinia Antler, Lisa Barsotti, Brennan Burns, Matt Evans, Fred Donovan, Stephany Foley, Gregg Harry, Alastair Heptonstall, Nick Hunter-Jones, Robert Laliberte, Myron MacInnis, Fabrice Matichard, Lucienne Merrill, Richard Mittleman, Ken Mason, Bryan Newbold, Sharon Rapoport, Pradeep Sarin, Brett Shapiro, Jonathan Soto, Andy Stein, Rainer Weiss, Marie Woods, Mike Zucker
LHO: Todd Etzel, Corey Gray, Hugh Radkins, Gerardo Moreno
LLO: Derek Bridges, Joe Hanson, Michael Meyer, Brian O'Reilly, Danny Sellers

Last spring (2007) we finished off the SAS experiments, see Recent Results of a Seismically Isolated Optical Table Prototype Designed for Advanced LIGO, P070127-01. The SAS is still in our Y-End Ham chamber, although its associated electronics have been removed.

The LASTI vacuum system has been modified; a septum plate has been installed between the BSC and mid-Y HAM chambers. The old oil lubricated turbo pump has been replaced with two magnetic bearing oil-free turbo pumps, one on each vacuum section. This allows the squeezing experiment in the mid-Y HAM and the Advanced LIGO testbed to independently vent without disturbing each other.

After the initial “dirty” construction (meaning the parts were not UHV cleaned), the two stage BSC-ISI has been cleaned and reassembled. It was then mated to the Noise prototype quadruple pendulum (an all metal version). While mounted on a test stand designed to mimic the BSC, we performed an initial phase of in-air testing.

This May the ISI with the suspension was inserted into the BSC vacuum chamber. We are currently in the process of commissioning the ISI, with results being posted on the LASTI and SEI logs. The ISI construction and initial commissioning has generated a long list (~60 items) of mostly minor changes, ranging from ease of assembly to improved performance.

Alastair Heptonstall has been on temporary assignment at LASTI, building and commissioning a laser welding and fiber pulling installation. That phase is almost complete, and he is about to move on to the first fiber pulling and welding tests. Partly as a result of this work, the suspension group decided to recommend that the Advanced LIGO test mass suspensions use cylindrical fibers instead of ribbons; this has now been accepted as the baseline plan.

There have been three bonding trips where members of the UK and US groups have traveled to MIT to bond ears and prisms onto the optics intended for use in the monolithic construction of the quadruple prototype.

Using the controls prototype quadruple suspension in the BSC and a small triple suspension in the X-End HAM, we investigated cavity locking schemes. This work was hampered by the inability to use the ESD on the test mass due to the temporary partly metal masses. In preparation for the monolithic installation the laser table has been reworked, with a reference cavity added to increase the laser stability.

Planned Work
In the up coming year we are planning to build and install the monolithic quadruple suspension, finish the ISI commissioning, and resume the cavity testing. Once we have a stable, quiet cavity there are a number of tests that we are planning. The highlights are: investigations of test mass internal mode Qs and damping techniques (apropos the parametric instability issue); characterization of the electro-static driver; continued studies of global feedback to the quad suspension stages; investigations of violin mode damping. Some time next year we should be constructing and installing a HAM-ISI to put in the X-end HAM, under the small triple suspension.

7. 40 meter Interferometer

Accomplishments in FY2008 (with brief historical summary)
Caltech: Yoishi Aso, Rana Adhikari, Stefan Ballmer, Jenne Driggers, John Miller (Glasgow), Osamu Miyakawa, Andrey Rodionov, Alberto Stochino (Sienna), Stephen Vass, Rob Ward, Alan Weinstein, Many visitors and REU students.

MIT: Nergis Malvalvala and Keisuke Goda

The 40m as AdvLIGO optical configuration prototype
The 40-meter Laboratory was rebuilt in 2001-2005 to fully develop and test the optical configuration and control scheme for Advanced LIGO, including an inital LIGO PSL, a 13 m suspended-mass mode cleaner, a detuned signal cavity (coupled to the power-recycling cavity: dual recycling), and an improved digital control system. The more complex dual-recycled optical configuration makes it significantly more difficult to control than for the initial LIGO interferometer. This makes it essential to develop a reliable scheme to bring the interferometer from an uncontrolled state into one which is optimized for gravitational-wave detection. At the beginning of FY2006, we were able to bring the interferometer into full lock in the Advanced LIGO configuration, via multiple paths of varying complexity and robustness against environmental and technical noise. We measured the optical response of the detector, (dominated by a high frequency (~4 kHz) RSE peak and a low frequency (~40 Hz) optical spring resonance, both due to the detuned signal cavity (published in CQG). The noise spectrum, however, was dominated by technical noise sources so that the expected quantum-limited sensing noise spectrum

was not observed. Continued development of robust lock acquisition, including experiments with new sensing signals (eg, 3f), continued through FY2007 and FY2008.

DC Readout
In FY2006 we developed and commissioning a DC readout system. This was then used to sense and control the DARM degree of freedom. We observed a reduction in the "junk" light at the asymmetric port, and improved overall noise in the gravitational-wave channel (in comparison with RF readout), above 600 Hz; a displacement sensitivity of 2 x 10^{-18} m/rHz was achieved at approximately 1 kHz. We completed a broad range of measurements of noise couplings with DC and RF readout (laser frequency noise, intensity noise, oscillator noise, etc); it appears that the expected benefits of DC readout are being realized in practice (published in CQG). These techniques: dither alignment and length locking, in-vac cavity, in-vac photodetectors, are being used as the core features of the Enhanced LIGO upgrade.

Squeezed vacuum injection
In FY2007, Goda, Miyakawa and Sharaf implemented a vacuum squeezing apparatus for injection into the interferometer. A 3.1 dB or 43 percent increase in displacement sensitivity was observed above 30 kHz where the interferometer was limited by photon shot noise. The configuration for this experiment was a signal recycled Michelson interferometer with no Fabry-perot arms or power recycling. Since this demonstration was carried out on a prototype interferometer with suspended mirrors, and a readout and control system similar to those used in existing gravitational-wave detectors, it is a major step toward implementing squeezing enhancements on long baseline gravitational-wave interferometers (published in Nature Physics).

Dual-recycled interferometer with DC readout
By the end of FY2008 we once again achieved full lock of the 40m in the full AdvLIGO configuration: power- and signal-recycled Michelson with Fabry Perot arms, now with DC readout and control of the DARM degree of freedom. Noise spectra and noise couplings were measured and compared with predictions (thesis and publication to come soon).

Auxiliary laser locking
Work began in FY2008 to develop a method for locking the arms independently of the central part of the detector, using laser light brought to the ends of the arms via stabilized fibers and injected through the ETMs. This work is ongoing in FY2009.

Upgrade to new AdvLIGO configuration
Experience with locking and controlling the 40m in FY2004-2006 led to changes in the baseline design of Advanced LIGO: RF modulation frequencies, cavity finesse, and schemes for tuning the sensitivity. Work began in FY2008 to redesign the 40m to bring it into line with new thinking about AdvLIGO: lower RF frequencies for the control sidebands generated with AdvLIGO-like input optics; modified coupling of RF sidebands to the signal cavity; much longer power recycling and signal cavities; broadband RSE with dynamically detuned signal cavity; lower finesse arm cavities; lighter ITMs (to

enhance radiation-pressure effects at the 40m); AdvLIGO-like (PCIX and Myrinet) controls architecture.

Development of digital camera network
During FY2008, GigE digital cameras were tested for use in monitoring the position and transverse profile of pickoffs from IR beamlines, as well as the scattered light from suspended mirrors. A new Gigabit ethernet network (with associated CPUs and image processing software) was designed and installed in order to acquire and real-time-process information from these cameras. Networking software and image processing software from this effort will be exported to the observatories for Enhanced LIGO.

Precision Interferometry development and diagnostics
Work during FY2008 included: development of adaptive feed-forward for noise cancellation to aid in lock acquisition, reduce certain noise couplings, and to cancel gravity gradient noise (described elsewhere in this document); testing of AdvLIGO-like RF photodiodes; development of high-power beam dumps using stainless steel “horns”; hosting the eLIGO OMC construction; development of a new RFAM monitor; development of noise budget code; development of scripts to automate suspension optimization, lock acquisition, alignment, control and other now-routine functions; and many small improvements to the 40m PSL, suspensions, environmental monitoring system, and interferometer plant.

Training, collaboration and outreach
The 40-meter team continues to work closely with the Advanced LIGO Interferometer Sensing and Control group, the enhanced LIGO group, the LIGO e2e simulation group, and LIGO Laboratory engineers and management. Numerous graduate students, REU (Research Experience for Undergraduates) summer students, visiting students, and visiting scientists have learned about interferometry and contributed to all aspects of the project over the last seven years. In particular, REU students have made major contributions to design and implementation of the DC readout and vacuum squeezing systems, as well as many other aspects of the interferometer. We will continue to involve students and visitors with all aspects of the project and its goals. The laboratory continues to be a popular tour site for local students, journalists, scientific visitors, and dignitaries.

Planned Work for FY2009

Upgrade to new AdvLIGO configuration
We will reconfigure the 40m interferometer to more closely resemble the new AdvLIGO optical/control design. This will involve the replacement of the ITMs, new layout of the recycling cavities, the addition of several in-vacuum steering mirrors, new RF electronics and electro-optics, and a new PCIX-based control system. The newly-configured interferometer will be commissioned, lock acquisition and control systems developed and optimized, and noise spectrum and noise couplings studied.

Dual-recycled interferometer with DC readout
This work will be completed, thesis written, and paper describing the results written and submitted for publication.

Continuing efforts
Work will continue in FY2009 in:

- Improved lock acquisition and control schemes, including the development of improved sensing signals during lock acquisition process.
- Development of adaptive noise cancellation feed-forward schemes to aid in lock acquisition.
- Development of an auxiliary laser arm locking system.
- Development of a digital camera network and image processing system.
- Continued optimization and automation of all systems.
- Training of and collaboration with visiting students and scientists from the GW community, and public outreach.

8. LHO Research
Accomplishments

Completion of S5 Run
The continuous collection of search data for S5 ended on September 30, 2008 and we began a process of final characterization and documentation of the interferometers. During this time, we also made a large investment of labor in resolving discrepancies between different calibration methods.

Calibration
A major effort was expended to understand discrepancies between the "standard" calibration method for our interferometers, based on extrapolation over many orders of magnitude of the response function for our voice-coil actuators, and the newly developed photon calibrators, which use radiation pressure from small lasers to push the mirrors by sub-picometer distances. A number of improvements were made during S5 to ensure more reliable and uniform results from the photon calibrator, in collaboration with University of Michigan graduate student Evan Goetz. The end of the S5 science running allowed many tests and measurements to be performed which were not feasible during the course of the run. The source of the discrepancy was eventually identified as a systematic error in the standard calibration.

Core Optics Characterization
We developed a standard method of imaging large optics at LHO with a high resolution IR camera. These images show the details of the scattering from the HR surface. One of the most important results from these images is the characterization of the scattering showing the contribution due to point scattering and micro-roughness. There are

unanswered questions that remain about the images, with the most pressing being the source of the streaks that are evident in all ITM images. These images provide baseline information for future studies of possible contamination of optical surfaces.

Mirror Cooling Experiment

A target-of-opportunity experiment was performed using the H1 control system to cool the suspended mirrors to bring the differential length degree of freedom of the four-mass, 2.7-kg effective mass oscillator as close to the quantum ground state as possible. This required no changes of hardware, but a re-tuning of the length controls to achieve a strong restoring force for the differential length degree acting as a cold damped spring. Microkelvin cooling was achieved, the first such demonstration or cold damping in a kg-scale oscillator.

Investigation of Possible Alignment Instabilities

The first direct measurement of the radiation pressure effect on the dynamic angular response of interferometer mirrors as a function of power stored in the arms was done for H1 and H2 in collaboration with graduate student Eichi Hirose of Syracuse University. The data indicate that both H1 and H2 are "naturally unstable" (Sigg-Sidles instability) at the S5 laser power level, and that they are only kept stable by the angular control servo using wave-front sensors. A simplified Simulink model was developed, which agreed well with the measurement.

Stabilization of Light Transmitted Through an Optical Fiber

An REU/SURF student is investigating stabilizing laser light carried by an optical fiber from the corner station to the end station. This technique may be useful for providing a quiet laser reference to the end stations of interferometers. Individual arm-length stabilization is one possible application of this technique. The initial project will evaluate phase stabilizing light transmitted through a long fiber by measuring light reflected from the injection end of the fiber and actuating on the injection optics.

Developing Squeezing for LIGO AS Ports

A test of squeezing the anti-symmetric port of interferometer H1 during the planned 6-month interval between the end of H1-L1 coincidence operation in S6 and the deconstruction of H1 for Advanced LIGO is under consideration. A conceptual design of such a squeezer test program has been developed and presented to the LSC in Spring 2008. A review committee has been appointed to study the feasibility and merits of performing this squeezing test as a risk reduction measure for AdLIGO.

Interferometer Commissioning

Interferometer commissioning in 2008 focused on reductions of control currents in the voice coils to reduce upconversion noise and improve robustness of operation and a characterization of problems encountered with running H2 at higher laser power to improve its sensitivity. The control system work resulted in far better data quality and sensitivity in H1 after Feb 2008. Unfortunately the issues with running H2 were not resolved, although the work was useful as part of a diplome thesis (for AstroWatch participant Berit Behnke) at AEI.

Planned Work

Enhanced LIGO Commissioning

Installation of hardware for the enhancement of H1 will be completed in summer of 2008 and the process of making it all work will be pursued in the fall and early winter.

Core Optics Characterization

We will continue imaging core optics as an ongoing program, to track any contamination of the HR surface. This will be used to discover if the particulate seen on the surface is being deposited during the vent cycle, or is accumulating over time while under vacuum. Overall, the goal is to image the optics between each venting activity, and to imaged the optics periodically while under vacuum.

Using PEM Data to Improve Interferometer Controls and Noise

PEM data has been used to guide design of interferometer controls, to investigate mechanisms by which environmental effects contaminate the data, and to provide data quality flags and vetoes for data analysis. In contrast to these passive uses of PEM data, we will investigate techniques to actively tailor interferometer controls to evolving environmental influences and to reduce noise by subtracting out environmental influences. As an example, one can imagine different optimizations of an active seismic-reduction system (e.g., a HEPI or Fine-Actuator system), depending on the changing mix of influences (e.g., microseism, wind-driven tilts or anthropomorphic noise). Since the time scales for evolution of these noise influences is of order hours, it should be possible to monitor these influences and re-optimize the control-loop shapes as the instrument operates.

Developing auxiliary loop gain monitor

Our interferometers operate with better sensitivity and reliability if we can provide constant gain in the control-system loops. This has improved over time as we have improved the alignment controls and the low-frequency performance of the DARM loop. Graduate student Szymon Steplewski (WSU) will be working with staff to extend this gain monitoring to the MICH and PRC loops. This will provide better diagnostic and data quality information during S6 than was available for the S5 run.

Developing Squeezing for LIGO AS Ports

The planning and review process for the squeezing experiment will continue throughout the upcoming year. We expect long-lead items will need to be purchased toward the end of this period.

9. Beyond Advanced LIGO

9.1 Interferometers with Nongaussian Modes

Accomplishments

LIGO Staff and students who have contributed to this work

Caltech: John Miller, Phil Willems and Riccardo DeSalvo

While implementing the PDH locking mechanism it was found that stress on the folding mirror would introduce a lensing element which stopped the mesa beam mode from resonating. We designed a power recycling cavity folded around the present interferometer, on the same suspended structure and its mechanical support to avoid the mirror stress problem but determined that it is impossible to make a significant power recycled interferometer without changing all mirror reflectivities, including remaking the Mexican hat mirrors. We abandoned the power recycling project to work on wave front phase sensing for angular controls.

Planned Work

We will try out the remaining Mexican hat mirrors to confirm the calculated sensitivity of the mesa beams to Mexican hat mirror construction imperfections. Further possible experiments with the present setup include obtaining from QED Mexican hat mirrors built with the Magnetorheological Finishing (MRF) process. This process would represent an alternative to the corrective coating currently used to fabricate mirrors. The MRF process would also allow us to build and test the concentric Mexican hat cavity that would presumably be used in a large interferometer (for angular power instability reasons) and that is impossible to build with the short radius required by our small cavity with the corrective coating technique. We proved the feasibility of Mesa beams to produce wider beams that reduce the effects of thermal noise without increasing diffraction losses.

9.2 Tiltmeter

Accomplishments

LIGO Staff and students who have contributed to this work

Caltech: Riccardo DeSalvo

Low frequency, precision tiltmeters are needed for measurements of ground motion for geophysical reasons and to provide feedback in controls of GW seismic attenuation systems, both in Advanced LIGO and in Virgo. Precision measurements of tilt would allow subtraction of the Earth's gravity induced tilt term from the horizontal acceleration signal of accelerometers Several design were tested, mostly based on Bendix flexures. The quality factor of the flexures is in principle sufficient to achieve sensitivities better 10^{-9} rad/√Hz @01.Hz, but always presented orders of magnitude excess noise at low frequency. This excess noise is likely due to hysteresis of the flexures. A design of a new tiltmeter was made in collaboration with various external Virgo collaborators. It is based on a flexure design previously studied in LIGO and allows the easy replacement of the flexure to test different materials and material treatments, to identify materials with sufficiently low hysteresis to reach the theoretical performance.

Planned Work

A first prototype may be built this year to test the mechanical design and the behavior of a number of flexures. Successful tests of this prototype could be followed by the production of two units to be tested in parallel to separate common signal and internal noise. Tests of these tiltmeters would need to be made in parallel with horizontal accelerometers and in a quiet location. The horizontal accelerometers for a joint test could be done in collaboration with Virgo, and the tests could be performed at the Homestake mine.

9.3 Homestake mine studies

Accomplishments

LIGO Staff and students who have contributed to this work
Caltech: Riccardo DeSalvo

The Homestake mine is available for use in scientific experiments. NSF has asked if the location could be useful for a future underground GW observatory. A study was started to measure the seismicity of the site as a function of depth and of rock properties.

Planned Work

This summer several seismic monitoring stations will be established at different depths, using continuous and synchronous readout. We may continue with extended measurements, including measurements of rock movements using optical bar measurements across opposite walls in existing excavations.