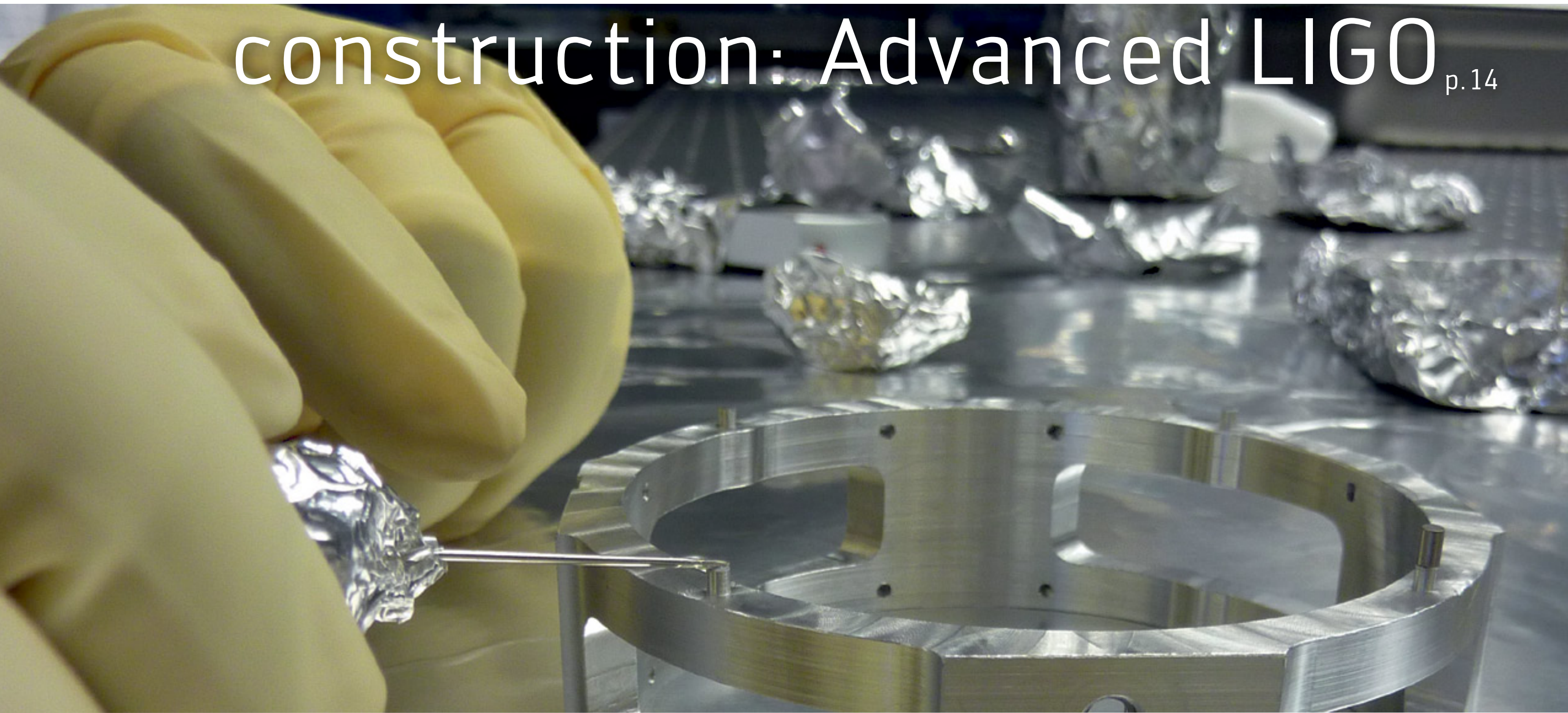
issue 1/2012

LIGO MAGAZINE



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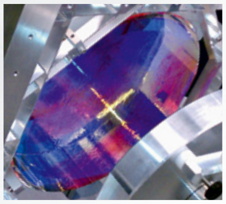

Monolithic Suspensions

Technology Insights p.20

... and more!

Title image

Small magnets are precisely glued to optic holders in an ultra clean-environment, using tiny amounts of a special vacuum-compatible epoxy to reduce the risk of contamination of the optical surfaces. The magnets are part of a system of sensors used to measure and control the position of suspended optics that precisely align the laser into the Advanced LIGO detector (Giacomo Ciani)

Upcoming events (compiled by the editors)

March 2013 LSC meeting
University of Maryland, College Park,
Maryland, USA, March 18-22, 2013

Gravitational Wave Tests of Alternative Theories of Gravity in the Advanced Detector Era (Workshop),
Bozeman, Montana State University
April 5-7, 2013
http://www.physics.montana.edu/gravity/workshop/workshop.htm

Tenth Edoardo Amaldi Conference on Gravitational Waves (including GR20)
Warsaw, Poland; July 8-13, 2013

September 2013 LSC Meeting
Albert Einstein Institute, Hannover,
Germany; September 23- 27, 2013

27 th Annual Meeting of the American Society for Precision Engineering
San Diego, CA USA; October 21-26, 2012,
http://aspe.net/

SnowPAC 2013 Black Hole Fingerprints: Dynamics, Disruptions & Demographics
Snowbird Ski Resort, Utah; 17-23 March
2013, http://www.physics.utah.edu/snowpac/index.php/snowpac-2013

APS Meetings 2013
- Baltimore, MD; March 18-22, 2013
- Denver, CO; April 13-16, 2013

The Seventh Huntsville Gamma-ray Burst Symposium
Nashville, Tennessee, USA
14 - 18 April, 2013

Black holes, jets and outflows
Kathmandu, Nepal, 29 April - 3 May 2013
http://www.iasfbo.inaf.it/events/nepal2013/

The Fast and the Furious: Energetic Phenomena in Isolated Neutron Stars, Pulsar Wind Nebulae and Supernova Remnants
XMM-Newton Science Operations Centre
at ESA; 22-24 May 2013
http://xmm.esac.esa.int/external/xmm_science/workshops/2013_science/

CLEO 2013
San Jose, CA, USA; 9-14 June 2013
http:// www.cleoconference.org/home.aspx
Pacific Rim Conference, Kyoto, Japan
1–4 July, 2013

Waves and Particles: Multi-Messengers from the Universe, Annual Meeting of the German Astronomical Society (150 Years German Astronomical Society)
Tübingen (Germany)
24-27 September 2013
http://astro.uni-tuebingen.de/~AG2013

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Image credits

Photos appear courtesy of LIGO Laboratory/LIGO Scientific Collaboration unless otherwise noted.

p. 6 Neutron Star simulation: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

p. 7 Sloan Digital Sky Survery: M. Blanton and the Sloan Digital Sky Survey (and http://www.sdss.org/)

p. 16 IMC noise budget diagram by Christopher L. Mueller, University of Florida

pp. 22-23 technical drawings: Alan Cumming, University of Glasgow

p. 24 Atlas diagram: Provided by Konstantinos Nikolopoulos

p. 31: Photos by Tobias Westphal, Albert Einstein Institute

p. 32 Photo by Andreas Freise, Unversity of Birmingham

p. 33: Photo by Marco Cavaglia, University of Mississippi

Welcome to the first issue of the LIGO Magazine!

Gaby (Gabriela) González
LSC spokesperson

I hope you are as excited as I am seeing this first issue of the LIGO Magazine, which we hope to produce about three or four times a year. Many people, and not just LSC members, said many times they want to know more about what's going on, about people in the LSC, and of course also about science and technology done in the LSC. Although we all know there are venues to find all the information we need and more in the many documents and web pages we produce and in the presentations and conferences we attend, I still find myself drawn to material on a variety of topics put together in a nice reading format (even if electronic!), with nice pictures.

Many people were very enthusiastic about the idea of a LIGO Magazine when first talked about in the last LVC meeting in Cambridge, MA, in March 2012, and I am especially grateful to Andreas Freise, who accepted my request to be Editor in chief, and the many members of the Editorial Committee listed in page 35 – they have found a very nice set of topics and the writers for this magazine, and I hope you agree they've done an excellent job! It is impressive that an issue came together in a short time, and you'll be glad to know the next issues are already in preparation.

The Editorial Board of the LIGO Magazine and myself in particular are very eager to hear from you with feedback, constructive criticism and suggestions for future issues - we'll take your compliments too. Please write to us and let us know what you think!

Andreas Freise
for the Editors

Andreas Freise

This magazine is made by and for you, members of the LIGO Scientific Collaboration, and many of you have already been involved. Our main vision for the magazine is to enable you to share stories and find out more about all facets of our community. Regular features include reports on conferences, student experiences and outreach activities, news items, upcoming events and job announcements.

For the inaugural issue we have collated more than 30 pages of interesting news, entertaining stories and fascinating photos. We decided to take a close look at Advanced LIGO, covering both the current status of the installation and the historic evolution of the project. I spent my first years in the gravitational wave world in and around the vacuum tanks of the GEO600 detector, installing and then commissioning the interferometer within; I remember very intense but extremely exciting times! Now, I cannot help but envy the students, post-docs and staff who are working in Livingston and Hanford, building the Advanced LIGO detectors! Will these lasers, these mirrors, these control systems be the ones to perform the first direct detection of gravitational waves? I think so!

Advanced LIGO will remain a regular topic in future issues. In particular we will showcase some of the instrumental subsystems that are essential parts of the detectors, starting today with the monolithic mirror suspension. The main topic of the magazine, however, will be different each time, and `Black Holes' will be our focus in issue number two. We hope that you will enjoy this issue and look forward to receiving your feedback. Please send comment, suggestions and contributions to **magazine@ligo.org.**

LIGO Scientific Collaboration News

As you may already know, the LIGO Scientific Collaboration (LSC) is already the size of a small village, with almost 900 members! As such, it's difficult to keep up with what's going on in the many groups of the Collaboration. And there are many, many groups! You should guess first, and then count them in the LSC org chart.

Many of the members and chairs of these groups are elected, and I take this opportunity to thank all of those who stand for election, and to the LSC Election and Membership committee who organizes those.

The latest elected chairs in 2012 are Duncan Brown (new chair, Compact Binary Coalescences group); Brian Lantz (new chair, Suspensions and Seismic Isolation group); Laura Cadonati (re-elected, Bursts group); Gregg Harry (re-elected, Optics group); Nelson Christensen (re-elected, Stochastic group); Keith Riles (re-elected, Continuous Waves group).

The LIGO Academic Advisory Committee has now two co-chairs, Nelson Christensen and Alberto Vecchio.

Szabi Marka was appointed chair of the Education and Outreach Committee, following many years of successful work of the group created and chaired by Marco Cavaglia (who is now the Assistant Spokesperson – a new position in which I deeply appreciate his help!).

Of course, if you are reading this you already know about the new LIGO Magazine and its Editor in Chief, Andreas Freise: I am very excited about this new project!

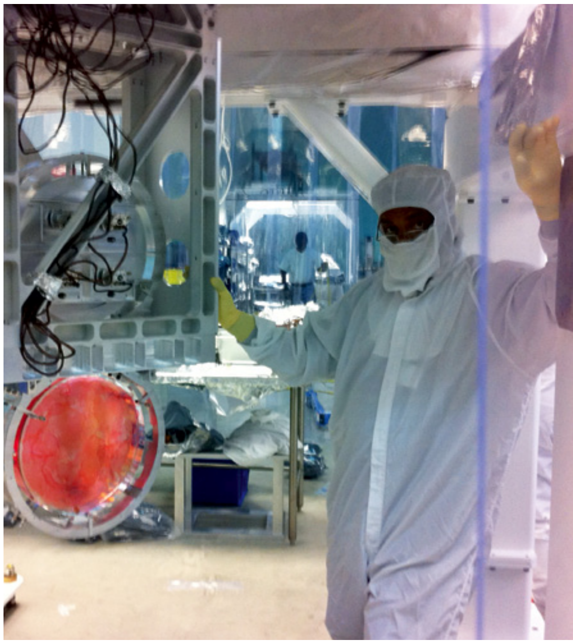
We also elected four new at-large members to represent you in the LSC Executive Committee – we thank Mike Landry, Peter Saulson, Peter Shawhan and Mike Zucker, who served as representatives for an over-extended period of time, and welcome the newly elected members Laura Cadonati, Nergis Mavalvala, B. Sathyaprakash and Norna Robertson. Please feel free to let them know of any issues you'd like to get considered by the LSC Executive Committee, and on your opinion on any of the issues that are discussed.

Apart from the exciting science we do, there are several "hot" issues being discussed in different forums in the LSC; some of these at the time I'm writing this article are:

- A collaboration agreement with KAGRA.
- Allocation of "scientific monitors" in Advanced LIGO runs.
- Initiatives for increasing LSC diversity.
- A plausible plan for the early science runs with Advanced LIGO and Virgo detectors.
- Results from the first two engineering runs, and goals for the next ones.
- Methods for remote participation and teleconferences replacing EVO.

I encourage you to tell me and your colleagues your opinions about those issues and any others – I am *very* interested in your feedback!

Gaby (Gabriela) González,
your spokesperson.



Experts from Laser Zentrum Hannover working on the installation of the Pre-Stabilized Laser at Livingston. This was the first completed subsystem installation for Advanced LIGO (top).

Geneva Winton making final adjustments to the Beam Splitter prior to installing it into the Livingston interferometer (below).

Laura Nuttall

Laura Nuttall is a grad student working on detector characterisation and electromagnetic follow up to gravitational wave events at Cardiff University. Laura is also a LAAC student representative, netball captain for Llanrumney ladies and cake mistress amongst the Cardiff grad students.

How far is 300 Mpc?

300 Mpc is the expected maximum distance at which advanced LIGO will be able to observe binary neutron stars after a few years of operation.

Anyone who works within the gravitational wave (GW) community or is particularly enthusiastic about the subject is likely to have heard some version of this quote in the last few years. The Advanced LIGO detectors, which should start to become operational in 2015, promise to enormously increase the distance by which we are capable of observing gravitational waves. But what does 300 Mpc actually mean? How far is it and what is there within 300 Mpc of our galaxy?

300 Mpc can be thought of in a variety of ways:

In light years 300 Mpc is equal to 1 billion light years; if we observe light, or gravitational waves from 300 Mpc away we are looking at events that happened a billion years in the past. 300 Mpc is also equal to 9x10^{24} metres or about 60 trillion times the distance between the Earth and the Sun. It is hard to comprehend such vast distances. If you think that a marathon is a long way consider that 300 Mpc is equal to 200 quintillion marathons!

With the Initial LIGO detectors

the average sensitivity to neutron star mergers was around 20 Mpc, this allowed us to observe the Virgo supercluster, a collection of galaxy clusters of which the local group, containing the Milky Way, is a member.

Advanced LIGO

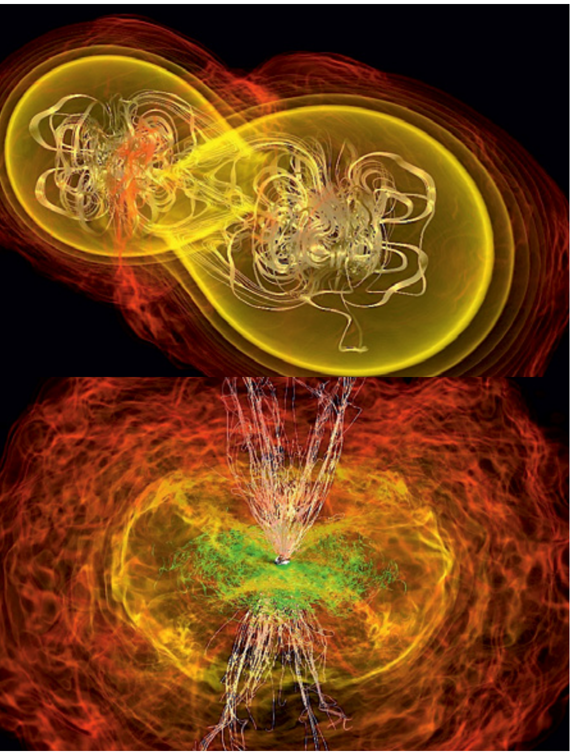
will be sensitive to a volume of space more than a thousand times larger than this, allowing us to observe gravitational wave signals from roughly 100 superclusters including those that lie in the plane of our galaxy, which are very difficult to observe with electromagnetic facilities because of the interference from the Milky Way. With a little imagination we can estimate that Advanced LIGO will search through some 3 million large galaxies and over 250,000 trillion stars for that elusive gravitational wave signature.

While 300 Mpc truly is a colossal distance, it is still a small fraction when compared to the full size of our universe. In terms of cosmological distances 300 Mpc equates to a redshift of only 0.07. The Sloan Digital Sky Survey, one of the most expansive astronomical surveys undertaken, has thus far imaged 35% of the sky with galaxies as far as a redshift of 0.7, we are hoping to see a tenth this far with Advanced LIGO. Even this distance is small compared to the most distant galaxies observed with the Hubble Space Telescope at a redshift of 10. Compared to these distances we will only be observing the backyard of our universe.

There is however, every reason to be optimistic as LIGO personnel prepare the instruments to open a new window on the universe. Studies have estimated the number of gravitational wave signals we should find every year using Advanced LIGO. Using binary neutron star systems observed in our own galaxy and extrapolating for the vast distance that Advanced LIGO will cover, we expect to observe at least tens of mergers every year.

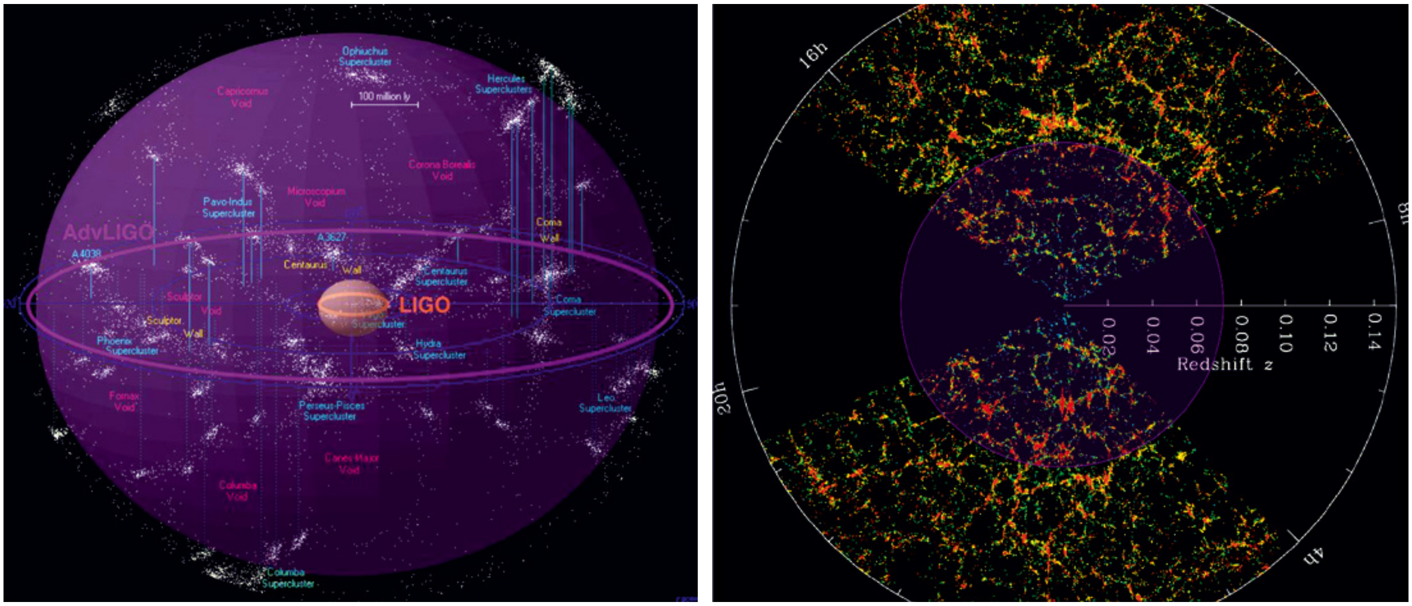
Plans for upgrades and also space-missions that will significantly improve observation distances are already in the works.

The advanced era will indeed be an exciting time!



Numerical Simulation of a neutron star merger.

© L. Rezolla (AEI) & M. Koppitz (AEI & Zuse-Institut Berlin)



The superclusters within 300 Mpc (left) and the Sloan Digital Sky Survey (right)

Rough Distance scales			
Diameter of Earth	1 x 10^4 *km*	1 x 10^{-9} *ly*	4 x 10^{-10} *pc*
Earth-sun distance (1 AU)	1 x 10^8 *km*	1 x 10^{-5} *ly*	5 x 10^{-6} *pc*
Distance to nearest extra-solar star	4 x 10^{13} *km*	4 *ly*	1 *pc*
Distance to centre of the Milky Way	3 x 10^{17} *km*	3 x 10^4 *ly*	8 x 10^3 *pc*
Typical galaxy size	9 x 10^{17} *km*	1 x 10^5 *ly*	3 x 10^4 *pc*
Distance to nearest galaxy (Andromeda)	2 x 10^{19} *km*	2 x 10^6 *ly*	8 x 10^5 *pc*
Size of the local group	1 x 10^{20} *km*	1 x 10^7 *ly*	3 x 10^6 *pc*
Initial LIGO sensitive distance	6 x 10^{20} *km*	7 x 10^7 *ly*	2 x 10^7 *pc*
Diameter of Virgo supercluster	9 x 10^{20} *km*	1 x 10^8 *ly*	3 x 10^7 *pc*
Distance to next nearest supercluster	2 x 10^{21} *km*	2 x 10^8 *ly*	6 x 10^7 *pc*

A distance ladder from solar system distances up to the sensitive distances of the LIGO detectors.

One lightyear (ly) is the distance that light travels in a year; one parsec (pc) is the distance at which a star would shift by 1 arcsecond relative to distant objects during one orbit of the Earth about the Sun.

A brief history

The evolution of Advanced LIGO

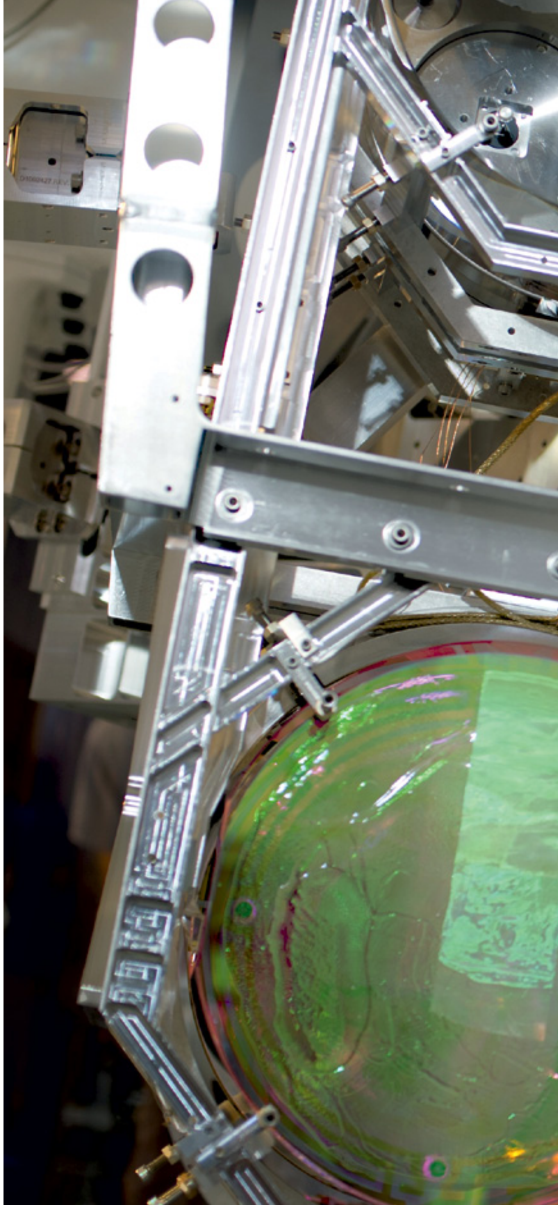
Starting in late 2007 and ending in 2015, the Advanced LIGO (aLIGO) Project will deliver detectors which will have locked for several hours and will be capable, after post-Project tuning, of a factor of 10 improvement in sensitivity over initial LIGO. This brings an increase in the volume of space that can be searched of a factor of 1000, and with an increase also in the frequency range down to 10 Hz, detections of the standard candle of binary neutron stars are expected weekly to monthly. Three interferometers are built, with the current plan to place one of the three in India to extend the baseline of the LIGO – and worldwide – network of detectors. This note gives an overview of the evolution of Advanced LIGO from the first ideas to the projected completion.

The path to the Advanced LIGO design

When LIGO was proposed to the NSF in 1989, we saw well how to make a detector that could plausibly detect gravitational waves. However, it was clear that further developments in the instrument design would be needed to assure detection and the creation of a new astrophysical tool. While the first generation LIGO instruments went through design and fabrication, R&D for the second generation was already underway. Much of it was carried out in the greater gravitational wave community, as the Lab scientists and engineers were fully occupied with the task of bringing initial LIGO into being.

By 1999, a few key notions had gelled that helped establish a conceptual design for Advanced LIGO and gave some exciting predictions for the sensitivity that could be achieved: the low-frequency noise limit would be determined by the suspension thermal noise in fused silica fibers; the quantum noise would be managed through the use of dual recycling; and the laser power would be the maximum that could be tolerated with the lowest absorption coatings and substrates available. The notions were drawn together into a White Paper (see 'Further Reading' at end) by Ken Strain of Glasgow, Eric Gustafson of Stanford, and David Shoemaker of MIT. Rai Weiss of MIT, who had laid out the vision for interferometric gravitational-wave detectors in 1972, co-signed.

There were still a number of key design decisions to be made. *Should a passive approach using multiple pendulums be used for the seismic isolation, or an active servo-control approach?* The multiple passive approach had been shown to be quite successful in Virgo, but several technical points tipped the decision in favor of the active system – the ability to handle a payload of



Betsy Bland assesses the H2 ITMY test mass, prior to insertion into a Hanford vacuum chamber. The greenish hue is due to the application of FirstContact(TM), a temporary barrier that shields the optic from particulate contamination.

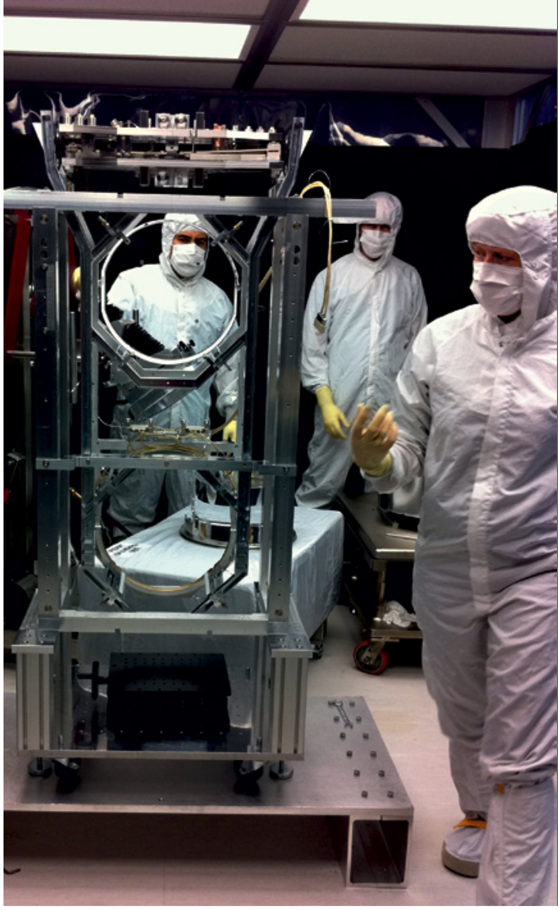
David Shoemaker

David Shoemaker is the Director of the MIT LIGO Laboratory. On the imaginary axis labeled 'spare time' he plays thrash acoustic guitar and keeps an 1847 colonial house above water.

multiple optics; and the possibility of making trades on performance metrics after installation by tailoring the control laws.

Should the test mass substrates be sapphire, with attractive properties of thermal conductivity and low mechanically losses, or should the safer approach of fused silica be used to avoid fabrication and polarization complications? Several full-size 40 kg sapphire prototype test masses were produced and characterized, and many of the required characteristics were demonstrated. However, at the same time, we started to realize that the dielectric coating on the mirrors would dominate the thermal noise at mid--frequencies, and that the thermo-elastic noise in the sapphire substrates would dominate at low frequencies. A last very important point relates to a philosophy that drove the design of Advanced LIGO: we wanted to be confident that we were choosing low-risk technologies, and when a decision needed to be made, sapphire held too many uncertainties to be selected.

The 10 tonne BSC6 chamber departs the Y mid-station at LIGO Hanford, destined for the end station building. The chamber was relocated to transition the H2 interferometer from it's Initial LIGO 2 km length to that of Advanced LIGO, 4 km. With the advent of LIGO India, the H2 chambers now remain empty, an opportunity for future interferometer configurations.



(L-R) Gerardo Moreno, Giles Hammond and Betsy Bland with the ITMY test mass, newly suspended from a penultimate mass. The test mass is suspended from the penultimate one by CO_2 laser-welded fused silica fibers, forming a monolithic structure.

How should the gravitational-wave strain be read out, using synchronous demodulation, or at the baseband by shifting slightly away from the interference minimum? The synchronous modulation-demodulation approach had been used in all of the instruments to date, but the approach brought light which had been low-pass filtered by the storage time of the 4 km arm cavities to interference with the 'fresh' light from the laser, putting extreme requirements on the frequency stabilization. After some careful modeling and some prototype experiments, we chose the new DC offset readout.

What approach to creating a 200 W laser would be best: amplifiers, injection locking, stable or unstable resonators? Several groups around the world built prototypes and characterized them, and we found that multiple approaches could probably be made to work, but again we chose the approach which was most sure to work, a master oscillator, amplifier, and injection-locked power stage.

For all of these key decisions, the newly-formed LSC Working Groups took on the charge of jointly planning research, and making decisions about paths not to follow, and establishing adequate but not excessive duplication of research. In parallel, a Project Office was established in the LIGO Laboratory, and both the technical baseline and the cost and schedule profile was made concrete and documented. The design had matured considerably by 2003, leading to a proposal to the NSF for a complete replacement of the LIGO detectors while reusing the infrastructure established for initial LIGO. A number of successful reviews followed, and in October of 2007 the Advanced LIGO Project started.

The Project profile

The aLIGO Project is carried out under the NSF's Major Research Equipment and Facilities Construction account. The NSF cost is $205 M US; a consortium of UK institutions contributed ~$14 M in research and equipment in the domain of suspensions, Max Planck's AEI contributed also ~$14 M in research and pre-stabilized lasers, and Australia contributed ~$2 M in research and sensing equipment. At the end of June 2012, the NSF had delivered $175 M in funding, exactly according to the plan; thank you, NSF!

The Project has uncertainties in both schedule and cost, and this is accommo-

Figure 1: The Project staffing in Full-Time Equivalent persons as a function of date

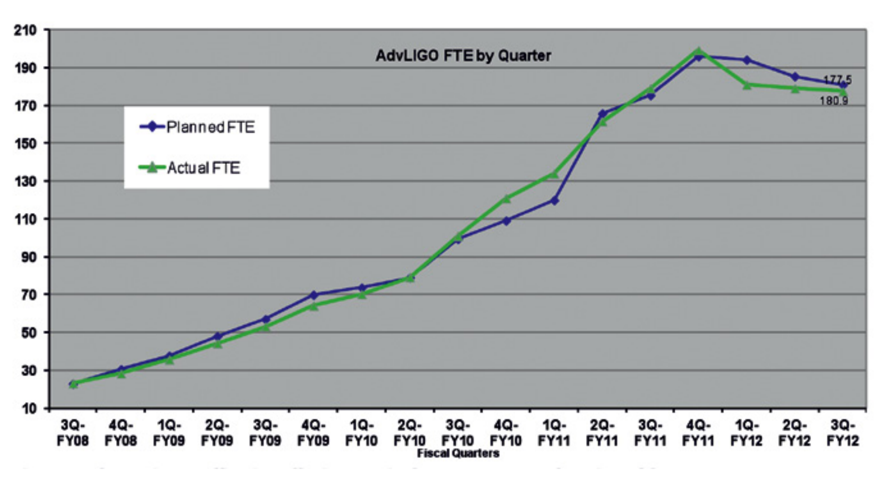
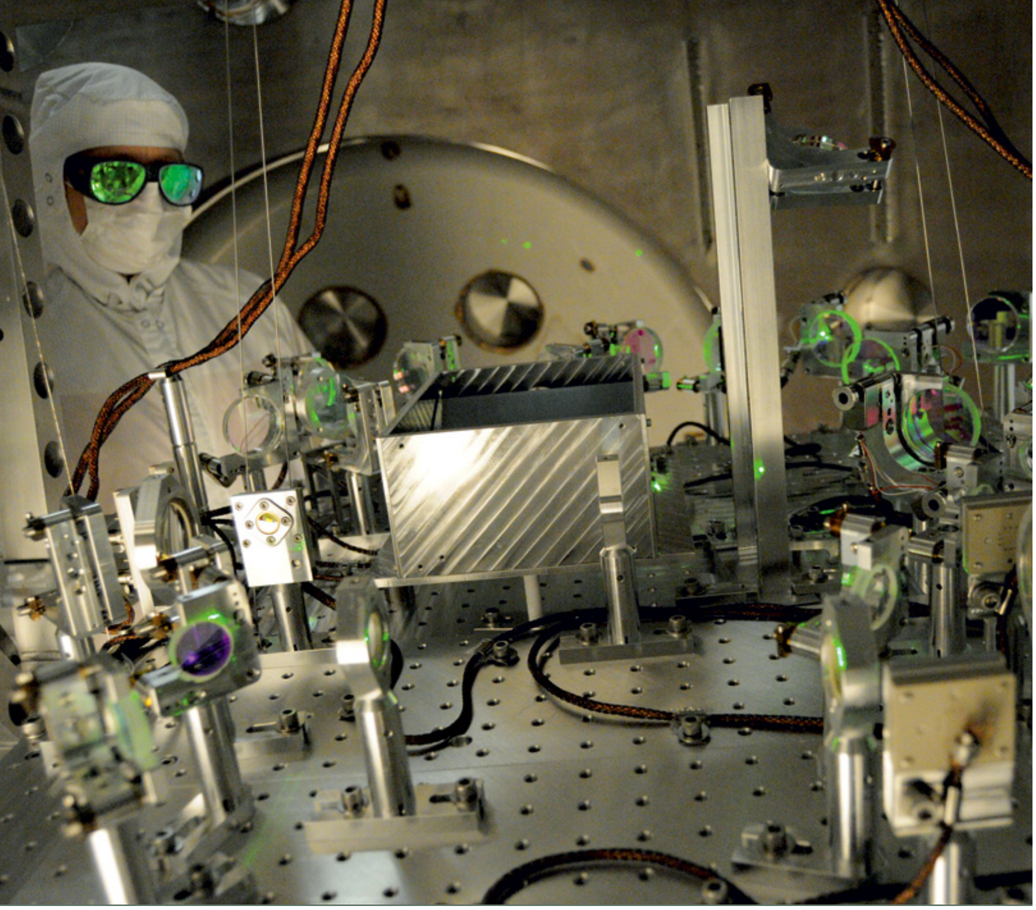


Figure 2: The aLIGO Project 'earned value' - progress as measured by the funds expended. The vertical scale is in thousands of dollars, and the horizontal axis is in fiscal years (Oct 1 – Sep 30).June 2012 is indicated by the vertical line. The 'step up' toward the end of 2014 is due to the just-in-time procurement of computing resources for data analysis.

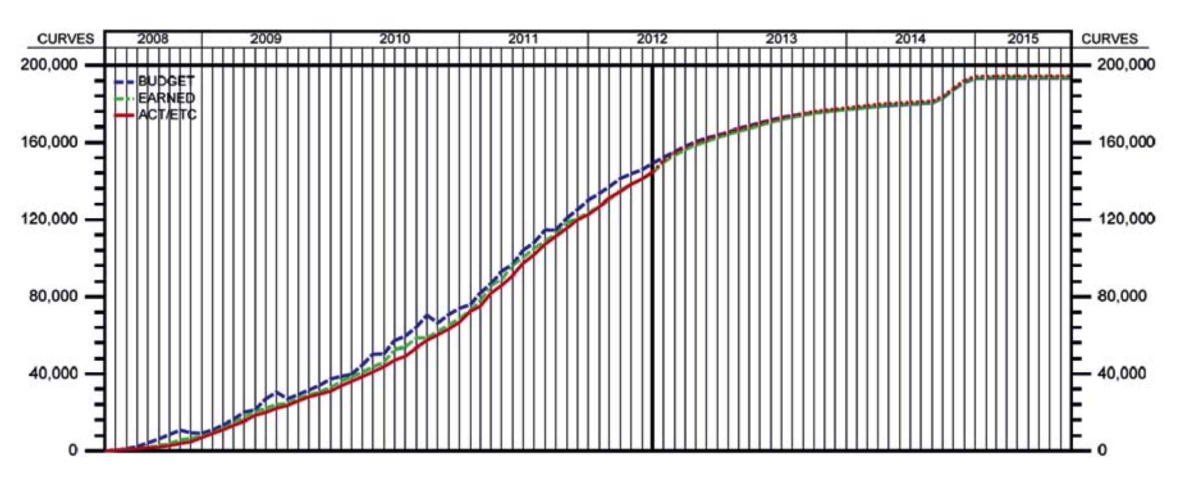


Keita Kawabe inspects the in-vacuum Transmission Monitor at one of LIGO Hanford Observatory's two end stations. The suspended bench and optics are intended to receive infrared light transmitted from an interferometer arm. Furthermore, these dichroic optics also transmit green laser light into the arms, providing a simple way to initiate the control of interferometer test masses (lock acquisition).

dated in the plan with cost and schedule contingency. The cost contingency was estimated at the beginning of the project, based on engineering practice, and 23% of the initial funding total was designated to handle unexpected costs. The schedule of roughly 70 months had also 7 months of schedule contingency for each interferometer. We have used both, roughly in proportion to the completion of the project to date; we are working hard to preserve enough contingency to successfully complete the project, as no additional funding can be supplied.

The Advanced LIGO Project is currently at peak staffing levels for the project, and in fact most of the cost contingency use to date has been for increased staffing over the originally planned levels. Staffing at the end of June 2012 includes ~232 individuals representing ~170 Full Time Equivalents (FTEs). From this point forward, people will start to move off the aLIGO payroll, with all gone at the end of the Project. Many of the people working on the Project are LIGO Lab long-term staff, and will play roles in the operation of the instrument when their Project responsibilities are finished. (Figure 1 previous page).

A snapshot in June 2012 shows that the project is 3/4 complete.



Almost all equipment has been fabricated and assembled, the infrastructure is updated, and the instruments are being installed. (Figure 2 previous page).

The project is organized technically into subsystems: SUS (suspensions), SEI (seismic isolation), PSL (pre-stabilized laser), PM (project management), ISC (interferometer sensing and control), IO (input optics), INS (installation/integrated test), FMP (facilities modifications and preparations), DCS (data computing and storage), DAQ (data acquisition), COC (core optics), and AOS (auxiliary optics system). Most of these elements are ~90% complete. INS is the major activity at present, and DCS is held off until the end of the project to get the best computing power per dollar (taking advantage of Moore's tendency). (Figure 3).

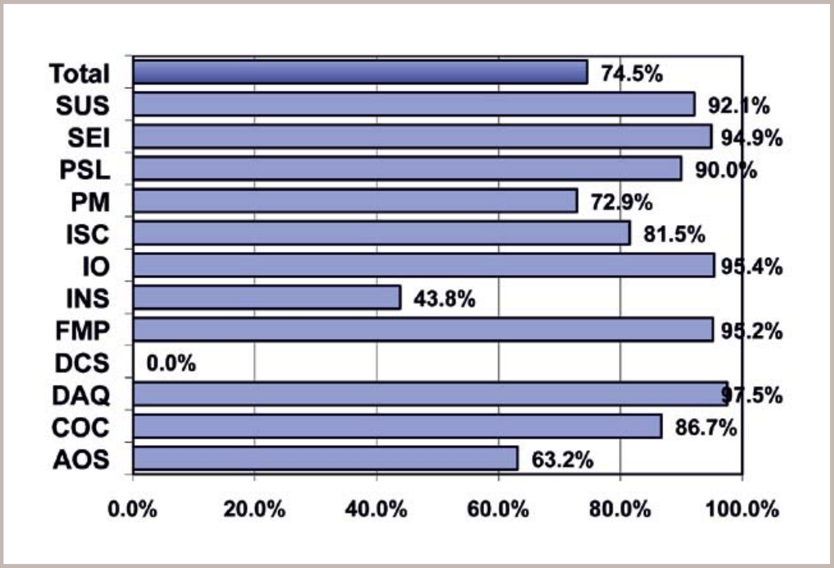


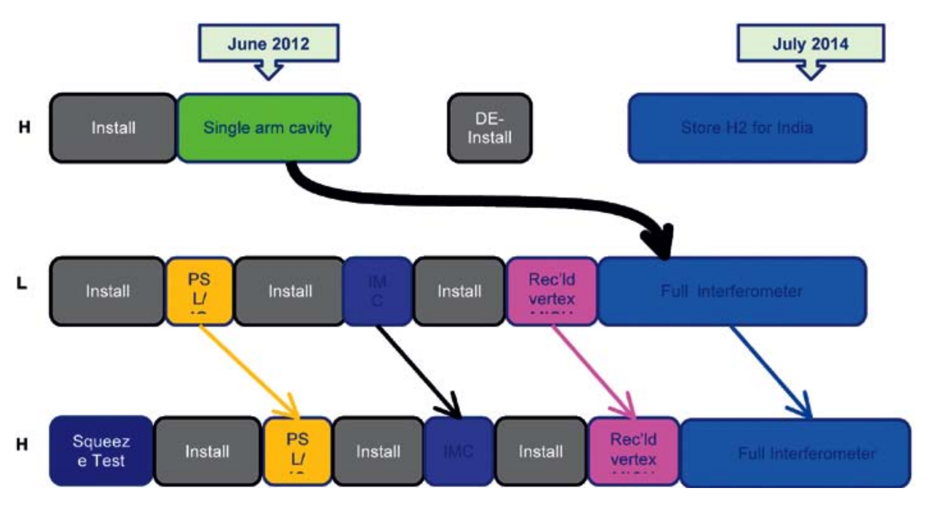
Figure 3: Completion by subsystem as of June 2012.

Lessons learned from Initial LIGO

Initial LIGO required a quite lengthy process – referred to as 'commissioning' – to make the transition from the point of 'all equipment installed' to operating at full sensitivity. This was in some measure due to the fact that it was the first km-scale instrument to be brought into operation, and we had a lot to learn! But we realized that we could make changes in both the instrument design as well as the process of installation and integrated test for Advanced LIGO that could speed up this process. In the instrument design, an arm-length stabilization system was included – the 4 km Fabry-Perot cavities are illuminated from the back with a wavelength of light for which the mirrors form a low-finesse cavity, offering a much broader range over which useful control signals can be recovered. This gives an independent control over the length, making the initial 'locking' of the system more deterministic. In the installation/integration, we chose a path that has extensive testing of subsystems before they are installed, key

Figure 4

The flow of the Project. The Hanford H2 interferometer is in July 2012 demonstrating the arm-length stabilization system; it will then be de-installed and the parts set aside for LIGO-India. The information from the Single Arm Cavity will inform the Livingston L1 detector where the Input Mode Cleaner (IMC) will be first tested, followed by the Recycled Vertex Michelson. All the results from the L1detector will inform the installation and testing of the Hanford H1 detector.

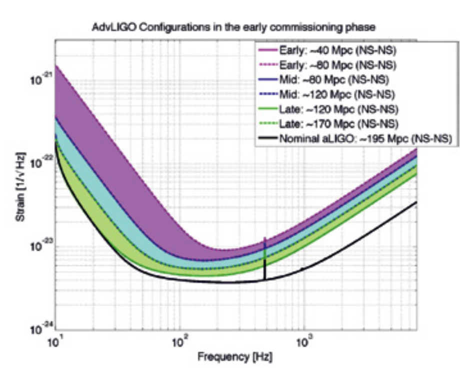


elements tried together as early as possible, and lessons learned then passed to the next detector. With this philosophy in mind, we are now (July 2012) testing this arm-length stabilization system on one arm of the Hanford detector, which also provides tests of the optics, thermal focus compensation, suspensions, seismic isolation, and data acquisition systems. We will be shortly be testing the central Michelson interferometer at Livingston in a similar spirit. (Figure 4)

With these changes, we believe that the aLIGO detectors can reach an interesting astrophysical sensitivity not long after the handoff from the Project back to the Laboratory and the greater Collaboration. Our best guess at the evolution of sensitivity at this time suggests that a first observational run could take place in 2015, and a sensitivity that would lead to detections from year-long runs in 2016 or 2017.

Figure 5:

Plausible evolution in the sensitivity of the Advanced LIGO detectors through the tuning process. While it will certainly take several years to reach the full sensitivity enabled by the design, science runs with a good chance of detection could take place by 2016.



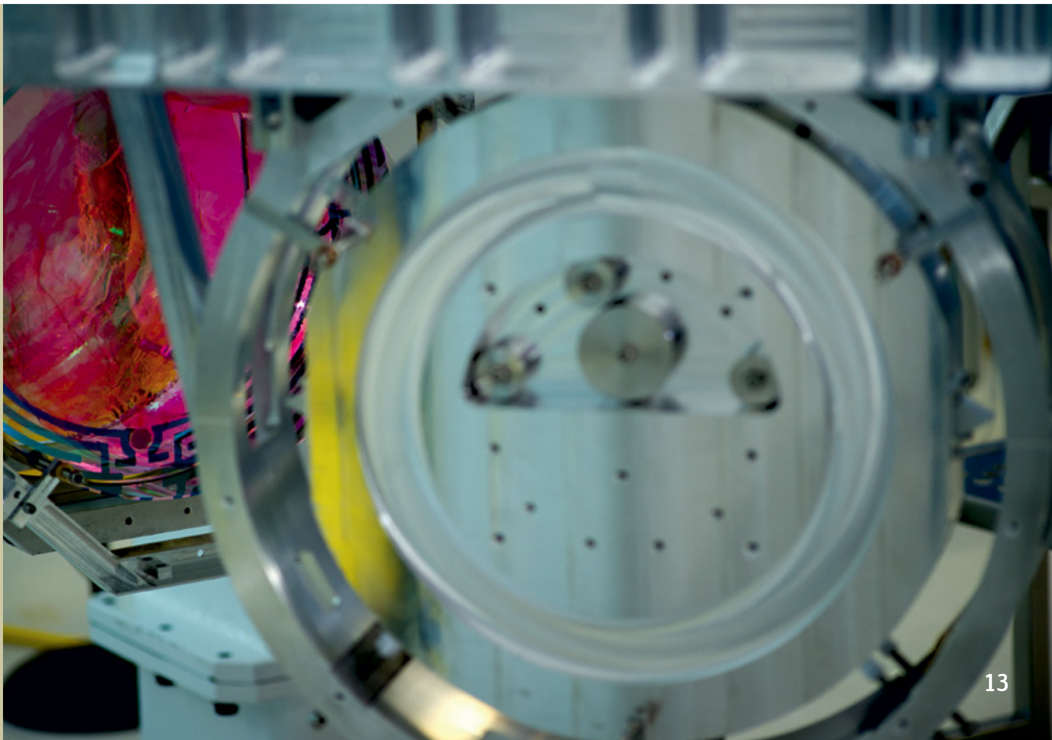
Further Reading:

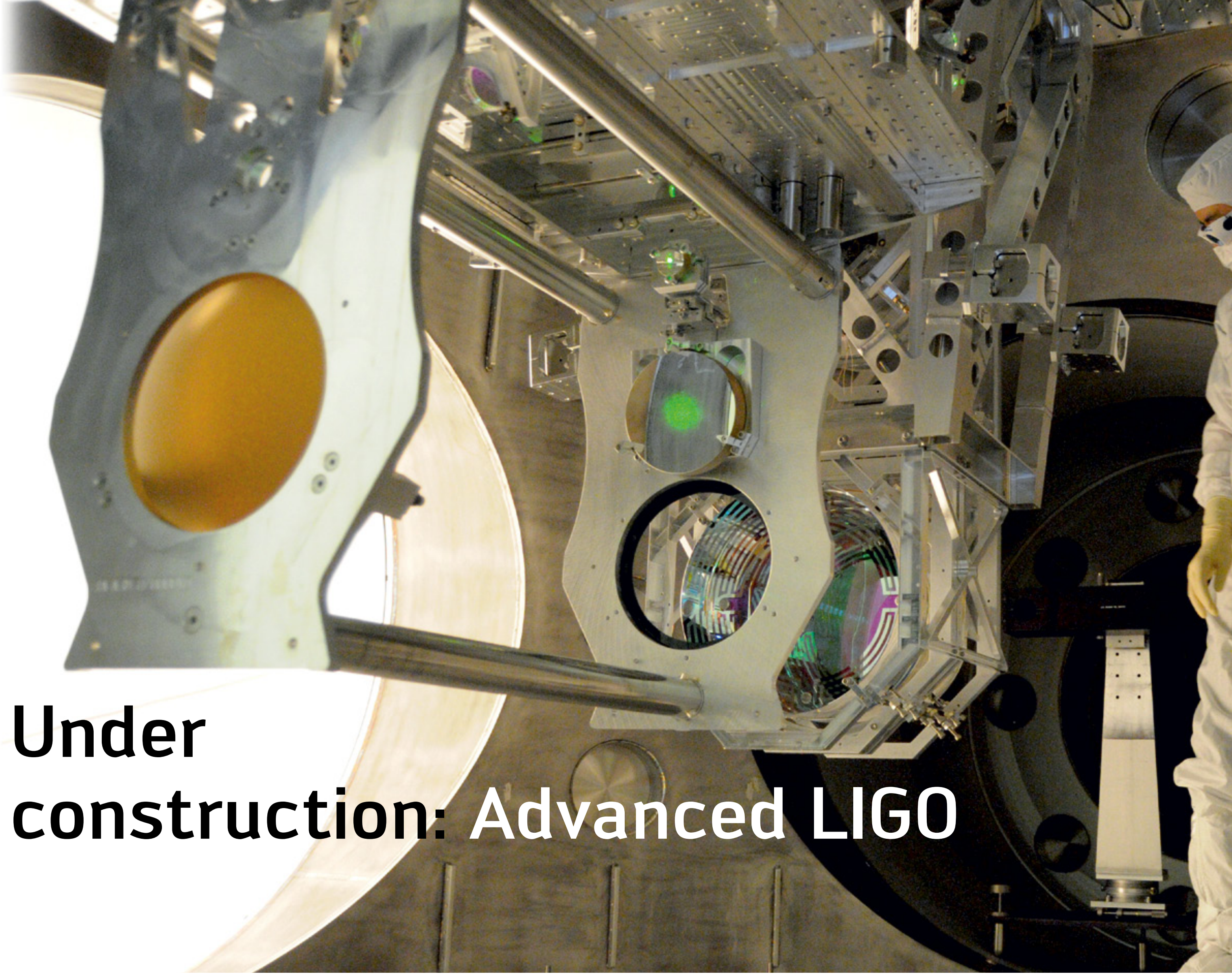
LSC White Paper on Advanced LIGO: LIGO-T990080-x0

Rai Weiss' 1972 article establishing the approach and the experimental challenges: P720002– v1

Advanced LIGO Web Pages: www.advancedligo.mit.edu

Multiple suspensions on a single seismic platform. In the background, pink-hued owing to the temporary application of a FirstContact(TM) contamination barrier, is the H2 ITMY test mass at LIGO Hanford Observatory. In the foreground is a metal dummy mass, standing in for the H2 FMY fold mirror. Prior to shutting doors on chambers and pumping down the vacuum envelope, FirstContact(TM) is removed from all optics.





Under construction: Advanced LIGO

Mike Landry

Mike Landry is a Lead Scientist at LIGO Hanford Observatory, where he heads up the local installation of Advanced LIGO. Mike spends the bulk of his non-LIGO time trying to keep up with, and recover from, his three young children.

Brian O'Reilly

Brian O'Reilly is a Senior Staff Scientist at the Livingston Observatory, where he oversees Advanced LIGO activities including installation. Young children, a dog, and the occasional hurricane account for that aspect of existence previously known as "spare time".

Towards Advanced LIGO

Advanced LIGO Installation began on October 20, 2010. At that time, both LIGO sites transitioned from a state of science-mode data collection, to one of complete disruption and moderately-controlled chaos as we deinstalled the existing detector which had served us so well. Our goal was clear: to install and test the new Advanced LIGO apparatus.

The planned installation has the Livingston Observatory (L) as the pathfinder: it is here we follow a natural progression of L1 installation and integration, from laser, to the input mode cleaner, to the vertex Michelson, finally adding 4 km arms. At the Hanford Observatory (H), with room for two interferometers, the path was more complicated. We were to deinstall on the H2 interferometer and assemble a single arm for testing of a new green-laser technique for interferometer lock acquisition. Concurrently we held off operations on H1 to allow for the addition of a squeezed light source at the dark port of that interferometer. After these important but disruptive experiments we were to continue with the installation along the lines of LLO on both LHO detectors. The advent of LIGO India has the Project Controls office furiously re-planning.

Deinstallation meant that chamber domes and doors had to be removed, and Initial LIGO payloads of seismic isolation, suspensions, optics, baffles, fixtures and photodiodes extracted. As staff perused the

Figure 1: In-chamber at the end-Y station at Hanford. Seen in the background are the suspended end reaction and test masses, while in the foreground is the Transmission Monitor telescope. Keita Kawabe and Dan Hoak are working on the alignment of the green laser, to be injected from the end station and into the 4km arm, part of the Arm Length Stabilization system for lock acquisition.

mounds of formerly-vacuum-compatible equipment lying out on the floor of the experiment halls, many were nostalgic about so much hard work seemingly lost. Fred Raab at Hanford had a different take: "Looks like progress", he responded. Many of these components were distributed to the collaboration for scientific use, or outreach efforts. Others were stored at the sites. Remaining items were recycled or scrapped.

In preparing for installation, we asked many people how to enact such a large-scale project safely for both staff and equipment, and yet do so within a realistic time and budget. Posed this question, former Fermilab director Mike Witherell recommended The Checklist Manifesto, by A. Gawande. In it, Gawande, a surgeon, describes the effectiveness of aviation-style checklists in the operating theatre, and indeed for use in any complicated undertaking. Unlike a detailed procedure, aviation checklists are minimalist, comprising only what you cannot afford not to do. We've thus added this flavor of checklist in our installation procedures at both sites.

Initial LIGO optics suffered from significant particulate contamination. We knew of a specific source of our own making: the chromium and iron oxides on chamber interiors, the result of a multi-hour 800 °C annealing process during fabrication. This dust source had to be removed in a way that introduced no hydrocarbons into the vacuum envelope. A protracted effort was launched to develop a cleaning and testing regime, including pneumatically-driven wire-brush tools with vacuum assist to liberate the oxide layer, laborious inspection, wipe-down and FTIR (Four-Transform Infrared Spectroscopy) analyses of chamber walls to ensure the process was clean. This back-breaking work is now largely complete at both sites.

LHO

Installation at LHO (LIGO Hanford Observatory) has initially centered on the H2 y-arm, and the green lock acquisition experiment there. Once the chambers were moved (see the article by D. Ingram in this issue on vacuum modifications), cleaned and the squeezer experiment completed, we were able to assemble the first "cartridge", comprising a BSC Internal Seismic Isolation (ISI) platform and a quadruple suspension. The fused silica test mass is laser-welded to the penultimate mass by glass fibers, forming a monolithic structure. The assembly, test, and installation of this precious scientific payload was not without incident however: on two occasions we broke the glass fibers that suspend the ITM test mass. On the first occasion, a dropped fastener defeated catch-pans, slamming into and shattering the glass supports. Once in-chamber, the replacement fibers too were broken, this time owing to errant shaking allowed by a bug in the front-end computer code.

Currently, we have science payloads installed in an end station (Fig. 1) and corner station, with green light injected from the end. The first integration experiment is thus underway, with cavity locking now routine, and tuning of seismic, suspension and interferometer sensing and control loops the daily challenge.

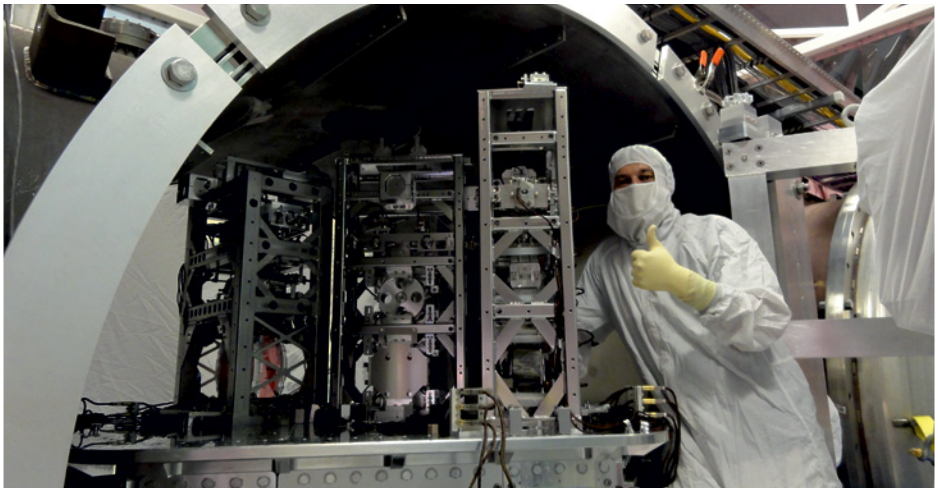


Figure 2: Matt Heintze expressing satisfaction that several triple suspensions are are safely installed in the vacuum system. This HAM2 chamber layout is the most crowded of any HAM chamber in Advanced LIGO.

LLO

The first major installation at LLO (LIGO Livingston Observatory) involved the removal of the existing Laser enclosure and the construction of a new improved version. Given that Advanced LIGO uses a 200 W laser the requirements for cleanliness are much stricter than that of the 10 W laser employed in Initial LIGO. The new PSL enclosure went up rapidly and by spring of 2011, the new laser was installed and commissioned. The laser was supplied by our colleagues at LaserZentrumHannover in Germany and came with a very capable team of experts, who worked with LIGO staff to achieve this milestone.

The HAM2 and HAM3 tables (see Fig. 3), which comprise the Input Mode Cleaner (IMC) have been populated with optics. This effort has been lead by our collaborators at the University of Florida and by our local suspensions team. The HAM2 chamber (Fig. 2) is easily the most complicated HAM table to populate and required a major effort by all concerned. By design the IMC volume is isolated by septum plates from the rest of the corner station vacuum envelope. This allows us to proceed with commissioning this piece of the interferometer while continuing the rest of the vertex installation.

Each installed chamber in the Advanced LIGO detector represents years of effort by many LIGO staff and scientists. It is very gratifying to report that after the installation our commissioning team was able to make rapid progress and align and lock the IMC in air. Commissioning is now proceeding with this volume under vacuum. The care taken in the design and installation is reflected in the fact that the initial alignment of the IMC required only minor tweaking by the commissioning team (Fig. 4).

Outlook

The Advanced LIGO project remains the prime focus of all LIGO lab activity. We are at an exciting juncture where years of design, testing and assembly are now coming to fruition. At LHO we are routinely locking a single arm of the advanced detector, at LLO we are likewise commissioning the input mode cleaner. By this time next year the L1 detector should be completely installed and H1 will not be far behind. At that stage, commissioning the detectors and moving towards our first science run will dominate our efforts. It is worth reflecting as we make this transition on the many people who have devoted significant portions of their careers to the success of this venture.

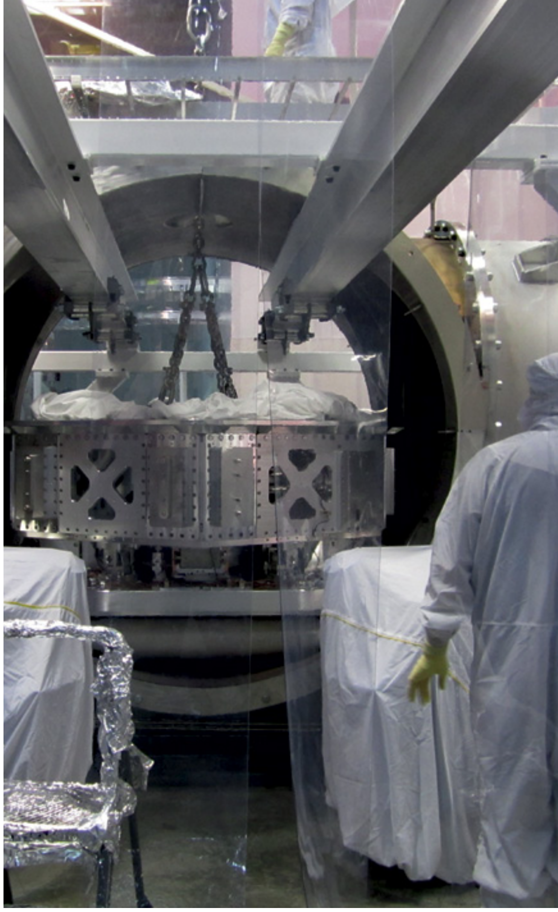


Figure 3: Insertion of a seismic isolation platform into the HAM3 chamber at Livingston. The table is lifted, rolled in on trolleys, transferred to the crane using an aperture in the ceiling of the chamber, and finally lowered onto the support tubes.

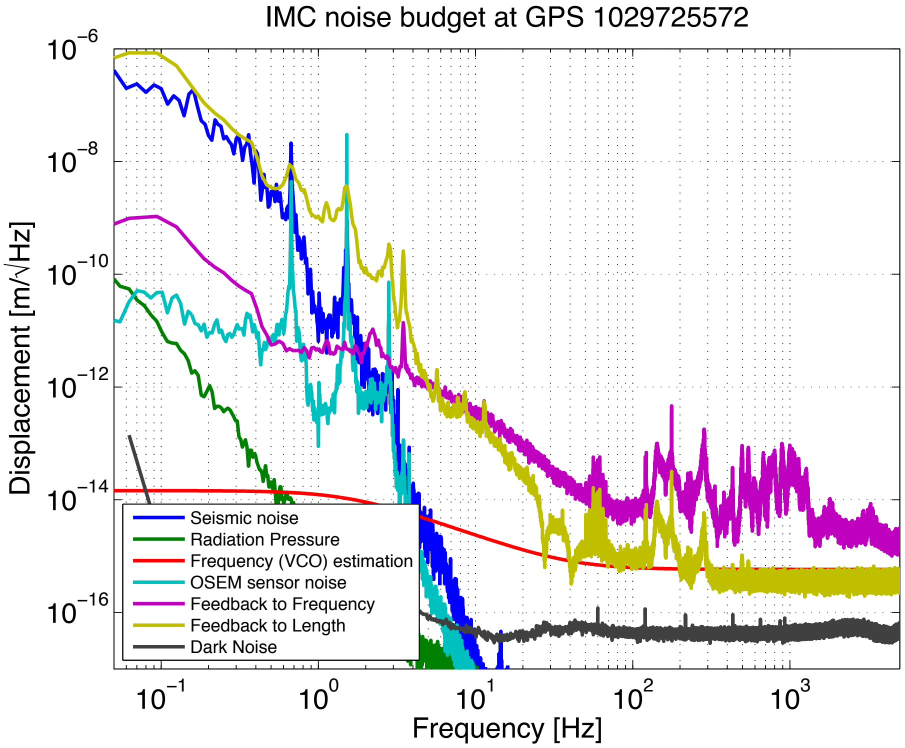


Figure 4: Measured displacement noise determined from length and frequency control signals in the Livingston Input Mode Cleaner on Aug 22, 2012. Also shown are estimates of noise contributions from seismic motion, radiation pressure, and VCO oscillator noise (the last estimated from Initial LIGO).

Inspecting the beamtube manifold for evidence of particulate contamination

In-chamber cleaning proved a laborious task – slow, meticulous work.

Vacuum System Modifications in Advanced LIGO

Dale Ingram

Dale Ingram is the Education and Outreach Coordinator at LIGO Hanford Observatory. He joined LIGO in 2004 after serving for 20 years as a science teacher near Portland, Oregon.

The Advanced LIGO program will place new interferometer components inside the detectors' vacuum systems. LIGO's vacuum infrastructure remains the same as the Initial LIGO design except for a limited number of changes that were completed at both LIGO sites in 2011. The Advanced LIGO vacuum modifications were driven by several design enhancements that will help boost the performance of the advanced detectors.

Tube section replacements

The input optics in a LIGO interferometer lie between the laser system and the beam splitter. Input optics prepare the laser light to reach the beam splitter and to travel through the long arms of the detector. The main Initial LIGO input optics were three suspended mode cleaner mirrors (to improve the quality of the light), three suspended mode-matching mirrors (to increase the beam size) and a single power recycling mirror. Power recycling in Advanced LIGO will require three mirrors instead of one. The chains of mode cleaning, mode matching and power recycling optics will create an Advanced LIGO beam path of greater complexity than the Initial LIGO input path. Additionally, the Advanced LIGO input suspensions are larger than their predecessors (see input-output diagram on next page).

The output line of a LIGO detector consists of the beam path between the beam splitter and the antisymmetric or detection port. The Initial LIGO detectors housed very few in-vacuum output optics. This changed in Enhanced LIGO (2009-2010) with the addition of output mode cleaners in single vacuum chambers at the end of the output beam paths. The Advanced LIGO detectors will contain a chain of three signal recycling optics plus, in the final output chamber, an output mode cleaner.

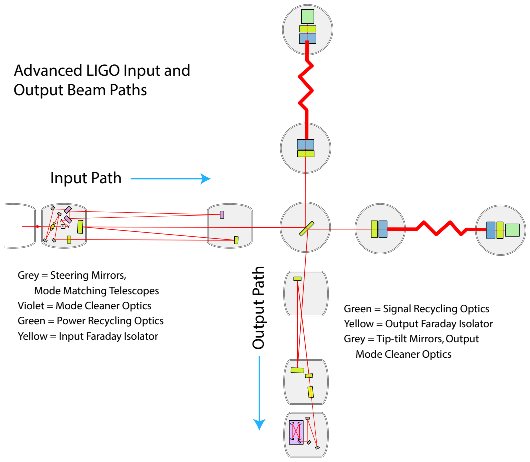
On the input and output lines in Advanced LIGO, more optical components and larger suspensions generate the need for a path of greater width in the vacuum system. To create the necessary interior space, crews at LIGO Livingston and LIGO Hanford removed the 76 cm diameter sections of input and output tubing and replaced these with 213 cm diameter sections manufactured by GNB Corporation. The 76 cm Initial LIGO sections were 14 meters in length with masses of 2820 kg. 14 meters of 213 cm tubing would exceed the lift capacity of LIGO's overhead cranes. GNB's replacement sections span roughly half of the length of the original tube sections; two of the replacement sections were joined together on each input and output portion of each LIGO interferometer to create the full vacuum paths. Even at 7 meters of length rather than 14, the new 4270 kg sections were a challenge to move into position and install.

Vacuum Chamber relocations

The Advanced LIGO input and output beam path changes described above also required the relocation of one horizontal access module (HAM, the smaller of LIGO's two styles of vacuum chamber) on each input and output line of each interferometer. Chamber relocation presented another industrial-scale challenge with a LIGO twist – how could a crew dislodge hundreds of pounds of concrete in which the HAM footings were encased without contaminating the clean LIGO Laser and Vacuum Equipment Areas (LVEA's) with concrete dust? The solution provided an opportunity for real-time problem solving as the chamber relocation crews devised an exhaust method that would capture dust from the chipping operation before the particulate could escape to migrate around the LVEA. Once cleaned and lifted into place, the 4360 kg HAMs were anchored and cemented after precision surveying was used to verify the chambers' position, level and alignment.

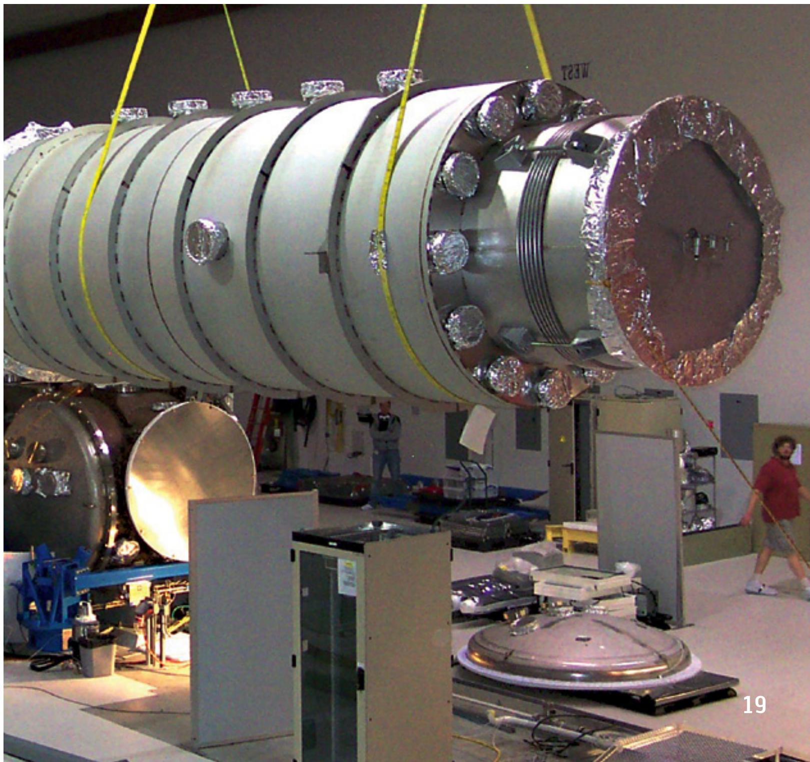
The Hanford site (LHO) houses two interferometers, one 4 km in length (H1) and the other 2 km in length (H2). Laser beams from the two detectors share the same beam tube along the detector arms. The Advanced LIGO design called for H2 to undergo conversion to the full arm length of 4 km. This required the removal of the pair of Beam Splitter Chambers (BSC's, the larger style of vacuum chamber with masses of 8600 kg each) from the middle of the vacuum system followed by the transport of the chambers down the arms and their relocation in the end-stations. The holes left behind at the mid-stations were sealed with replacement tube sections. The BSC moves occurred before the suspension of H2 infrastructure changes in light of H2´s possible relocation to India.

Advanced LIGOs vacuum system changes will not be obvious from a distant view, but the successful completion of these tasks provided a string of memorable challenges to the teams that did the work. Two companies – Excel at the Livingston site and Apollo Sheet Metal Inc. at the Hanford site – provided contract personnel that played lead roles alongside LIGO vacuum engineers in the craning of multi-ton objects through spaces that provided only centimeters of clearance and in the mounting of these pieces into their final positions with tolerances in the hundreds of microns. The precision of these operations provides a key step in the path towards Advanced LIGO design sensitivity.



The Advanced LIGO beam layout. Note the folded input and output paths.

Moving a HAM chamber(below left), installation of an Advanced LIGO input tube (below right).



Monolithic Suspensions: From the Lab to Advanced LIGO

At the heart of each Advanced LIGO (aLIGO) detector are four large mirrors – test masses – made of fused silica, two in each arm of the interferometer. To look for gravitational waves we measure and compare the relative separation of the test masses in each arm. Each of these 40 kg mirrors is delicately suspended from another silica mass by four silica fibers – a considerable change from the design used in Initial LIGO, where the mirrors were each suspended by a single loop of steel wire. The new construction is known as a "monolithic" suspension since the suspension fibers, the mirrors, and the bonds between them are a single piece of a single material. Why the change? In this article we aim to answer that question and to describe how the aLIGO monolithic suspension design was developed from early lab experiments at Glasgow and elsewhere to the final product currently being installed.

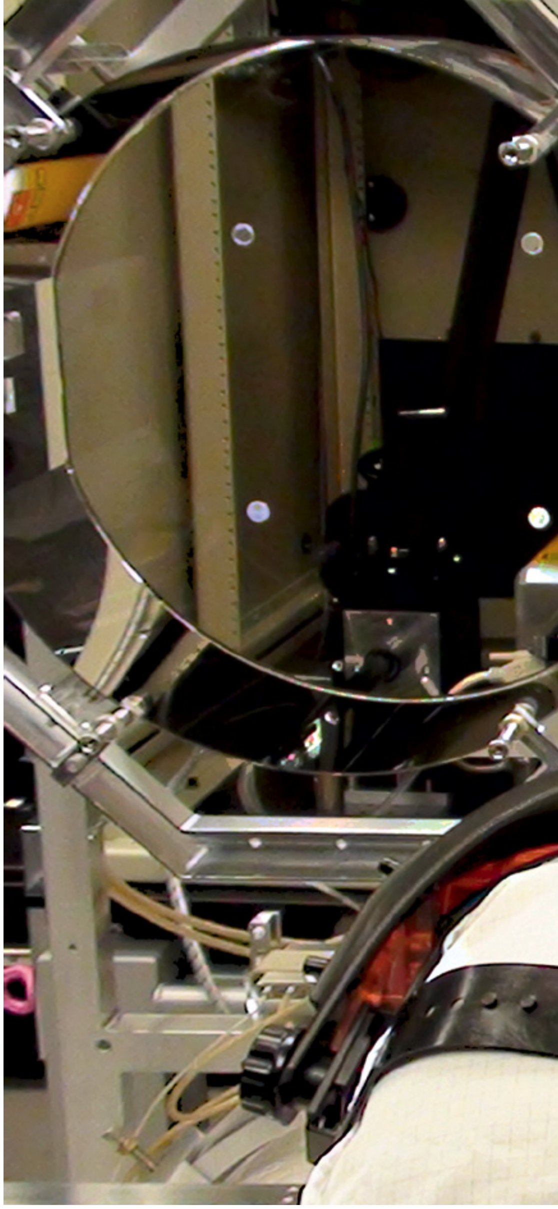
New technology needed

The principal job of each suspension is to support a mirror while isolating it from external motion. Any motion that does get through the seismic isolation system and the suspension contributes seismic noise that could mask gravitational wave signals. To reach the sensitivity goal of aLIGO, the suspensions must be much more complicated than those used in initial LIGO. Instead of simply hanging the test mass from the suspension point, a chain of suspended masses is used, where each additional stage provides ever greater attenuation of seismic noise. But attenuating the external motion alone is not enough: the suspensions also contribute some additional motion of their own – thermal noise – and this must also be reduced.

Thermal noise arises from the random movement of atoms in the material from which the suspension is made. The magnitude of the noise is related to the amount of mechanical loss in the material – it's a mechanical analogue of Johnson noise in resistors, familiar to electrical engineers. Reducing the thermal noise motivated the change from the steel wires of Initial LIGO to fibers made of fused silica – the same material as the mirrors – which has intrinsic losses three orders of magnitude lower than steel! The technology needed to build today's all-glass suspensions are a product of decades of experience.

Early work

Early work on fiber based suspensions for the gravitational wave community began with research conducted by the Moscow group on the development of low-loss suspensions in the late 1980's. This included the development of a torsion balance based on a 5 m fused silica fiber for testing the Newtonian law of Gravity. From 1990


Welding the monolithic suspension at LIGO Hanford

Norna Robertson

Norna Robertson is a lead scientist in the LIGO Lab at Caltech and heads the Advanced LIGO Suspensions team. She has worked in the field of gravitational wave detection for more than thirty years, much of which has been in the area of suspensions and vibration isolation.

Giles Hammond

Giles Hammond is a Reader within the Institute for Gravitational Research at the University of Glasgow. His research focuses on the measurement of charging and thermal noise in gravitational wave detectors, the development of suspensions for current and future detectors, and the design and fabrication of MEMS for gravity sensing.

onwards, the Moscow group worked on the development of ultra-low-loss monolithic fused silica pendulum suspensions. The mechanical loss is quantified using a Quality, or Q-factor, where higher Q-factors imply lower losses.

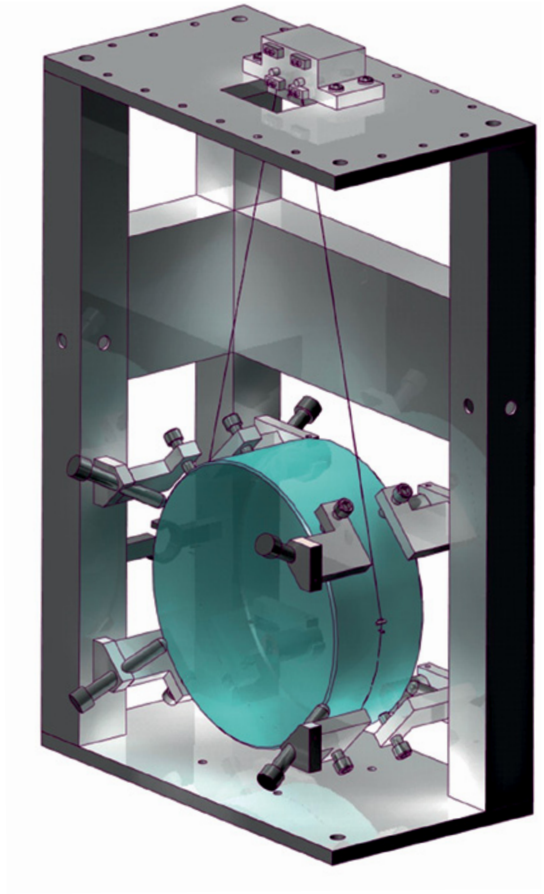
Early measurements of pendulum Q-factor were made on a single fiber pendulum with a suspended mass of 30 g. Later work increased the mass up to 2 kg with quality factors in excess of 100 million. By comparison, the Initial LIGO steel wire suspensions show a Q of around 100,000. This work showed the promise of fused silica as a material for advanced gravitational wave detectors and was built on in parallel by the Glasgow group.

Experience at GEO

The use of fused silica was adopted at an early stage (circa 1996) in the baseline design of the GEO600 detector located in Ruthe, near Hannover in Germany. The shorter arm length of the GEO detector (600 m), compared to VIRGO (3 km) and LIGO (4 km), required the use of advanced suspension techniques to suspend the optics of the interferometer to lower the thermal noise contribution. GEO600 uses a triple stage pendulum suspension with a lower stage of fused silica.

Fused silica was the material of choice as it could be formed into strong fibers and readily welded with a hydrogen-oxygen flame to attachment points on the side of the test masses. These attachment points, or "ears", are bonded onto the side of the fused silica mass using a process called hydroxide-catalysis bonding. This bonding technique was developed for the Gravity Probe-B mission in order to manufacture a rigid star tracking telescope which would maintain accurate pointing under a variety of thermal and mechanical loading conditions. The transfer of the bonding technology to the gravitational wave community was carried out collaboratively between Stanford and Glasgow and continues to be an important area of research at Glasgow for both current and future detectors, with possible application to alternative materials such as silicon.

Techniques to draw fused silica fibers for GEO600 were developed in Glasgow during 1992 to 2004. Initial work focused on using an RF oven to melt the silica, a standard



Initial LIGO steel loop suspension.

process used in industry. However, experience showed that a pulling machine based on an hydrogen-oxygen flame was a more flexible system for pulling fibers of different geometries. The flame pulling system would heat the silica stock with a hydrogen-oxygen mixture before turning off and rapidly pulling a 30 cm long fiber of diameter 200 microns. With both the procedure for bonding and pulling fibers in place a selection of dedicated personnel, both in UK and Germany, fabricated, installed and commissioned the suspensions for the GEO600 detector. These suspensions have been operating for over 13 years and show the robustness of fused silica as a suspension material. It was also clear from the success of the GEO suspensions that the advanced detector network (aVIRGO and aLIGO) would utilise fused silica suspensions as a baseline design.

Fiber-pulling with lasers

Following on from the success of the GEO work the Glasgow group continued to improve the fiber pulling process. A laser pulling machine was adopted due to the tight reproducibility of the fiber dimension and the fact that laser heating does not produce water and gas byproducts, unlike the hydrogen flame technique used earlier. The use of a 130 Watt carbon dioxide laser (with 10.6 μm wavelength) was found to be an effective method of heating the fused silica to its melting point. By drawing the silica at different speeds a variety of fibers from diameter 25 microns to more than 400 microns could be fabricated with high precision. (See the sidebar text, “CO_2 fiber pulling” for more details on the process.)

The laser-pulled fibers have been shown to be identical in strength to their flame pulled counterparts via a variety of novel strength testing procedures. Ultimate tensile stresses of up to 5 GPa are typical values for pristine fibers which exhibit no surface defects. It is amazing that a 60 cm long fiber will stretch by 4 cm before breaking at this stress! For aLIGO suspensions we hang 10 kg per fiber and the extension is about 6 mm at the nominal working load of 800 MPa. In Glasgow our tests have shown that the suspensions are extremely robust. This has included transporting an entire suspension around the Physics building much to the amusement of onlookers. Opening a lift door to find a fully suspended monolithic suspension was certainly not what you expect on a Monday morning!

Advances in fiber geometry

The particular geometry of the fibers – how the cross-sectional shape evolves along the length of the fiber – has important effects on the thermal noise of the resulting suspension, since different geometries emphasize different loss terms. An important breakthrough occurred in 2001 when collaborators from Caltech and Glasgow discovered that, for certain fiber geometries operated under a particular load, two of the thermoelastic loss mechanisms could be made to cancel out.

During 2002-2008 a variety of different fiber geometries were considered for the baseline design of aLIGO. This work was carried out in parallel by several members of the LSC including Glasgow, Caltech, and MIT. Ultimately, this research, combined with experience pulling fibers, led to the adoption of a fiber geometry with circular cross-section, thicker (800 microns diameter) around the bending regions at the ends in order to exploit the thermoelastic noise cancellation effect, and thinner (400 microns) in the center to increase the frequency of the violin mode (the mode in which the fiber would vibrate if “plucked”).

aLIGO Production

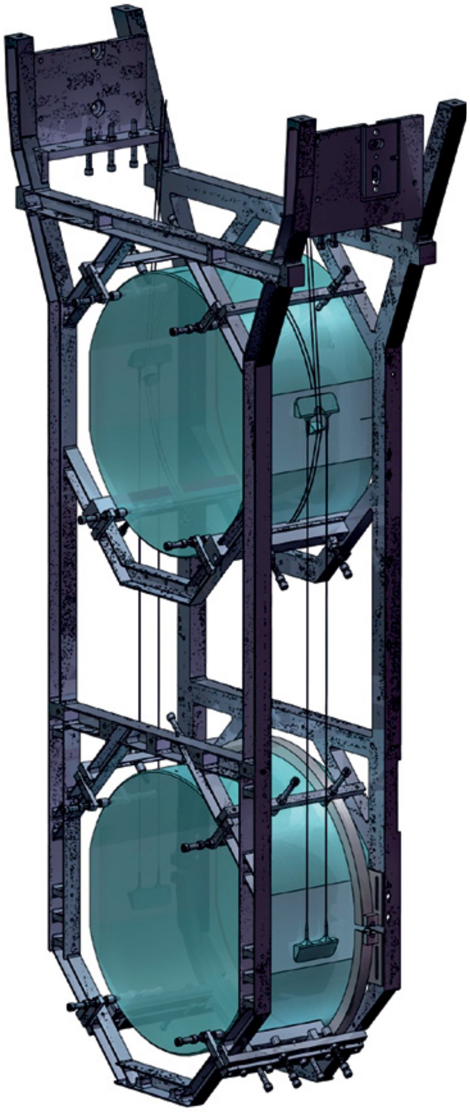
By 2008 the Glasgow group was at a stage where full scale prototype suspensions could be built and tested in the laboratory, using the CO_2 laser to pull the fibers. The same laser beam steered through an articulated arm was used to carry out welding. During welding the fiber is manipulated with a 3-axis tweezer allowing positional accuracy of better than 0.2 mm. The automated operation of the welding system has resulted in a robust and repeatable technology which was relatively easily transferred from the lab to aLIGO. In 2010 an important milestone was reached when Glasgow personnel travelled to MIT to first weld up 2 metal test suspensions, and later weld and install the first monolithic prototype at MIT. Violin mode measurements on the MIT suspension fit well with our model, giving us confidence that the suspension was behaving as expected. The fundamental mode at 500 Hz had a quality factor of 600 million, the highest value ever measured for a fused silica suspension. Once excited, the violin mode takes several days for the amplitude to decay away!

In summer 2010 the pulling and welding set-up was moved from MIT to LIGO Hanford. For aLIGO installation, all fibers are pulled in Hanford while two further lasers were procured to give each observatory its own portable welding system. Training on pulling, welding and characterization of fibers has been an important step in transferring knowledge, involving several two week trips to Glasgow for LIGO staff. Installation of the first monolithic suspension at LIGO Hanford took place in autumn 2011, realizing a major milestone for the project. As a tribute to the successful transfer of the necessary skills, all welding was performed by Livingston and Hanford staff with Glasgow personnel there to offer advice and support. At the time of writing we are preparing to carry out the first monolithic suspension at LIGO Livingston.

The future

What next? Our first priority is to complete all the monolithic suspensions for aLIGO. Assuming LIGO India goes ahead, we will also need to train our Indian colleagues, as well as help them to build up the infrastructure and equipment necessary to carry out the construction of monolithic suspensions. We are already thinking of possibilities for incremental upgrades to the current suspension design to allow us to push the noise down even further. And future detectors may involve using cryogenics and/or other materials such as silicon. There is no shortage of research and development to keep us busy.

LIGO 2012

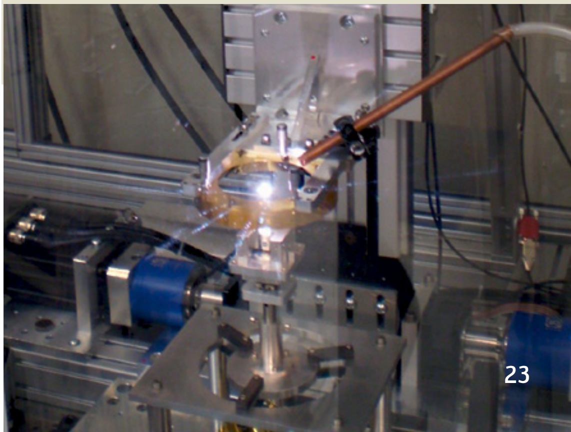


aLIGO monolithic fused silica suspension.

CO_2 fiber pulling

An important innovation in the development of monolithic suspensions was the use of laser heating for fiber pulling, using a high-power carbon dioxide laser. The first step of the process is to polish the fused silica stock by heating the surface with a laser power of approximately 80 W. The beam is slowly moved across the surface of the fused silica stock in order to heal or remove surface defects/cracks, leading to an improvement in the strength of the resulting fibers. The fibers are then produced using a feed-pull method in which the lower end of the stock is rigidly clamped onto the pulling machine base while the upper end is attached to a moveable motor driven arm. As the stock is heated the upper arm is moved upwards while the laser beam is continuously moved downward using a mirror attached to a second motor driven arm, ensuring that there is a constant melt volume from which to draw the fiber. Uniform heating of the stock is provided by continuously rotating the CO_2 laser beam around the circumference of the stock with a spinning mirror attached to the base of the pulling machine. The diameter and length of the fiber can be chosen by adjusting the speed and distance moved by the pulling motors. This allows production of the tapered fibers necessary for aLIGO.

CO_2 laser fiber pulling machine at Glasgow.



Konstantinos
Nikolopoulos

Kostas Nikolopoulos is a Birmingham Fellow working on Higgs searches at the ATLAS experiment at the CERN Large Hadron Collider. He is coordinating the searches for/studies of the Higgs boson in the decay channels through two Z bosons.

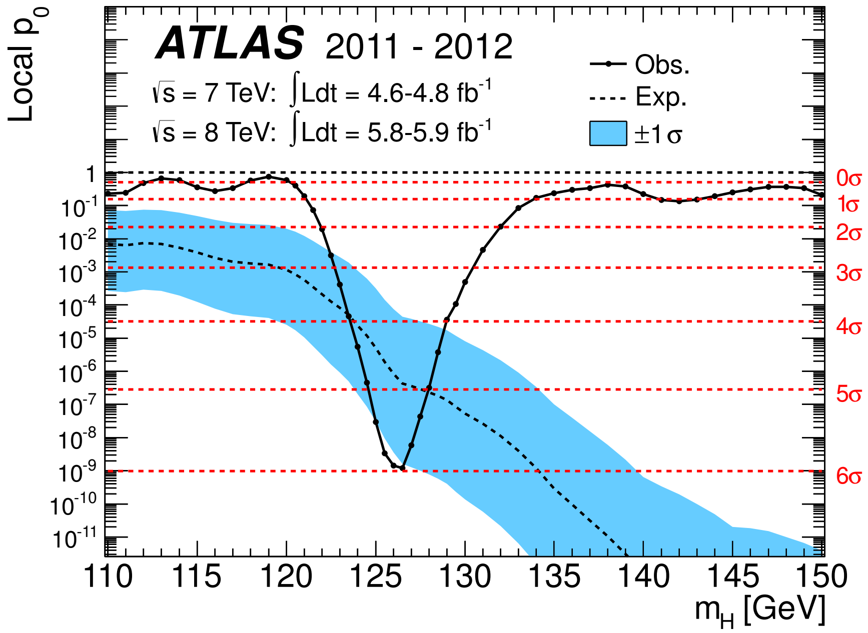
New particle observed in the search for the Standard Model Higgs boson

On July 4th 2012, during a special seminar organized at CERN, the ATLAS and CMS collaborations presented evidence of the observation of a neutral boson, compatible with the production and decay of the Standard Model Higgs boson. This was the successful conclusion of a search spanning over four decades and several particle colliders and experiments.

The appearance of a massive spin-0 particle associated with spontaneous symmetry breaking was mentioned explicitly for the first time in 1964 by Peter W. Higgs. In 1967, Steven Weinberg and, independently, Abdus Salam produced what is known today as the Standard Model of electroweak interactions, incorporating the Higgs mechanism to the electroweak unification proposed by Sheldon Glashow. It was not until 1972 that the theory was proved, by Gerard t'Hooft and Martinus J.G. Veltman, to be renormalizable and thus able to provide quantitative predictions. In the context of the Standard Model the Higgs boson mass is a free parameter, but once fixed, all the Higgs boson properties can be calculated. The search for the Higgs boson became a high priority in the experimental agenda after the discoveries of the Weak Neutral Currents in 1973 and the W+/- and Z bosons in 1983. Searches for the Higgs boson were conducted at CERN's Large Electron-Positron collider (LEP), and at Fermilab's Tevatron proton-anti-proton collider. The construction of the Large Hadron Collider (LHC) itself was motivated to a large extent by the search for the elusive particle.

The results of July 4th 2012 were hardly a surprise.

The Higgs searches at the LHC have been picking up pace throughout 2011: starting from the first ATLAS paper based on 40 pb$_1$ from the 2010 LHC run (Eur.Phys.J. C71 (2011) 1728), continuing with the results presented with 1fb$_1$ at the European Physics Society Conference in Grenoble in July 2011, and subsequently all the major particle physics conferences of the year, and - finally - with the special seminar organized at CERN on December 13th 2011 on the occasion of the annual CERN Council meeting. In this last case, both ATLAS and CMS collaborations presented results using the complete 2011 dataset, consisting of ~5 fb$_1$ at a centre-of-mass energy of 7 TeV, only a few weeks after data-taking was completed. The results of December 13th 2011, provided the first strong hints that,



The observed (solid) local p_0, the probability of a background-only experiment (i.e. in the absence of a signal) to look at least as signal-like as the observed data, as a function of the Higgs boson mass hypothesis (m_H) in the low mass region from the ATLAS experiment. The dashed curve shows the expected local p_0 under the hypothesis of a Standard Model Higgs boson signal at that mass, and the band corresponds to the plus/minus one sigma fluctuations. The horizontal dashed lines indicate the p-values corresponding to significances of 1 to 6 sigma.

potentially, there was something interesting in the mass region around 125 GeV: ATLAS reported a local excess of events over the background-only hypothesis at the level of 3.5 standard-deviations at m_H = 126 GeV (Phys.Lett. B710 (2012) 49-66), while the corresponding result from CMS was 3.1 standard-deviations at m_H = 124 GeV (Phys. Lett. B 710 (2012) 26-48). As a result the interest shifted towards the low mass range, in order to clarify whether the intriguing excesses reported by the experiments were genuine signal events or merely a fluctuation of the background.

Providing a comprehensive account of the events leading to the announcements of July 4th 2012 is a formidable task, that by no means will be attempted here: Hopefully the complete story will be written with insights from both collaborations as was the case for other significant discoveries in particle physics. Nevertheless, it is worthy to review in general terms the strategy followed by the experiments after December 13th 2011.

Firstly, it was of paramount importance for both collaborations to ensure that the choices made on the event selections for the 2012 dataset, would not be affected by the actual observed result presented on December 13th 2011. Usually, this is referred to as 'blinding' of the analysis. This is a fundamental principle of data analysis and was already applied to all analyses, and in particular to the Higgs searches. The qualitative difference this time was that the 'blinding' was enforced at the collaboration level. As a result, all the details and progress of the analysis were presented to and reviewed by the collaboration (not only the Higgs working-group) in regular intervals, well before the actual analysis of the 2012 data begun. Permission was required before actually un-blinding the data and investigating the signal region.
Secondly, both experiments tried to improve their sensitivity to a low mass Higgs boson. The experience gained from the 2011 data analysis was valuable to identify potential improvements. Moreover, it was known that all these improvements/modifications had to be performed before the analysis was un-blinded. All event selection improvements were completely based on simulated signal and background events, while signal-free control regions in the 2011 and early 2012 datasets were heavily used to demonstrate good understanding and control of the background expectations.

For the 2012 run,

the LHC was scheduled to run at a centre-of-mass energy of 8 TeV. This was a very welcome development since it implied improved sensitivity for the Higgs signal, owing to the scaling of production cross-sections for the potential Higgs signal and the main background processes with the centre-of-mass energy, provided that the performance of the detector could be kept at the same level. However, with the 2012 machine configuration a much higher pile-up was to be expected (pile-up refers to multiple proton-proton collisions taking place at the same bunch crossing), even exceeding the design specifications of the detector. This meant that improvements were needed (and were implemented in time for the analysis) to a much lower level: at the reconstruction and identification of physics objects (like photons, electrons, etc).

The months of May and June were definitely very exciting and intense. After un-blinding the analyses at the early part of June, and as the 2012 data became available, you could really see the picture forming step-by-step! The analysis teams – but also everyone involved in the process from data preparation to computing – were working around the clock for the timely delivery of the result and to prepare all the possible additional cross-checks to confirm its robustness. This dedication and enthusiasm was really the key to overcome any issues that would appear.

Formal procedures

The ATLAS and CMS collaborations have formal procedures for the approval of results, both for preliminary results intended for conferences and for publications. The "approval meetings" were very well attended by collaboration members who provided comments, suggestions and constructive criticism. It is also interesting to note that members of one collaboration did not have access to the results of the other collaboration, before these become public on July 4th.

Finally, in the results, as submitted for publication, ATLAS reports a local excess of events over the background-only hypothesis at the level of 5.9 standard-deviations at m_H = 126 GeV (http://arxiv.org/abs/1207.7214), while the corresponding result from CMS is 5.0 standard-deviations at m_H = 125 GeV (http://arxiv.org/pdf/1207.7235.pdf). The mass estimates for the new particle are 126.0+/-0.4(stat)+/-0.4(sys) GeV and 125.3+/-0.4(stat)+/-0.5(sys) GeV, respectively.

July 4th 2012 was an excellent day for particle physics!

Now, the aim is to measure as precisely as possible the properties of the new boson: the mass, the spin and parity, the couplings, and any deviations from the Standard Model predictions, while continuing to look for other potential signs of New Physics.

We Hear That ...

Awards

Ben Farr (Northwestern) and **Jenne Driggers (Caltech)** were elected graduate student representatives of the APS topical group on Gravitation.

Lynn Cominsky (**Professor of Physics and Astronomy and Chair of the Department at Sonoma State University (SSU))** was selected as the APS Woman Physicist of the month for September, at http://aps.org/programs/women.

Ryan DeRosa (LSU) and **William Zach Korth (Caltech)** were awarded the annual LIGO Fellowship for projects to be conducted at LIGO Livingston Observatory. Ryan's proposal is titled, "Feed-forward scheme using the new mode cleaner integrated system at the Livingston observatory"; Zach's project will "See the aLIGO Output Mode Cleaners (OMC) through assembly and testing as well as install and commission the L1 OMC at LLO."

Rutger van Haasteren's (AEI Hannover) dissertation, "Gravitational Wave detection and data analysis for Pulsar Timing Arrays", completed at the University of Leiden, was awarded the GWIC thesis prize for 2011, and honorable mention for the Stefano Braccini thesis prize.

Alexander Khalaidovski (AEI Hannover) was awarded the Stefano Braccini prize for his dissertation, "Beyond the Quantum Limit: A Squeezed-Light Laser in GEO600".

Career updates

Alessandra Corsi, currently a post-doc at Caltech, will begin a faculty appointment as an assistant professor in the physics department at George Washington University.

César Costa, previously a post-doc at LSU, is now a Research Fellow at the Brazilian National Institute for Space Research - INPE, in Sao Jose dos Campos, Sao Paulo, working with LIGO Detector Characterization and on R&D for the Brazilian GW spherical detector.

Thomas Dent has left his Cardiff postdoc position and joined the scientific staff at AEI Hannover in the observational relativity group.

Nickolas Fotopoulos, previously a post-doc at Caltech, is now a Sr. Algorithms Architect at Synaptics in Santa Clara, CA working on R&D for touchscreens and touchpads.

Gregg Harry reports: "I have been at American University as an assistant professor for just over a year now, moving from my long time position as a research scientist at MIT." He is also happy to report that the book "Optical Coatings and Thermal Noise in Precision Measurement", co-edited with Timothy Bodiya and Riccardo DeSalvo, was recently published by Cambridge University Press.

Amber Stuver has begun dual appointments as a "Data Analysis and Education and Public Outreach Scientist" at LIGO Livingston Observatory and as an instructor in the physics department at LSU.

Sam Waldman, previously a staff scientist at MIT LIGO Lab, is now a senior engineer at Space Exploration Technologies (better known as SpaceX). Sam is applying LIGO physics to spacecraft sensors and is always happy to give tours and read resumes for interested scientists.

Matthew Evans has worked as a Research Scientist at MIT for the last 5 years and will be moving onto a junior faculty role at MIT.

PhD graduations

Priscilla Canizares finished her PhD in the Institute of Space Science, Barcelona (Spain). Priscilla's dissertation was titled "Extreme-mass-Ratio Inspirals: Modelling and Test of an Alternative Theory of Gravity" and it was defended on October 23, 2011. Now she is a post-doc at the Institute of Astronomy in Cambridge (UK), working on Gravitational-Wave modelling and Parameter Estimation.

Sarah Caudill completed her PhD at LSU with a thesis titled "Searches for Gravitational Waves from Perturbed Black Holes in Data from LIGO Detectors", defended on July 3rd. She is now starting a post-doc at University of Wisconsin, Milwaukee where she will split her time between work on LIGO and the Palomar Transient Factory.

Kate Dooley defended her dissertation about the Input Optics and Angular Sensing and Control for Enhanced LIGO on September 30, 2011 at the University of Florida and is now a post-doc at the Albert Einstein Institute in Hannover, Germany, working on squeezing at GEO600.

Paul Fulda defended his thesis on "Precision Interferometry in a New Shape: Higher-order Laguerre-Gauss Modes for Gravitational Wave Detection" at the University of Birmingham in June 2012 and is now a post-doc in Florida, working on thermally actuated adaptive optics for Advanced LIGO upgrades.

Tobin Fricke defended his dissertation titled "Homodyne Detection for Laser-Interferometric Gravitational Wave Detectors" at Louisiana State University on October 24, 2011 and is now a post-doc at the Albert Einstein Institute, working on the 10 meter prototype interferometer.

Eliu A Huerta was approved for a PhD degree from University of Cambridge on August 3rd 2011 by Prof Anthony Lasenby and Dr Leor Barack with a thesis entitled "Source modeling of extreme and intermediate mass ratio inspirals". Now at Syracuse University, he continues working on the development of waveform models to explore what we could learn form future detections of compact binary coalescences. He is also involved in the analysis of data obtained from the ongoing engineering runs of the LIGO detector using the off-line pipeline "ihope".

Kiwamu Izumi will graduate on September 27, 2012 from the University of Tokyo with his dissertation "Multi-Color Interferometry for Lock Acquisition of Laser Interferometric Gravitataion-wave Detectors" and will be joining the commissioning at the LIGO Hanford Observatory as a post-doc.

Alexander Khalaidovski defended his (award-winning; see above) dissertation at the Max Planck Institute for Gravitational Physics and the Institute for Gravitational Physics of the Leibniz University of Hannover, Germany, on December 21st, 2011. Currently, Alexander is a post-doc at the Albert Einstein Institute, working on all-diffractive interferometry using dielectric gratings.

Frank Ohme, previously a PhD student at the AEI in Potsdam, Germany, is now a post-doc at Cardiff University, UK working on waveform models and searches for GWs of compact binaries.

Nicolas Smith-Lefebvre defended his dissertation titled "Techniques for Improving the Readout Sensitivity of Gravitational Wave Antennae" at the Massachusetts Institute of Technology on May 4th, 2012 and is now starting a post-doc at Caltech.

Dipongkar Talukder defended his Ph.D. on "Multi-baseline searches for stochastic sources and black hole ringdown signals in LIGO-Virgo data" on May 29, 2012 at Washington State University and has joined University of Oregon as a post-doctoral research associate.

Send us an update!
Have you changed jobs, won an award, or do you have another update you'd like to share in the next issue's "We Hear That" feature? Email us at **magazine@ligo.org.**

Recent papers

The last six months (as always!) have been a busy time for LIGO scientists with over 70 papers written by members of the LIGO Scientific collaboration being submitted to scientific journals. It would be impossible to do justice to all of these papers in this magazine, so instead here we focus on the most recent observational results, released by the LSC and our Virgo colleagues since March of this year.

Gravitational research, electromagnetic astronomy and neutrinos

With Advanced LIGO due to begin operation in the middle of this decade, gravitational wave astronomers are increasingly keen to build strong ties with their colleagues working in electromagnetic astronomy. Of the six LSC/Virgo observational papers sent to press in the last six months, three of them focused on cooperative searches combining information from electromagnetic, gravitational wave and in one case, high-energy neutrino observatories. A long history of cooperation between gravitational wave and electromagnetic astronomers already exists in the gamma-ray burst community. Gamma-ray bursts are especially interesting for gravitational wave scientists as these phenomena, which emit vast amounts of electromagnetic radiation, are also believed to emit large amounts of energy as gravitational waves. A sub-class of gamma-ray bursts, known as "short" gamma-ray bursts are especially interesting because the most likely progenitor of such events is the merger of two compact objects, the prime source for the first gravitational wave observation.

In **http://arxiv.org/abs/1205.2216** the results of the most recent search for gravitational waves coincident with gamma-ray bursts is discussed, although sadly no detections were made. Given the sensitivity of the initial LIGO and Virgo detectors, a detection of a gravitational wave counterpart to a gamma-ray burst would have been very lucky. However, in the advanced detector era, with a much greater volume being searched, a coincident observation is much more likely.

In a similar vein, the first results of a new collaboration between LIGO/Virgo and high-energy neutrino scientists working on the ANTARES detector is available at **http://arxiv.org/abs/1205.3018**. In this venture, potential neutrino triggers observed by the ANTARES detector were used to search for potential gravitational wave events at the same time in gravitational wave data. While no coincident observations were made, this work represents another bridge built between the gravitational wave and electromagnetic communities.

An alternative

to using electromagnetic observations to trigger searches of LIGO data is to do the opposite. If a potential gravitational wave signal is observed and constrained to a specific point, or region, in the sky, then we can ask electromagnetic telescopes to point at the sky location and attempt to detect coincident electromagnetic emissions. A pilot project, called LOOC-UP was run during LIGO's sixth science run to do just this. One telescope that participated in this program was the Swift satellite. In addition to a wide field-of-view Burst Alert Telescope that scans the sky for gamma-ray bursts, the Swift satellite has two instruments with smaller fields of view. These two telescopes can rapidly point towards a location in the sky and determine the location of sources very accurately, making them particularly useful for targets of opportunity like LIGO-Virgo candidate events. Swift's X-ray telescope can see a section of the sky that is about four tenths of a degree on each side and its ultraviolet/optical telescope can see a slightly smaller area. Two loud events in the LIGO instruments observed in late 2010 were used to point the Swift focused instruments within roughly half a day of the events and take images of the potential events. Although both of these events were later determined not to be gravitational events it emphasizes the prospects of what can be possible in the era of Advanced LIGO. More details can be found at **http://arxiv.org/abs/1205.1124**.

Einstein@Home

Who wouldn't want their home computer to search for gravitational waves when it isn't in use? The long-running Einstein@Home program does exactly that. Easy to set up and use, Einstein@Home uses your computer's idle time to search for weak astrophysical signals from spinning neutron stars, or pulsars, using data from gravitational wave detectors as well as the Arecibo radio telescope and Fermi gamma-ray satellite. In the recent paper **http://arxiv.org/abs/1207.7176** a search for such systems in gravitational wave data from LIGO's fifth science run is performed. While no gravitational wave signals were observed, the scientists were able to place upper limits on the strength of gravitational waves from spinning neutron stars arriving at the Earth.

Requirements

The observational results described above, rely on a lot of hard work before the analyses even begin. Before being able to make observations, it is vital to understand the instruments. Data taken with gravitational wave observatories is neither Gaussian nor stationary, so identifying whether a "loud" transient in the data is due to gravitational waves or some other, more mundane, cause is a difficult task. An important method of helping with this task is to identify, understand and, if possible, remove causes of non-Gaussianities in the detector.

Some causes of these non-Gaussian events, such as faulty electronics, can be fixed to prevent recurrences. Other causes, such as seismic activity cannot be removed, although the best effort is made to mitigate its effect. However, we know when loud Earthquakes happen and can therefore identify non-Gaussian behavior at these times as due to seismic noise and not due to gravitational waves. Our colleagues in Virgo have recently put together a work available at **http://arxiv.org/abs/1203.5613** describing their very successful "glitch hunting" strategies in the Virgo detector during the 2nd and 3rd Virgo science runs.

LIGO and Virgo 2009-2010

A short paper was also released that documents the attained sensitivity of the LIGO and Virgo detectors between 2009-2010. More details about how far our detectors could see in our most recent science runs can found it at **http://arxiv.org/abs/1203.2674**. The data presented in this work and in the accompanying web-accessible data files are released to the public as a summary of detector performance for compact binary searches during the most recent LIGO and Virgo science runs.

Ian Harry

Job Announcements

ICTP South American Institute for Fundamental Research, Sao Paulo, Brasil

The new ICTP South American Institute for Fundamental Research in Sao Paulo, Brasil invites applications for a 2-year post-doc position from candidates interested in working on data analysis with particular emphasis on signals from coalescing binaries, theoretical modeling of the 2-body motion in gravity theories, and theoretical modelling of gravitational waves from coalescing binaries. The position can begin at any time.

Apply at at **www.ictp-saifr.org**.

Indian Institute of Science Education and Research

The Indian Institute of Science Education and Research Thiruvananthapuram, India, invites applications for two post-doc positions which will focus on gravitational wave detection and parameter estimation issues of binary systems for second generation and future interferometric detectors. The closing date is October 1st.

Contact Archana Pai at **archana@iisertvm.ac.in** for details.

Nikhef, Amsterdam

The gravitational physics group at Nikhef in Amsterdam, The Netherlands, invites applications for a postdoc position in the development of instrumentation for the detection of gravitational waves. The closing date is October 1st.

Details at **http://tinyurl.com/ceol7kv**.

University of Chicago

The University of Chicago is currently accepting applications for 2012-13 South Pole Telescope Winterover positions. Two positions are available.

For details or to apply, select requisition 090508 at **https://jobopportunities.uchicago.edu/**

University of Mississippi-Oxford

seeks an Astronomy Instructor/Lecturer. The one-year position is available for the Fall or Spring 2012 term.

Send inquiries to Prof. Don Summers at **summers@phy.olemiss.edu**.

University of Waterloo

The University of Waterloo's Institute for Quantum Computing's (IQC) is currently advertising faculty positions with cross-appointments with Engineering and with Physics and Astronomy. The searches are focused on experimentalists with strong research accomplishments in the field of quantum information.

Details at **https://service.iqc.ca/applications/positions/iqc-faculty-engineering/**

University of Sheffield

The gravitational wave data analysis team at University of Sheffield seeks a post-doc in signal processing. Closing date is September 14th.

For complete details, find the ad online at **http://tinyurl.com/shefgravjob1** or contact Ed Daw.

University of Wisconsin-Milwaukee

seeks an Assistant, Associate, or Senior Scientist with a passion for scientific computing to research distributed, high throughput, grid, and cloud computing in support of LIGO research, manage their data center, and contribute to the broader LIGO project. Applications will be accepted until the position is filled.

Apply at **http://jobs.uwm.edu/postings/9082**.

LIGO Magazine invites the submission of job announcements. Please include a brief description of the position, the closing date, and a contact person or website.

Email us at **magazine@ligo.org.**

Peter Shawhan

Peter Shawhan is an Associate Professor at the University of Maryland who works on data analysis for GW burst searches, and various other things. His son (age 2.5 at the time) once made an 'interferometer' out of construction paper, aluminum foil and a flashlight.

Hanging out with the astronomical instrumentation crowd

In early July I flew to Amsterdam to attend the SPIE Astronomical Telescopes and Instrumentation conference. Many experimentalists probably know that SPIE is one of the main professional societies for optics and photonics, and it runs a large number of specialty conferences each year. This particular one brings together astronomers and instrument builders covering the whole spectrum from radio to gamma rays, on the ground and in space. It actually encompassed about 10 parallel sub-conferences, and there were over 2000 attendees in all!

My goals for the meeting

I had two main goals for going to this meeting. The first was to give a talk about the present status and future of gravitational wave detectors, in particular to try to reach a different audience than the conferences we usually go to. My talk was in the "Observatory Operations: Strategies, Processes, and Systems" track, and I emphasized how we operate multiple detectors as a global network and analyze the data coherently. I talked about lessons learned from our first attempt to enable rapid EM follow-up observations in S6/VSR2+3, as well as our ideas for the future.

My second main goal was to find out the latest news on gamma-ray and X-ray satellite missions that might be operating during the advanced detector era; in fact, I spent at least as much time in the "Space Telescopes and Instrumentation: Ultraviolet to Gamma Ray" sessions as in "Observatory Operations". This is really important for our hopes for multi-messenger science with gravitational waves. The Swift and Fermi missions are the current workhorses for detecting many gamma-ray bursts (GRBs), localizing them and alerting astronomers who often follow up with observations from the ground, but it is unknown whether Swift and/or Fermi will still be around (i.e., working and funded) when Advanced LIGO and Advanced Virgo ramp up to good sensitivity and first detections. It is not yet clear if some other mission(s) will be launched to provide those capabilities, which has us (and the high-energy astronomy community) worried.

SVOM, the Space-based Variable Objects Monitor

One mission we've been anticipating is a French-Chinese project called SVOM, which is more-or-less a replacement for Swift, with large-field monitoring for gamma-rays and hard X-rays as well as pointed instruments and autonomous slewing (see http://www.svom.fr/). There is also a ground component to the project, with a wide-angle camera to try to catch prompt optical emission plus two other telescopes dedicated to following up GRBs. The speaker at SPIE, Olivier Godet, described the status as "expected launch after 2015, and duration of 3 to 5 years". I asked him afterward what the deal is with "after 2015", and he said there is a political stalemate right now about the cost of the spacecraft platform, which by their agreement is supposed to be purchased from a French supplier but the Chinese think it is too expensive. Meanwhile the instrument development is doing fine. He was optimistic that it will eventually be built and fly, but could not predict how or when the stalemate will be broken.

LOFT, the Large Observatory for X-ray Timing

I was interested to learn about LOFT, the Large Observatory for X-ray Timing, which is one of four candidates for an ESA M-class mission to launch around 2022-2024. (See http://www.isdc.unige.ch/loft/.) In addition to a large-area pointed X-ray detector, the mission design includes a Wide Field Monitor for X-rays that will be able to pick up GRBs. I also heard about a number of other X-ray missions, some approved (SRG/eROSITA; Hard X-ray Modulation Telescope) and others in various stages of development (Athena; "Wide Field X-ray Telescope"), but those all have instruments with rather narrow fields of view and are intended more for programmed surveys and pointed observations than for chasing transients like GRBs.

Miscellaneous

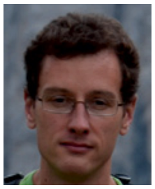
I also attended some other sessions on various topics that sounded interesting, but I really only scratched the surface of the conference. At one of the poster sessions I saw a great deal of creative work on adaptive optics and optical interferometry, along with other topics. I was pleasantly surprised to run into an old friend, Aaron Roodman from SLAC, whom I worked with when he was a postdoc and I was a grad student doing experimental particle physics at Fermilab. He is now heavily involved in the Dark Energy Survey project being commissioned in Chile.

Amsterdam

The weather in Amsterdam was really lovely while I was there, and I enjoyed walking and eating some meals outdoors. After the conference ended I had a free half-day before flying home, and I spent it exploring the streets, canals, and historical buildings. One time I hopped off a tram and came upon an artist selling neat little sculptures of bicycles and musical instruments, each fashioned from a single piece of wire. We struck up a conversation and it turns out that he is a big fan of science, who follows many articles and TV programs. We talked for about 20 minutes about the LHC, the Higgs boson discovery, black holes, and gravitational waves (of course!). It was an delightfully unexpected part of a memorable trip.

GWADW Conference

Gabriele Vajente



Gabriele Vajente is a post-doc at INFN Pisa working on Advanced Virgo optics and control design. He was also part of the Virgo commissioning group and in his free time he is an amateur astronomer.

"Per aspera sic itur ad astra" (a rough road leads to the stars) wrote the Latin philosopher Seneca the young. This is so often true in our everyday research work. But sometimes things get a bit better, as happened during this year Gravitational Wave Advanced Detector Workshop which was held, for sure you all know it, on the Big Island of Hawaii. We indeed could see many stars, literally, but not only. And, if one forgets the never-ending flight from Europe, we did not meet any harsh condition.
We might spend hundreds of words on the many interesting talks that showed how much we are progressing in the understanding, design, and construction of our advanced detectors.

We might also spend thousands of words describing the interesting new results we heard: about interferometer configurations, beating the quantum limit, seismic isolation, coating optimization, thermal noise reduction, adaptive optics, and so forth.

But, let's be honest: a few years from now, we will not remember this workshop for some enlightening talk. We will remember it for the beautiful scenery where it was set. We all enjoyed the wild natural environment, the amazing beaches covered with sand of all colors: white, yellow and black. And green also, for those of us who got enough nerve up to drive on something which for sure can't be called a road (in this case Seneca was not so wrong...).

We could also swim with myriads of colorful fishes and sea turtles, so elegant in the water and so clumsy on the sand (so much like us, but the other way round...).

And finally, what was, for me at least, the most amazing experience of the entire holiday, oops! conference: the night sky from the summit of the Mauna Kea mountain. In this case Seneca was right, since we had to really drive per aspera to finally reach the countless stars. We spent long cold nights at more than four thousands meters elevation, hardly breathing for the lack of air but also for the wonder of the sight. And standing by the giant instruments of modern astronomy was indeed very inspiring, giving the hope that we will soon join them in the quest to understand the Universe.

Explaining the curvature of space-time at the Big Bang Fair in Birmingham 2012.

How many people know what is LIGO?

On stage at the 2nd USA Science and Engineering Festival

Marco Cavaglià

Marco Cavaglia is Associate Professor of Physics and Astronomy and PI of the LIGO group at the University of Mississippi. When he does not work on LIGO's "stuff," he enjoys getting his motor running and heading out on the highway.

Since April 2012, quite a few more! That's when LIGO's cool science and technology was featured at the Second USA Science and Engineering Festival in Washington D.C., one of the most compelling, exciting, educational and entertaining science festivals ever organized in the United States. This was the second time that LIGO participated in the USA Science and Engineering Festival, keeping up our tradition of participating to major science festivals across the globe. At the inaugural USA Science and Engineering Festival in October 2010, the LIGO exhibit "Astronomy's new messengers: Listening to the universe with gravitational waves" attracted crowds of visitors and budding scientists eager to experience first-hand the work and excitement of LIGO scientists and engineers. With "Astronomy's new messengers" traveling across the country in April 2012, this year's festival showcased a newly-designed LIGO booth. Along with one of the classic "Astronomy's new messengers" hits – the black hole hunter game (http://blackholehunter.org), the LIGO booth featured a portable table-top interferometer (courtesy of Dennis Ugolini and Trinity University) projecting fringe patterns on a screen. The short documentary made by Milde Communication on the occasion of the International year of Astronomy looped on a monitor, while children and adults alike tested their skills at detecting gravitational waves by listening to the sounds of colliding stars. Yo-yo's, postcards and print-outs of LIGO's Science Summaries were passed along to the public.

The LIGO booth was staffed by Martin Hendry (Glasgow), Peter Shawhan (Maryland), Dennis Ugolini, a bunch of very enthusiastic students from the Maryland group, and by the author. They were all kept very busy for three full days by a countless number of attendees. The Festival organizers estimate that more than 150,000 people participated over the three days of the event! The Festival Sneak Peek on April 27 was attended by nearly 28,000 students, teachers, military families, government officials and press. The public response was overwhelmingly positive, with most visitors asking when and where the next Festival will be (and when LIGO will finally detect a gravitational wave!) We also had a few "returning customers" – LIGO's "aficionados" who already attended our booths at the previous USA Science and Engineering Festival and other large celebrations of science where LIGO was present, such as the NYC World Science festivals. But that's not all! Our booth neighbor was Bill Nye the Science Guy and attendees at the LIGO booth included… (hear, hear) Star Wars' R2-D2 and Albert Einstein! We all enjoyed meeting these and other science celebrities, helping thousands of visitors learn how LIGO operates and inspiring the youngest among them to explore careers in science. And so we look forward to the next USA Science and Engineering Festival. À bientôt, Washington!

LIGO's participation was funded by the University of Mississippi through the generous support of the National Science Foundation. Travel of the LIGO booth staffers were covered by their home institutions.

Playing the Black hole Hunter Game: Martin Hendry helps a " prospective LIGO scientist" detect gravitational waves at the 2nd USA Science and Engineering Festival. Hundreds of visitors of all ages stopped by LIGO's booth during the three days of the event.

LIGO Then and Now: A graduate student‘s story

In June 2007, Jaclyn Sanders traveled from Michigan to LIGO Hanford Observatory (LHO) for a ten-week summer undergraduate research internship after completing her sophomore year at Kalamazoo College. A year later, she returned to LHO for another summer of research. In June 2012, after a three year absence, Jaclyn was welcomed again by Observatory staff, this time for a six month stay as a fourth-year graduate student in physics at the University of Michigan. She's working on the instrumentation portion of her doctoral research during her current visit.

Known to acquaintances as Jax, her journey through physics education continues to involve LIGO. "My undergraduate physics program was excellent," Jax recalls, "and Kalamazoo was a fine school, but in 2007 I was looking for a summer research opportunity that would be richer in hands-on instrumentation than what I experienced at school. I applied to a number of summer programs and received an appointment offer from LIGO, which I happily accepted (although I didn't know much about LIGO at the time)." A participant in Caltech's SURF program, Jax worked with LIGO's Robert Schofield on assessing the potential impacts of Newtonian gravity noise on gravitational wave interferometers. "I enjoyed the 2007 internship and was ready to come to LIGO again the following summer." She received another LIGO SURF appointment in 2008 and spent the summer working with Dick Gustafson on a method for stabilizing optical fiber signals for use in Pound-Drever-Hall locking. A somewhat similar method now finds use in the Advanced LIGO arm length stabilization subsystem.

"Michigan was a natural choice for graduate school," according to Jax. "The physics program is very good. I enjoy the overall environment of the university, and I have some family history there." Jax eventually moved into the research group of LIGO Scientific Collaboration member Keith Riles. "Keith is a very good advisor. He's a good communicator, and he and I are able to discuss our expectations for my graduate experience frankly and comfortably." Under Riles' supervision, Jax will complete a research program for her Ph.D that contains both instrumentation and data analysis emphases. On the instrumentation side, she will collaborate with LIGO personnel at Hanford on the one arm test, an effort to test newly installed Advanced LIGO subsystems along a single interferometer arm. Her focus lies in developing the cavity locking system and in measuring properties of the locked cavity such as the free spectral range and cavity finesse. Other work, such as contributing to the installation and testing of input optics, might lie ahead during her stay.

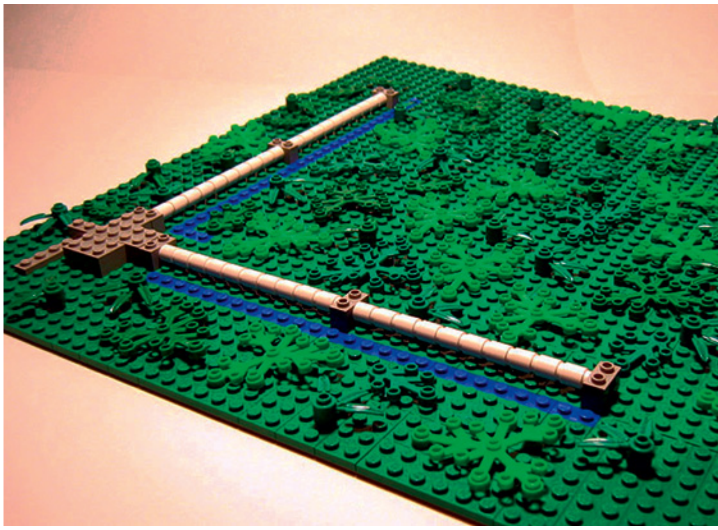
In data analysis, Jax is working on methods for the identification and characterization of millisecond pulsars, methods that could involve the integration of Gamma ray, radio wave and gravitational wave data. When asked about the combination of instrumentation and data analysis in her thesis research, Jax said "I like the dual approach. I've always enjoyed tinkering and putting my hands on equipment, but the astrophysics is very interesting and obviously very important. I appreciate the opportunity to include both in my research."

Graduate school doesn't leave much room for recreation, but Jax manages to find time to participate in the fencing club at UM. She also enjoys knitting, scuba diving and games. When asked about her future, she indicates an interest in both teaching and research, but she hasn't settled on a particular direction yet, nor a particular field of work. "I want to keep my options open," she said. "I'm taking things one adventure at a time." This strategy has brought her to LIGO Hanford three times; perhaps visit number four lies over the horizon.

When I'm not doing science

In my down time one of the things I like to do is build Lego models. I have been enamoured with these little plastic bricks since I was a kid, and have never stopped building (many adults who rediscover Lego describe the years not building as their "Dark Ages"). I build all kinds of things; my favorite stuff is space, and I build a substantial amount of REAL space.This has often included things near and dear to our hearts, such as LIGO (both Hanford: http://www.brickshelf.com/cgi-bin/gallery.cgi?f=77887 and Livingston: http://www.brickshelf.com/cgi-bin/gallery.cgi?f=78268 models) as well as a LISA sciencecraft: http://www.brickshelf.com/cgi-bin/gallery.cgi?f=429602.

I'm also a big fan of building in the "vignette" format, where you tell a story inside a 8 x 8 stud setting. You can see all of my Lego creations at my Brickshelf account: http://www.brickshelf.com/gallery/graviton/



The LIGO Livingston site in LEGO.

Shane Larson
is an assistant professor of Physics at Utah State University, working on the interface between traditional astrophysics and gravitational-wave astronomy.

LIGO Magazine

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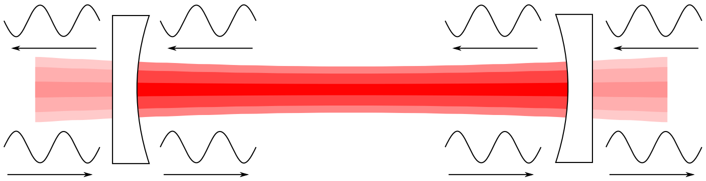
How does it work? An optical cavity

What happens when two highly reflective mirrors are aimed at each other? One might think that light would get trapped between the mirrors, bouncing back and forth between them endlessly. In fact, something like this really happens, and the arrangement – called an optical cavity, Fabry-Perot cavity, or optical resonator – is a vital component of an interferometric gravitational wave detector.



The mirrors used to build such a cavity allow a small fraction of the incident light to pass through. This slight transparency allows light to be introduced to the cavity: when a laser beam is directed at the first mirror, a small fraction of the light gets into the cavity where it then bounces back and forth and is able to build up in intensity. For the light in the cavity to build up in power, the light entering the cavity must interfere constructively with the light that has already made one or more round trips inside the cavity. When this occurs, the cavity is said to resonate. For the cavity to resonate, the optical path length inside must be held very near an integer multiple of the light's wavelength. This is accomplished by a feedback control system, which measures the mismatch between the wavelength and the cavity length and continuously adjusts either one to maintain resonance. With the control system maintaining resonance, the system is said to be "locked".

Optical cavities are at the heart of many aspects of gravitational wave detectors!

Arms of GW detectors

The effect of a gravitational wave is a strain – a change in length by some very tiny percentage – between inertial test masses. By using two mirrors of an optical cavity as test masses, the small change in length caused by the gravitational wave is multiplied by the number of times the light bounces in the cavity. The effect of the gravitational wave becomes easier to detect.

Lasers

At the heart of every laser is an amplification medium, which increases the power of any light passing through it. To make efficient use of the amplification medium, it is put into a cavity so that light makes many passes through the medium before exiting.

Mode cleaners

The amplitude of the light exiting the cavity is an average of the amplitude of light that entered the cavity after varying numbers of round-trips. Because of this averaging effect, the light coming out is "cleaner" than the light going in: variations in intensity, frequency, and spatial uniformity are reduced. Mode cleaner cavities are used to clean the light before it enters the interferometer and after it comes out.

Length or frequency reference

A cavity constructed to have a very stable length can be used to improve the frequency stability of a laser, by using the control system to match (lock) the laser wavelength to the cavity. Conversely, by adjusting the cavity length to match the laser, a stable laser can be used to remove length fluctuations from a cavity.

Power recycling

A typical configuration for a gravitational wave detector is a Michelson interferometer tuned to the dark fringe, so that most of the incident laser light is reflected back towards the laser. To make use of this light again, a "power recycling mirror" can be added, forming an optical cavity comprised of the additional mirror and the Michelson interferometer.

Tobin Fricke

Preparing the Advanced LIGO mirrors.