

LIGO MAGAZINE

issue 6 3/2015



Fiat Lux:
Hanford joins
Livingston
in Full Lock

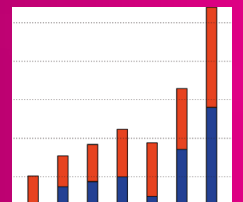
Detector Commissioning:
Control Room Days and Nights

An LHO engineer's perspective p.6



The Transition of Gravitational Physics
From Small to Big Science

Part 1: The role of the NSF and the scientific community p.14



... and a take on undergrad research in LIGO!

The cover image shows the LIGO Hanford X-arm end test mass (ETM). The image was captured by the Photon Calibrator Beam Localization Camera system. Behind the test mass hangs the reaction mass with its pattern of gold tracings that are part of the electrostatic drive control system. An arm cavity baffle partially occludes the view of the ETM surface.

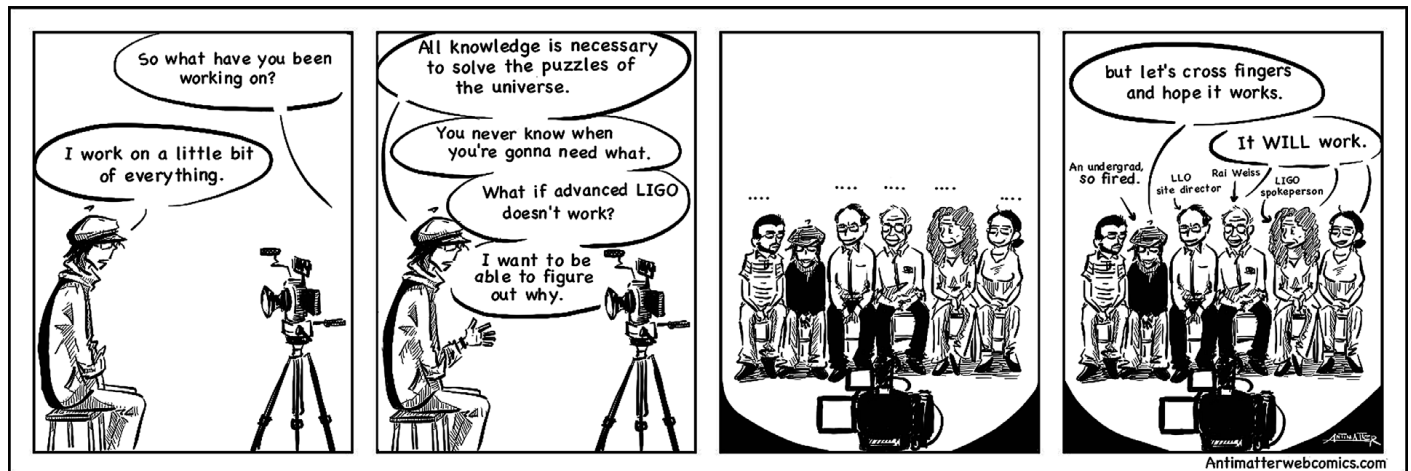
The Photon Calibrator, which was not operating when the photograph was taken, uses an auxiliary 1047 nm laser to induce calibrated sinusoidal displacements of the test mass via photon radiation pressure. The peak sinusoidally-modulated power in each laser beam is about 0.5 W. The beams reflect from the test mass surface at locations that are diametrically opposed and displaced vertically about the center of the mass. The positions of the beams must be maintained within a few millimeters of the optimum locations to avoid calibration errors resulting from elastic deformation of the mass. A Matlab-based procedure developed by Darkhan Tuyenbayev (graduate student from UTB) and implemented by Thomas Abbott (graduate student from LSU) uses images of the ETM surface such as this, taken when the beams are present, to determine the positions of the Photon Calibrator beams on the test mass surface.

Image credits

Photos and graphics appear courtesy of Caltech/MIT LIGO Laboratory and LIGO Scientific Collaboration unless otherwise noted.

- p. 3 Comic strip by Nutsinee Kijbunchoo
- p. 11 Diagram by Anamaria Effler
- p. 14 Caricature of the author by C. V. Vishveshwara
- pp. 14–17 Figures courtesy of Richard Isaacson
- p. 19 Diagram by Joe Betzwieser
- pp. 22–23 Photos courtesy of Nelson Christensen, Carleton College
- p. 25 Illustration by Nutsinee Kijbunchoo
- p. 29 Images courtesy of NASA/JPL-Caltech/ESO/R. Hurt and Ralf Schoofs
- pp. 30–31 Photos courtesy of Corey Gray
- p. 32 Cartoon by Nutsinee Kijbunchoo

Antimatter



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Upcoming Events (compiled by the editors)

LSC-VIRGO "March" Meeting

Caltech, Pasadena, California,
16-19 March 2015

The Rencontres de Moriond & GRAM Colloquium on Gravitation 100 years after GR

La Thuile (Valle d'Aosta, Italy),
21-28 March 2015

The Next Detectors for Gravitational Wave Astronomy

Kavli Institute for Theoretical Physics (KITPC),
China, 6 April - 8 May 2015

The APS April Meeting

Baltimore, Maryland, 11-14 April 2015

The 15th British Gravity (BritGrav) Meeting

University of Birmingham, UK,
20-21 April 2015

The 1st GraWIToN School

European Gravitational Observatory (EGO),
20 April - 8 May 2015

CLEO, Laser Science to Photonic Applications

San Jose, California, 10-15 May 2015

Hotwiring the Transient Universe conference

Santa Barbara, California, 12-15 May 2015

The Gravitational Wave Advanced Detectors Workshop (GWADW)

near Anchorage, Alaska, 17-22 May 2015

Workshop on Binary Neutron Star Mergers

Thessaloniki, Greece, 27-29 May 2015

The 18th Eastern Gravity Meeting

Rochester Institute of Technology,
28-30 May 2015

General Relativity and Gravitation: A Centennial Perspective

Penn State, University Park, 7-12 June 2015

Gravitational Wave Physics and Astronomy Workshop (GWPAW)

Osaka, Japan, 17-20 June 2015

The 11th Edoardo Amaldi Conference on Gravitational Waves

Gwangju, South Korea, 21-26 June 2015

Caltech Gravitational Wave Astrophysics School

Caltech, Pasadena, California,
July 6-10, 2015

LSC-VIRGO "September" Meeting

Budapest, Hungary,
31 August - 3 September 2015

A public web page with a calendar and list of upcoming conferences and meetings that may be of interest to members of the LSC is now available in [ligo.org](https://wiki.ligo.org):

<https://wiki.ligo.org/LSC/UpcomingConferencesAndMeetings>

Welcome to the sixth issue of the LIGO Magazine!



Welcome to the sixth issue of the LIGO Magazine. In the previous issue we explored life and work at the Livingston site. In this issue we feature Hanford and its H1 detector. The article “Detector Commissioning: Control Room Day and Nights” tells the story of ongoing commissioning work. And with perfect timing Advanced LIGO has just passed another major milestone, the achievement of H1’s first two-hour lock in its design configuration. We learn about the life around the LIGO Hanford site, for example with some beautiful hiking images in “When we’re not doing science.” The article “The Transition of Gravitational Physics – From Small to Big Science” represents this issue’s second main feature, starting a series that will look back at the beginnings of LIGO. We offer special thanks to article author Richard Isaacson for sharing his perspective from the National Science Foundation on LIGO’s development.

After three years we have refreshed and expanded our editorial team. I am pleased to report that several new editors joined us in time for the production of this issue and have already started to plan for the next one. Issue seven will explore the links between traditional astronomy and gravitational wave data. Of course we will keep an eye on developments at the detector sites. It is possible that O1, LIGO’s first advanced era data run, will be underway when you read the next issue of LIGO magazine! As always, please send your comments and suggestions to magazine@ligo.org.

Andreas Freise
for the Editors

LIGO Scientific Collaboration News



Gaby (Gabriela) González
LSC spokesperson

The future is here! We are all busily preparing detectors and gravitational wave codes to work together later in the year in the first “Observing Run” with the Advanced LIGO detectors. Although we may not detect gravitational waves in this first observing run, we may be hit by astrophysical surprises and will make steady progress to find those elusive gravitational waves soon enough (bets are on when – what’s yours?).

There have been many sleepless nights in observatories control rooms, as well as in laboratories and in front of computers in

many different time zones. Everything is going well, but there is still a lot of work to do – thanks to all of you, we are in good shape and making good progress on all fronts. News that will likely be old when you read them: the GEO detector keeps watch; the Livingston detector is sensitive enough to detect binary neutron star systems more than 130 Mpc away, with the Hanford detector locking stably; we are characterizing fresh detector data; we have written “search plans” for 21 different astrophysical sources; we are testing optimizing search codes to find gravitational waves and are seeking the needed com-

puting resources; we are explaining our priorities and needs to funding agencies... we are all very busy, but it's a very good kind of busy!

There is other news, of course: at the last LVC meeting in Stanford the LSC Council approved an anti-harassment policy reaffirming the collaboration commitment to ensuring a working environment free from any form of harassment; the LSC Academic Advisory Committee announced a new mentorship program for collaboration members who want to have regular contact with someone who is looking to share their insight about careers, research, and other areas of interest; a "Speakers Board" was created to coordinate, and provide oversight for, a more equitable distribution of talks among members of the collaboration; a new film by Kai Staats, "LIGO generations" has just premiered (with a Reddit AMA session!); the LSC Fellows program is steadily gaining steam to start in June with the first cohort; working groups

have elected new chairs (see "we hear that..."), and the LSC Council will elect a spokesperson in March. The LSC authored 13 papers in 2014, with several more under review – we are approaching the 100th paper – check their science summaries to make sure you appreciate the broadness of the science done by our Collaboration, and imagine what's coming with Advanced Detectors – the future is here!

Looking forward to a very productive and eventful 2015!

Gabriela González and Marco Cavaglia

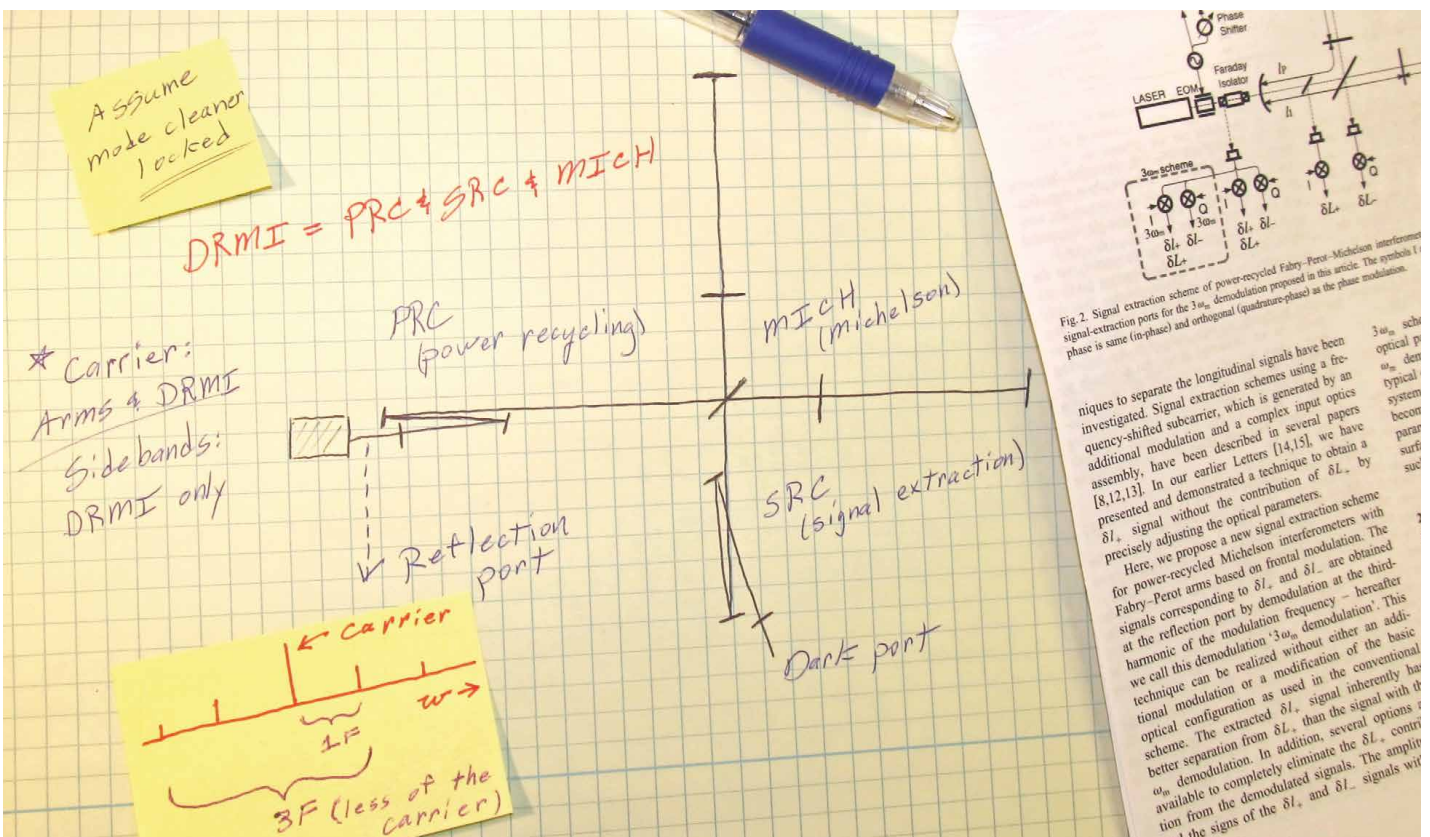
H1 detector update

Early in February 2015 LIGO commissioners obtained the first two-hour lock stretch on H1 with the interferometer working on DC readout. The most compelling difference between the advanced

version of H1 and its initial LIGO predecessor is the remarkable quietness of the beam spots. Even with only two auto-alignment servos operating, the beams are holding steady – beautifully demonstrating the value of the significantly superior seismic isolation systems.

Two very challenging months preceded the February milestone. In December 2014, the first attempt to fully lock the interferometer revealed a major problem with H1's end test mass in the Y-arm. Only half the expected light power build-up was observed in the vertex interferometer due to surface contamination on this test mass. A heroic cleaning effort by the installation crew just before Christmas fixed the problem, allowing commissioners to continue their efforts in January and ultimately leading to the two hour lock breakthrough.

Daniel Sigg



Detector Commissioning: Control Room Days and Nights



At LIGO Hanford, the major part of Advanced LIGO H1 installation reached completion in August 2014. Full resonance of the detector first occurred on December 3, 2014. The commissioning team entered 2015 with the goal of moving H1 forward as rapidly as possible in sensitivity and robust performance. It's a winding road.

Building the car from the ground up

Commissioning the interferometer's global control system is the primary goal of the local staff, until the instrument can operate at design sensitivity for several hours at a time. Bringing up this sensing and control system is difficult-at-best because sensors and actuators are designed to meet the final noise performance specifications. This usually means that global actuators are weak (and therefore low noise), and global



Jeff Kissel

Jeff Kissel bounces around between LIGO's many subsystems as the LHO Controls Engineer, a label that's ill-defined (or perhaps over-defined!) in the traditional LIGO experimentalist sense. Suffice to say that you'll find Jeff near any problem that involves control systems.

sensors need lots of light (high signal-to-noise ratio) in order to work well. This is exactly the opposite of what one has when getting started, when the individual components have not yet been brought to their best performance, and interferometric light build-up is low.

Before the global control system can take shape and perform well, the local controls in each seismic isolation system (composed

of both the in-vacuum seismic isolation systems and multi-stage suspension systems) must suppress ground motion to a level that allows the global interferometer controls to fully engage – see, for example, the discussion about MICH below. Through persistent tuning of local isolation systems, the interferometer becomes stable enough to gradually turn on the global control of each of the interferometer's degrees of freedom in succession. Further tuning of the global control system, e.g. switching between various available sensors and actuators that make compromises between functionality and noise, is required to keep all these degrees of freedom simultaneously on resonance for long durations. Once all of the interferometer's degrees of freedom are under global control and on resonance, the interferometer has enough light circulating inside that the designed amount of



▲
Members of the Commissioning team observe full resonance of the Hanford interferometer on December 3, 2014. Shown left-to-right are Lisa Barsotti (MIT), Evan Hall (Caltech) and Alexa Staley (U Columbia). For a late-breaking update on locking, see Daniel Sigg's article on page 5 of this issue.

light hits the low-noise global sensors. And then the noise hunting begins.

Some roads are straight; others full of twists and turns

Early on, various commissioning tasks can be performed simultaneously, since they involve discrete subsystem components that are not yet interconnected by the interferometer. For example, after initial installation of an end-station seismic isolation system, it takes a few weeks for the vacuum chamber to be pumped down to a pressure equal to the arms (the pressure in the arms is never allowed to rise; the long

arms are isolated via giant gate valves during installation activities). During this time, local sensors and actuators on the isolation system are used to gather quality assurance measurements, and tune the local control system to get the isolation most of the way towards final acceptable performance levels. Once these end chambers become connected to the corner station by the interferometer, however, commissioning must become more linear since the various pieces now need to work in concert.

More linear does not mean obviously linear. On a scale of months progress can look satisfyingly constant and the instrument performance will display a nice rate of improvement. This big-picture obscures the myriad day-to-day struggles, setbacks and even pauses where further advance is stymied.

Occasionally activity even becomes frustratingly circular; a once-solved problem can become troublesome again as the environment changes. In the fall of 2014, the Hanford corner station's interferometric control system was tuned to reduce the time it took to bring the dual-recycled Michelson (a subset of the full interferometer) on resonance from 15-30 minutes to just a minute or two. Two weeks later, in the face of more vigorous seismic noise, the same interferometer control scheme couldn't keep up the short acquisition times. So, another round of optimization was performed.

To assess progress toward our medium-term goals, the on-site staff meet on a bi-weekly basis. Day-to-day activities are adjusted accordingly. Further, because of the small nature of our teams, ongoing informal

discussions help us more successfully attack the new problems that arise each day.

Bumps in the road come in all different sizes

In order to defeat a single large problem, we must often defeat many small problems. An example: we realized an improvement was needed in the in-vacuum seismic isolation (ISI) systems' performance to reduce noise in the interferometer's Michelson (MICH) degree of freedom. MICH comprises the differential motion of three independent ISIs. "Great – challenge! Let's do it."

We sought to modify each ISI's control system to use sensors on the floor to subtract ground motion from the on-board ISI sensors, a technique known in LIGO as sensor correction. On our first attempt, we discovered that the ground sensors were wired in an unexpected way. Thus we needed to a) verify the current installation, b) propose a better solution, c) update the documentation, and d) make the necessary hardware changes, all taking a week's worth of time. But once finished, we could now get back to implementing sensor correction. Our second attempt improved the performance in one direction at each chamber but made the overall Michelson performance in a seemingly unrelated direction, worse. This drew our attention to the local angular motion sensor signal, which looked oddly high and very noisy. Why? The associated electronics chassis for the suspicious sensors were missing a tiny-but-vital, externally connected, switchable, configuration board. OK, then – we must find, install, and configure those boards for all three of the local sensors. Another two days. Once configured, a third attempt showed the noise still looked too high on the local sensors. Earlier we had tried to dead-reckon the digital calibration of the sensors based on our

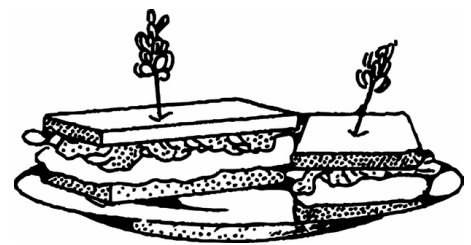
knowledge of the electronics chain; now a better calibration was required. We added two more days to the project.

Able now to trust our angular noise measurements, we pressed forward with another attempt at improving the sensor correction. But the MICH noise remained poor. The excess noise seemed to affect all three optics similarly. Could there be excess magnetic coupling to our feedback sensors on the ISI's? We measured the magnetic coupling on an ISI still under construction. We diverted personnel and fast-tracked the completion of the ISI for the sake of these measurements. Five days, only to discover that the problem wasn't magnetic coupling. Was it tilt-horizontal coupling? No. Was it cross coupling between sensor signals on cables? No – one more week to investigate these problems. We tried feeding the sensor correction to a different actuation point and saw an improvement, but why? More measurements. Finally we'd narrowed down the problem: our actuators were deforming the isolation platform in a small, but non-negligible way, so as to couple sensor correction control to angular motion. In our final attempt, we tried feeding sensor correction to an alternate actuation path. This worked! Using our new configuration, we finally made "... an improvement in the in-vacuum seismic isolation (ISI) systems' performance to reduce noise in the interferometer's Michelson (MICH) degree of freedom." Now, four weeks later, we could finally see improvement in the MICH, a large problem was finally defeated, and forward progress can be made. But you can guess what happened next – commissioners began looking at new plots in the control room and said "What's the excess noise we can now see in MICH between 300 and 400 Hz?"

Sometimes you get hungry on the road

As we progress through these stages of commissioning toward the final goal, we constantly investigate the sources of what is limiting performance. When the noise sources become exposed, linear (and non-linear!) action is taken to beat them down – more seismic isolation, better electronics on a sensor or actuator, better automated alignment of mirrors, new in-vacuum or out-of-vacuum components, etc. Each improvement requires reassessment by the globally controlled interferometer, the parameters of which may have changed (hopefully improved) in a way that requires further tuning. It's the commissioning triple-decker sandwich that we eat all the time: Model, measure, tune, measure, model, install, measure, tune, model. Paraphrasing Rana Adhikari, Professor at Caltech, here's the recipe:

The bottom slice of bread: Think. Consider the problem; form an expectation based on models, prior measurements or even intuition.



The meat: Make some measurements from here to there, see if they support your model.

Some lettuce: tune the control system based on your measurements.

Add another slice of meat: Measure again to confirm the tuning changes did what you expected. It's not quite yet what you want.

The middle slice of bread: Think. Model

what would happen if you improved some hardware in the system.

A tomato: install the new hardware.

More meat: Measure the same point-to-point to verify the new hardware works.

Top with a slice of cheese: tune up the system one last time to better take advantage of the new hardware.

Complete the sandwich with the top slice of bread: Think. Did the improvements match your expectations? Usually not, but either a yes or a no will lead you to the next steps.

Of course, like with any good sandwich, the chef is free to add, remove, and mix up layers as he or she sees fit, depending on the problem. A pragmatic assessment of the awesomeness of the day's sandwich can be found in "Dr. Frolov's Levels of Awesome" (paraphrasing Valera Frolov, LLO senior scientist and commissioning lead). In order of increasing awesomeness:

- 5) The change doesn't work and it makes the interferometer performance worse. Sometimes this level of "success" is accompanied by the phrase "and you broke something."
- 4) The change works, but it makes the interferometer performance worse.
- 3) The change doesn't work, and it doesn't affect the interferometer performance.
- 2) The change works, but it doesn't affect the interferometer performance.
- 1) The change works, and it improves the interferometer performance.

Members of the commissioning team are pictured here as they view parameters related to the locking of H1. Throughout LIGO, individuals less than 30 years of age continue to make key contributions to all aspects of detector operations and data analysis.

The commissioning sandwich, in all of its layers (modeling, measuring, changing, tuning, and thinking), often is riddled with the higher numbered items on this list, despite our best efforts. But on those occasions when you can achieve Level 1 awesomeness the sandwich really does make it worth the effort, and keeps us all coming back for more!

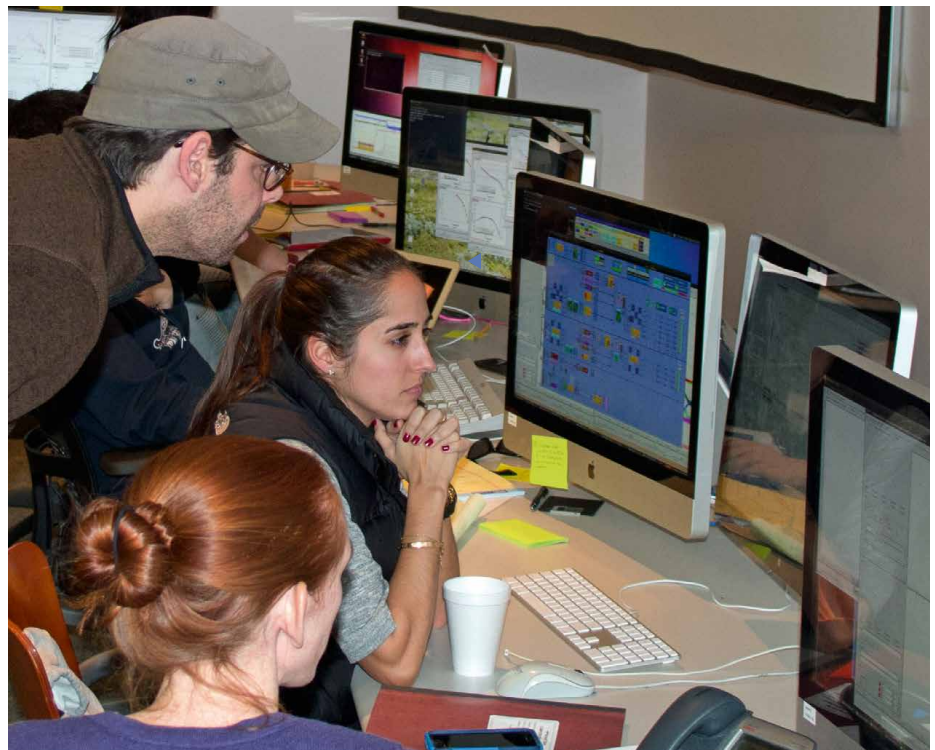
Who's driving?

A "commissioner" is anyone who contributes to the betterment of the interferometer. The lines between installation, engineering, and global control commissioning teams disappear as the full interferometer becomes operational. The commissioning program requires skills that range from electronics to optics to computer programming to mechanical engineering to public speaking to fundamental physics to creative and critical thinking. The multi-

threaded, multi-faceted nature of day-to-day commissioning requires a unified front from the local staff at each observatory, Caltech and MIT personnel, and many others across the LIGO Scientific Collaboration. We like to consider the collaboration one big, cohesive commissioning team.

We all get together on the phone every Friday (if not more often) and discuss the past week and future weeks to come. Often, off-site commissioners accrue significant frequent flyer miles shuttling to the sites. These visitors from all over the world fly in for special tasks, ad-hoc assignments, relevant side projects, some often staying for months to a year or more helping out. LIGO continues to find personnel who have helped the project stay on schedule, on budget, and, most importantly, on the path to a level of detector performance that will make regular detections possible.

LIGO₂₀₁₅



Salsola Siege



For several weeks each year, high winds out of the Cascade Mountains rip through the LIGO Hanford site. Often in excess of 40 km/h (25 mph) with a maximum 173 km/h (107 mph) recorded at the observatory, these winds transport thousands of Russian thistle plants, or tumbleweeds, across the desert.

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.

The thistle, or Salsola tragus, is considered a noxious weed and is an invasive species, which arrived around 1873 from the steppes of Russia in sacks of flaxseed and fixed a tenacious grip on Oklahoma and neighbouring states [1]. The plants grow in scarified dry soils, break at the stem, tumble in winds as a means to distribute their seeds, and begin their life cycle again. A single plant can deliver a quarter of a million propagules (seeds) in a swath many kilometers long.

The dead tragus periodically lay siege to our corner station and arms (see images on the right). At LHO, we pay tens of thousands of dollars per year in baling contracts to reduce the risks of wildfire. Baling compactifies the fuel and reduces ignition risk. The arms can be inaccessible for days while baling is underway, a process that often begins with the clearing of a single lane (image on left). Concerned about

◀ *The accumulation of the ever-present tumbleweeds is so big that Balers have to keep access roads clear.*

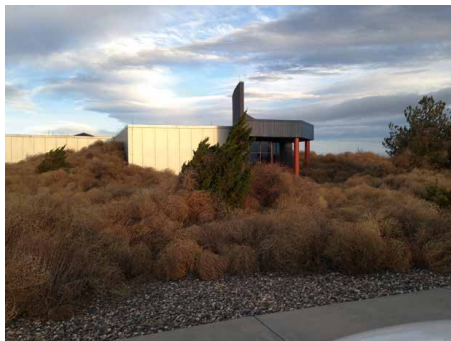
their potential as a transient gravity gradient source, people have even calculated their effects on test masses [2].

While the thistle can be starkly beautiful and make one nostalgic for the old west, they are primarily a nuisance. Tragus make the most alarming sound when caught in your car wheel well (until you pull it out). And as you roll down Route 10 on your motorcycle, with the interferometer beam tube off to one side, they can explode spectacularly under an excessive and wind-driven Galilean transformation.



[1] <http://en.wikipedia.org/wiki/Tumbleweed>

[2] T. Creighton, "Tumbleweeds and airborne gravitational noise sources for LIGO", Class. Quantum Grav. 25 (2008) 125011



▲ *Top: Tumbleweeds invade the corner station at LIGO Hanford Observatory. Bottom: The y-arm access road is buried under a 3m thick carpet of Salsola tragus.*

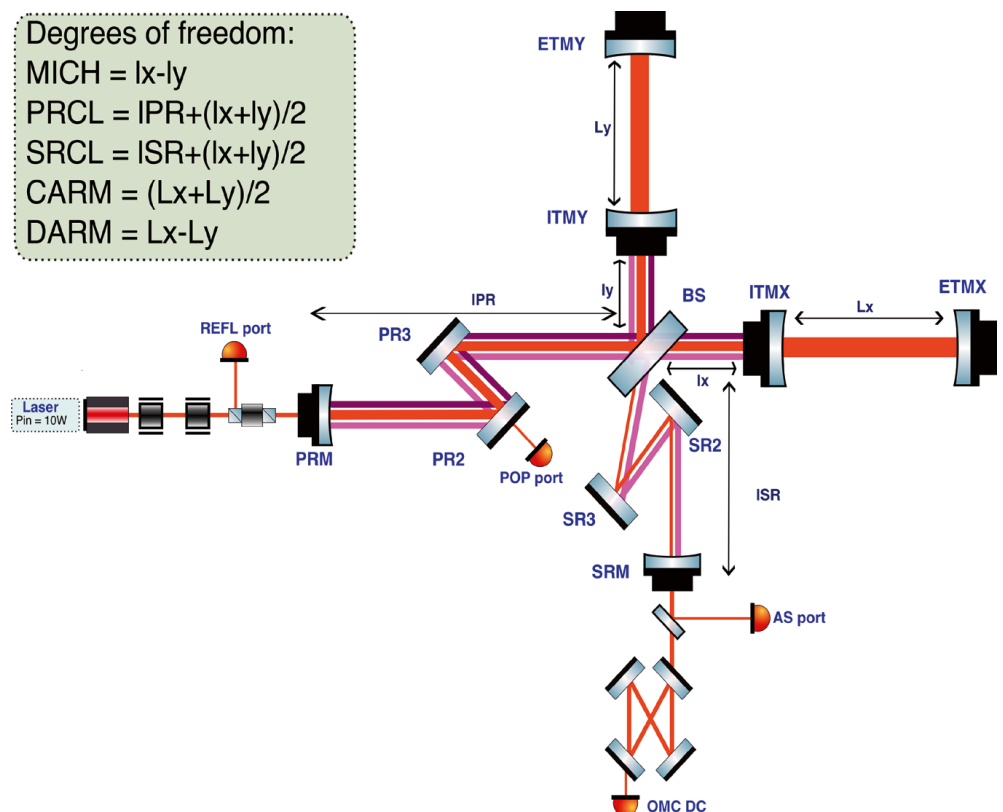
The red trace represents the main 1064 nm laser beam. The dark purple trace represents the 9 MHz radio-frequency sideband which resonates in the power recycling cavity. The pink trace shows the 45 MHz sideband which resonates in both recycling cavities. These modulations are applied to the main beam and together with their harmonics are used both to lock the interferometer and to control it in its locked state.

Some of the main beam is filtered through the signal recycling cavity and then is sent either to radio-frequency photodiodes (labelled "AS port") or is filtered again by the output mode cleaner (OMC) and then detected by the DC read-out photodiodes.

Diagram of a LIGO Explaining the Degrees of Freedom

A simplified layout of the LIGO interferometers showing the most important optical components and the various cavities which need to be controlled.

Degrees of freedom:
 $MICH = l_x - l_y$
 $PRCL = IPR + (l_x + l_y)/2$
 $SRCL = ISR + (l_x + l_y)/2$
 $CARM = (L_x + L_y)/2$
 $DARM = L_x - L_y$



Control Screens of aLIGO

Every complicated machine needs a control panel, and the LIGO interferometers are no exception. The interferometer is operated via a collection of hundreds of control screens accessible via the control room computer workstations. Each screen is a kind of cartoon showing how signals travel through the underlying real-time control systems, and allows important parameters to be adjusted. The screens themselves are a reminder of how the interferometer control loops work. They are drawn so that signals travel from left to right, and the screens are arranged in a top-down hierarchy so that you can “drill down” from the top level overview to any needed level of detail.

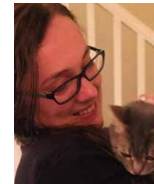
This is the main screen for the length sensing and control (LSC) subsystem, which keeps all optical cavities on resonance and extracts the gravitational-wave signal. The organization of the subsystem is similar to many others: signals come in from photodiodes (depicted on the left) and then are formed into linear combinations representing various degrees of freedom (DoF) via the input matrix (depicted as a grid of grey and green boxes; green boxes represent nonzero elements). The DoF signals are processed through digital filter modules implementing the servos (depicted in the center of the screen). The output matrix to the right sends these processed signals to the various actuators. The challenge of control screen design is to repre-

sent all of this complexity in a way that is accessible but not overwhelming.

The screen at first appears to be full of confusing acronyms. However, standard organization and naming conventions make it very usable and understandable for experienced interferometer operators and commissioners. After a few days working with the machine, these conventions become second-nature. For example, photodiodes whose names start with “POP” come from the “pick-off of the power-recycling cavity,” REFL pertains to the light reflected from the interferometer, and AS is the antisymmetric port. From the photodiode name you can also see where it is located, whether and at which frequency it is demodulated, and so on.

There are seven DoF that we control. DARM is the “differential arm length”, the all-important signal from which the strain output of the interferometer is derived, MICH is the simple Michelson interferometer formed by the beam splitter and the two input test masses. PRCL is the power-recycled Michelson length. SRCL, pronounced “circle” in the control room, is the signal recycling cavity length. CARM is the common arm length counterpart to DARM and X(Y)ARM are the single arm cavities.

Clicking on the button associated with a sensor, servo filter, or actuator brings up a more detailed screen dedicated to that

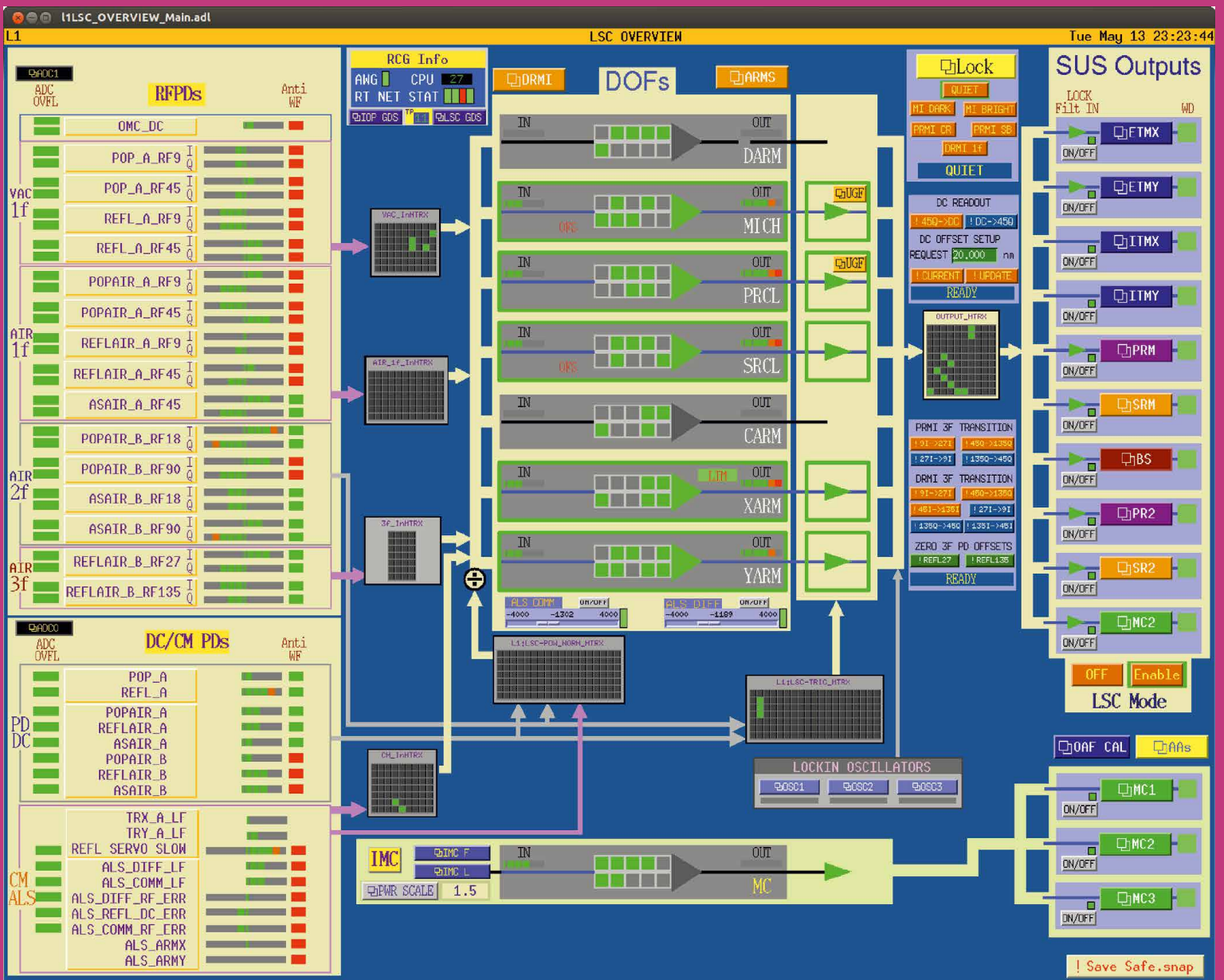


Anamaria Effler

Anamaria recently completed her Ph.D. at LSU working on aLIGO commissioning. She is partial to Louisiana weather, cats and pocket knives.

component, and each of these screens also has sub-screens, eventually exposing the entire operation of the machine.

The length-sensing-and-control system contains many convenient features. The sensors are normalized by the laser input power so that we do not have to change the loop gains when we change the laser power. Each sensor button opens a screen where we can set filters, gains, and, whenever relevant, analog whitening or phasing of radio frequency signals. The sensor inputs can be normalized in other ways. For example by the power buildup in a cavity. This keeps the relevant control loop stable in the presence of power fluctuations. The various orange and blue buttons above and below the output matrix call various locking and transition scripts which we use for automation. There is a triggering matrix that only allows the control signal to pass through to the actuator if some condition is met (for example high power buildup in an arm enables the arm locking servo). We can choose to turn off all LSC signals using the LSC mode button, so that the optics are not kicked around

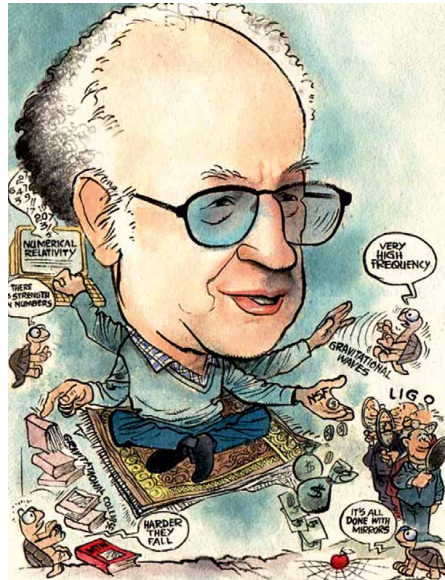


when we lose lock and the signals become garbage. In the bottom right the button " ! save Safe.snap" will take a snapshot of all the settings, and allow us to restore to that configuration in the event of a power outage or computer failure. Digital lock-in amplifiers allow us to apply a modulation and then demodulate any of the sensors with the applied signal.

The Transition of Gravitational Physics – From Small to Big Science

The role of the NSF and the scientific community in shaping the LIGO concept

In the second half of the last century, the field of physics led the scientific community in an inevitable transformation from “small” to “big” science. The need for a sub-field to reorganize to attack the current frontiers of research began in high energy physics, and spread through nuclear physics, atomic physics, condensed matter physics, and eventually even to theoretical physics. It was driven by the need to move from table-top research equipment under the control of individual university investigators, to remote shared centralized facilities, with cutting-edge instrumentation and enormous budgets. The move was always painful, and created major dislocations and reorientations for faculty, students, and university physics departments.



The author as seen by C.V. Vishveshwara .

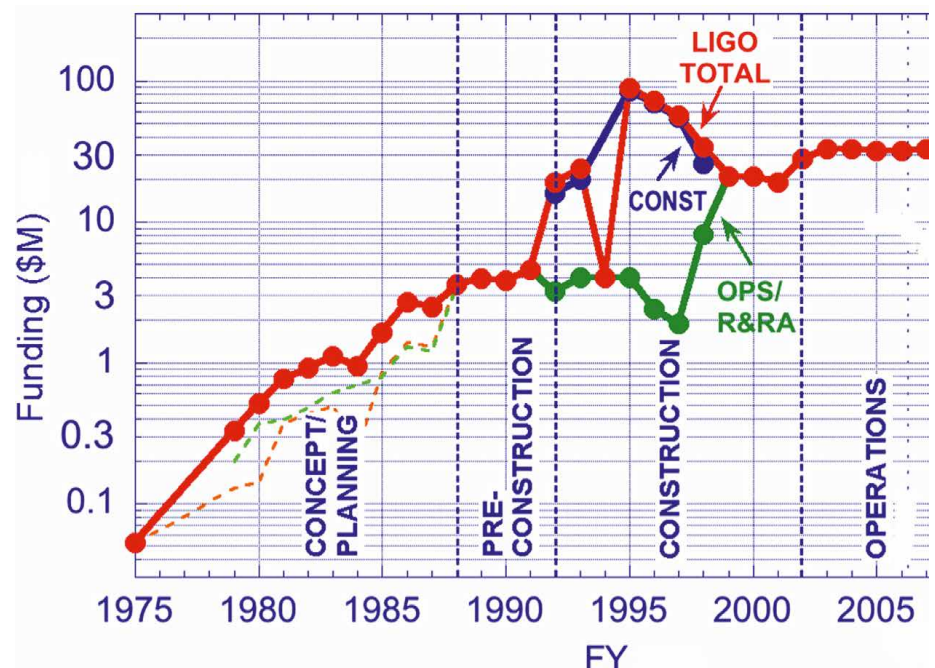
Richard Isaacson is a retired NSF Program Director for Gravitational Physics, currently doing independent research on, writing about, lecturing, and occasionally curating museum exhibitions on Central Asian carpets. Physics is still his hobby.

went an epoch of “inflationary expansion” in manpower, budget, and complexity during the last quarter of the 20th century. It only happened successfully through the intertwined planning efforts of visionary scientists, leading universities, and the National Science Foundation (NSF).

The graph in Fig. 1 shows the exponential growth in funding needed to create a large facility over three decades of time. From 1975 through 2005 there was a four-orders-of-magnitude funding expansion. During this period the project progressed through a number of developmental stages, each with important guidance supplied by NSF and the scientific community. I’ll discuss these stages and how they were managed. But when people say that “the government doesn’t do anything new” or “the government doesn’t do anything risky,” LIGO provides quite a counter-example.

This transition was perhaps most dramatic for gravitational physics, which reinvented itself and under-

LIGO is NSF’s most expensive project. It’s a long-term project with high risk but potentially commensurate high reward.



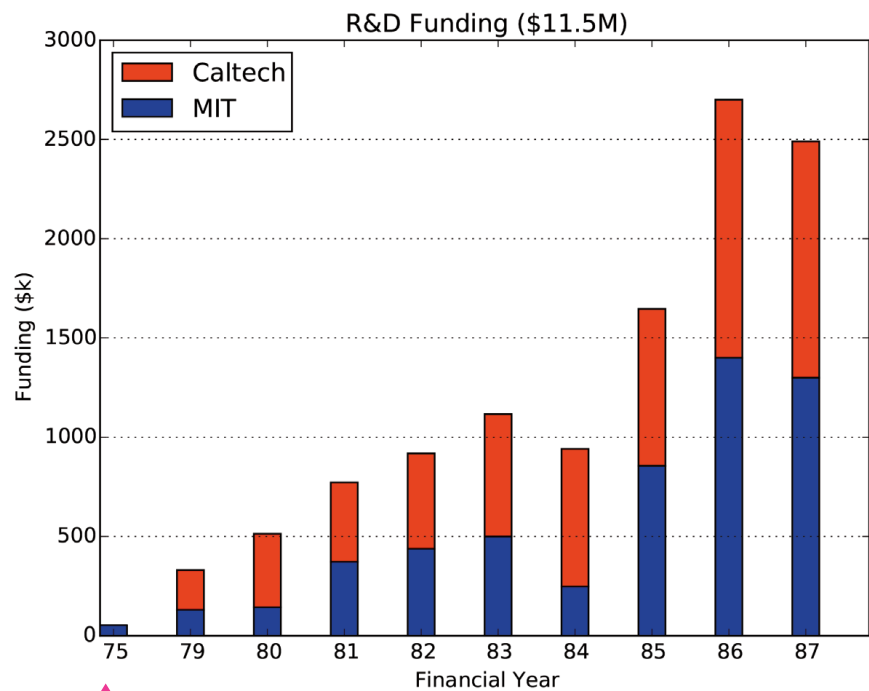
Many technologies were being advanced by several orders-of-magnitude simultaneously. This is totally crazy. Moreover, the field started out with basically no initial community of supporters or users. So while creating the instrument we had simultaneously to create a community to use it and to carry out the scientific program. Even crazier, this was run by universities as an “on-campus” operation, with issues such as academic freedom and intellectual property rights and the many, many other quaint university customs. If you’re designing a laboratory from scratch, the obvious way is to start by going somewhere off-campus and to hire brand-new people. You would then set up the rules to do what’s necessary to make a project happen on time and on budget. But amazingly, LIGO was still successfully managed as a university-run program.

The seed for the transformational project was planted at NSF the first day I arrived in August 1973. I was met at the door by Harry Zapolsky, my predecessor, who was about to go off to Rutgers as physics department chairman. While I helped him carry his things out to the car, he gave me the best piece of advice I ever had as a Program Director. He told me: “Rai Weiss is a clever guy. When he visits NSF again you should listen to him.” So that’s what I did for the next three decades. By 1975, two years after this suggestion from Zapolsky, Rai already had his first tiny grant from NSF for interferometer R&D. At that time the entire annual national effort in gravitational physics was \$1.4 million at NSF, split evenly between theory and experiment, and Rai Weiss had a grant for \$53,000. The budget was used to help support Rai, one postdoc, and a little bit of equipment.

NSF was the only agency whose mission allowed support for ground-based research in this subfield of physics. Marcel Bardon was the NSF Physics Division Director. He always watched what was happening in gravity very carefully, and he had a large role in all of the future developments. He really was crucial to the way the field progressed. Through his enthusiasm, skill, charm, and bureaucratic dexterity he enabled lots of things to happen. In 1975 Bardon had just wisely created a separate gravitational physics program, ignoring the advice to the contrary from his advisory committee for physics, and I became the first program director for gravitational physics.

Rai Weiss eventually managed to spend the small amount of money he was given. He came back, and not surprisingly, he asked for more. Ron Drever moved from Glasgow to Caltech, and he too asked for funding. The sum of the two requests was something very large to incorporate in the existing small NSF budget for the national

program of research in gravitation, because both groups wanted to build some larger-scale test apparatus and also have staff working in the laboratory. So what does NSF do when faced with such a critical choice? It did what we always did in those days, we got advice from the scientific community. I put together a technical review sub-committee to our advisory committee for physics, and they went around to all of the experimental gravitational-wave bar detector groups that were being funded by the NSF. Then they visited the potential newcomers at Caltech and MIT, returned and wrote a report. They endorsed a significant expansion of the NSF gravitational physics program to allow it to initiate studies of laser interferometry in gravitational-wave detection. Bardon used this report to get supplemental funding from NSF management to expand these efforts, as he was to do again and again over the coming decades. This began an epoch of exploratory R&D, and the concomitant growth of the budget.



◀ Fig. 1: LIGO Funding History

▲ Fig. 2: LIGO budget development

From FY1975 to FY1987 there were two interferometer groups being funded, Caltech and MIT. After spending a total of \$11 million shown in Fig. 2 by FY1987, the key ideas needed to enable the technology for an interferometer capable of detecting gravitational-waves were demonstrated: dark fringe operation, phase modulation, Fabry-Perot cavities, Pound-Drever-Hall stabilization, isolation, etc. Prototypes for all of the critical components for a large laser interferometer were proven.

In the early 1980s Rai Weiss reasoned that we clearly could build something capable of detecting gravitational waves with the technology already in hand, provided we were willing to spend enough money. A hundred-kilometer-long interferometer would do the trick, but would have astronomical costs. Instead of refining the state of technology further, Rai understood that he had to explore how we might build something more practical. Together with the engineering firms Arthur D. Little and Stone & Webster, he started looking into scaling laws governing large facilities. What part of the system was length dependent? What were the fixed costs? What kind of vacuum system is needed? Peter Saulson and Rai worked out all of the noise sources that would be competing with astronomical signals, and how they scaled with length. Stan Whitcomb collaborated with them to introduce some of the new optical techniques studied at Caltech that would make the device even more sensitive. The results were put together in the so-called "Blue Book", which was circulated in a small Xeroxed edition, and laid out everything needed for designing a multi-kilometer-long facility with the engineering solutions available in 1983.

The obvious next step was to start serious discussions with key players about a

large-scale facility to detect gravitational radiation, moving the process into a pre-construction epoch. From then on, all further steps would be subjected to screening by many community and government advisory groups that were involved with planning future ambitious and expensive concepts (see Fig. 3).

close attention, since this would be an extremely expensive, but also an extremely interesting possible major construction project, in competition with any other major NSF initiatives coming along. Following its detailed review, the NSB approved going ahead with more planning and feasibility studies to try and make a better and



▲ *Fig. 3: The obstacle course for initiating a large gravitational radiation detector*

To start the process off, there was a discussion with the NSF Physics Advisory Committee about whether they found this as interesting as other exciting possibilities for the future offered by high energy physics, nuclear physics, and atomic physics. Next, there was consideration by a sub-panel on gravitation, cosmology, and cosmic rays (the so-called "Wilkinson panel" of what became the Brinkman report) of the decadal study of physics priorities that the National Academy puts out. There were discussions in 1984 with the National Science Board (NSB) – the group running NSF, the president's science adviser, and with The Office of Management and Budget (OMB). The NSB was given an early warning via a very useful formal mechanism (which has unfortunately since been dropped) called a "Project Development Plan", and so it was alerted with an early flag to pay

more rigorous set of arguments. In 1986, the International Society of General Relativity and Gravitation approved the idea of initiating a large-scale interferometer project. Finally, a very significant meeting was organized in Cambridge in 1986.

I will expand on the key results shown in purple in Fig 3. First the Wilkinson sub-panel, reporting to the NAS: Their principal conclusion was: "We recommend that the NSF enhance its leadership in gravitational research by funding the Long Baseline Gravitational Wave Facility, while continuing to support a vigorous program to search for gravitational waves with resonant bar detectors." They were laying out priorities for the coming decade for government expenditures on big projects, and recommended construction of a large interferometer to detect gravi-

tational waves, concluding that this was a very high priority for further funding consideration by the National Science Board.

Second, the Project Development Plan to the Board: The NSB approved the following resolution: "Resolved that the National Science Board approves the continuation of the planning effort in support of the Gravitational Wave Detection System, limited to the demonstration of technical feasibility at the required sensitivity". Here, they did not approve constructing anything yet. But they allowed the NSF Physics Division to go ahead with support for expensive technical demonstrations which were necessary before NSF could make a further decision about something even more expensive and serious. Of course the NSB wanted to be kept informed about how the project was doing on meeting milestones, and the Physics Division would do that during the interim.

Lastly, the Cambridge Panel: Perhaps the crucial turning point in the transition of the field of gravitational physics from "small" to "big" science occurred at a review meeting in Cambridge in January 1987. A panel of outside scientists, including several current and future Nobel Prize winners, laboratory directors, and a future head of the APS, along with critics of the field, met in Cambridge for three days. They heard presentations from other scientists, including technical experts who had been doing research in industry in laser technology, optics, materials, etc, about what problems were outstanding and what possible solutions were available. The Cambridge panel made some very influential recommendations. It concluded that there was very strong science. However, it was very important for the project to have two sites with a single management in control. Consequently, if NSF were going to try to build

something major, the panel advised it not to proceed until the project could achieve such strong central management. At the time of the panel meeting there were two independent universities, loosely collaborating. However, for success, this project would require a single project leader of high stature, at least as high as the scientists who were involved, to direct this effort, plan and construct the facility, and act as a spokesman. This transformation would end the era of the individual PI. Following the successful choice of such a new director, the committee encouraged NSF to start serious planning for a possible construction project. The two universities were able to agree to reorganize the project into a single coherent effort. A single project leader, Rochus "Robbie" Vogt from Caltech emerged as the candidate that Caltech and MIT wanted to nominate as director of the project. He was a former provost of Caltech and chief scientist at JPL, and he had significant managerial experience that was crucial to the project at this stage.

To move to the next level of this process, it was now time to do large-scale preconstruction planning and feasibility studies (Fig. 4).

Caltech and MIT were not building a facility yet. Rather, during this period they were constructing test equipment and full-scale components to characterize the features of critical elements to be installed in the final apparatus. During the period FY88-91, about \$16 million was spent on these larger-scale and more expensive demonstrations. Vogt brought in strong central management and a significant team of engineers to go over the designs and ensure that it could be built. He organized a systematic R&D program, and all of this led to a conceptual design and the first realistic construction cost estimates that the project had generated. Simultaneously the science team demonstrated suspended optics, control systems, vibration isolation, spatial and temporal filters, high finesse cavities, high-power low-noise lasers, low-loss polishing and coating techniques – everything technically necessary to enable a large laser interferometer to work.

In 1988 Caltech and MIT were well-poised to be able to develop a proposal for the construction of the large facility which was to become known as the LIGO Project.

LIGO₂₀₁₅

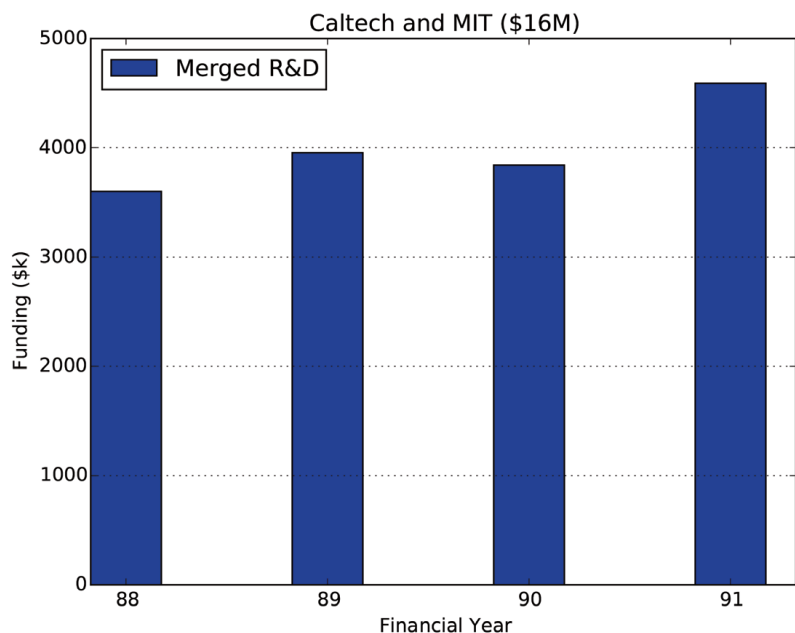
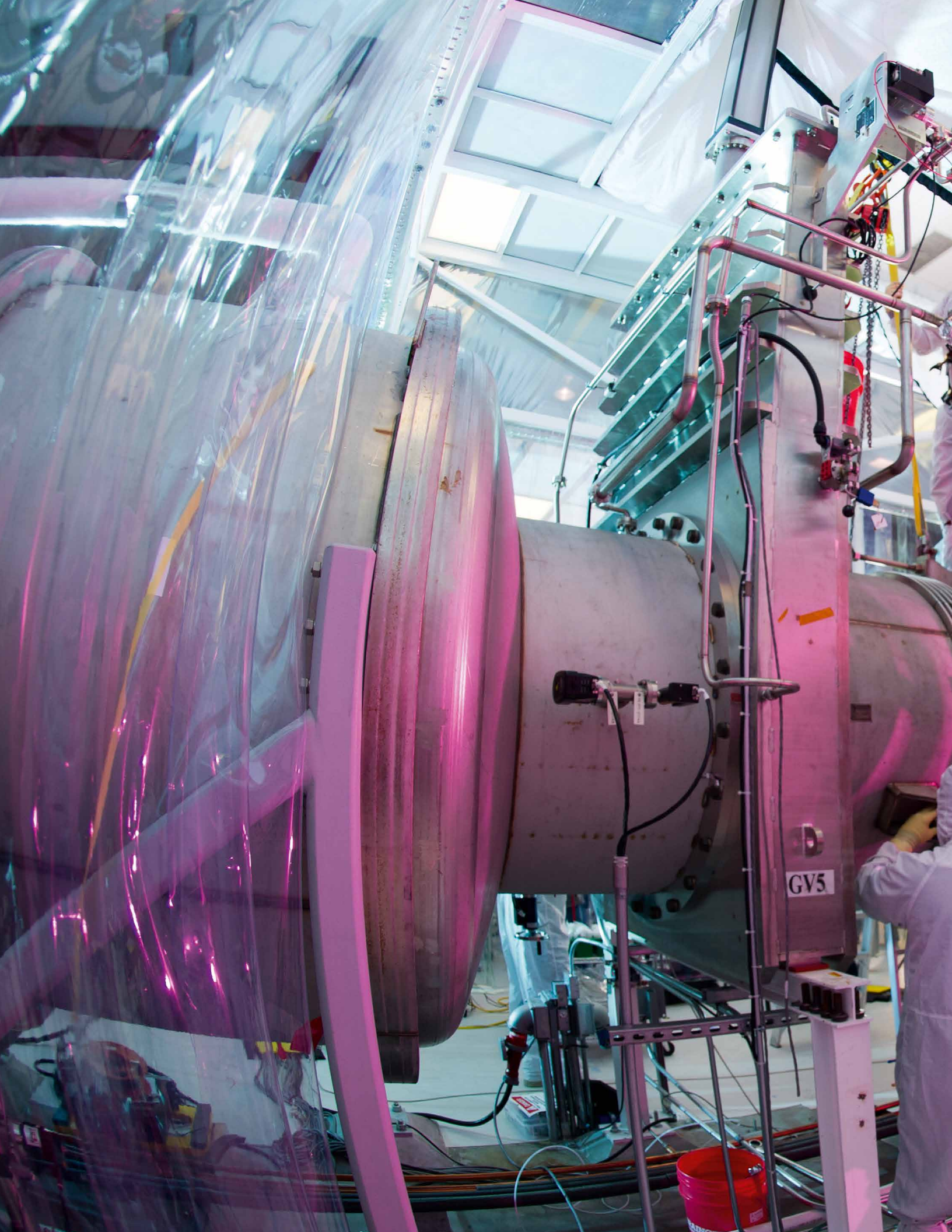
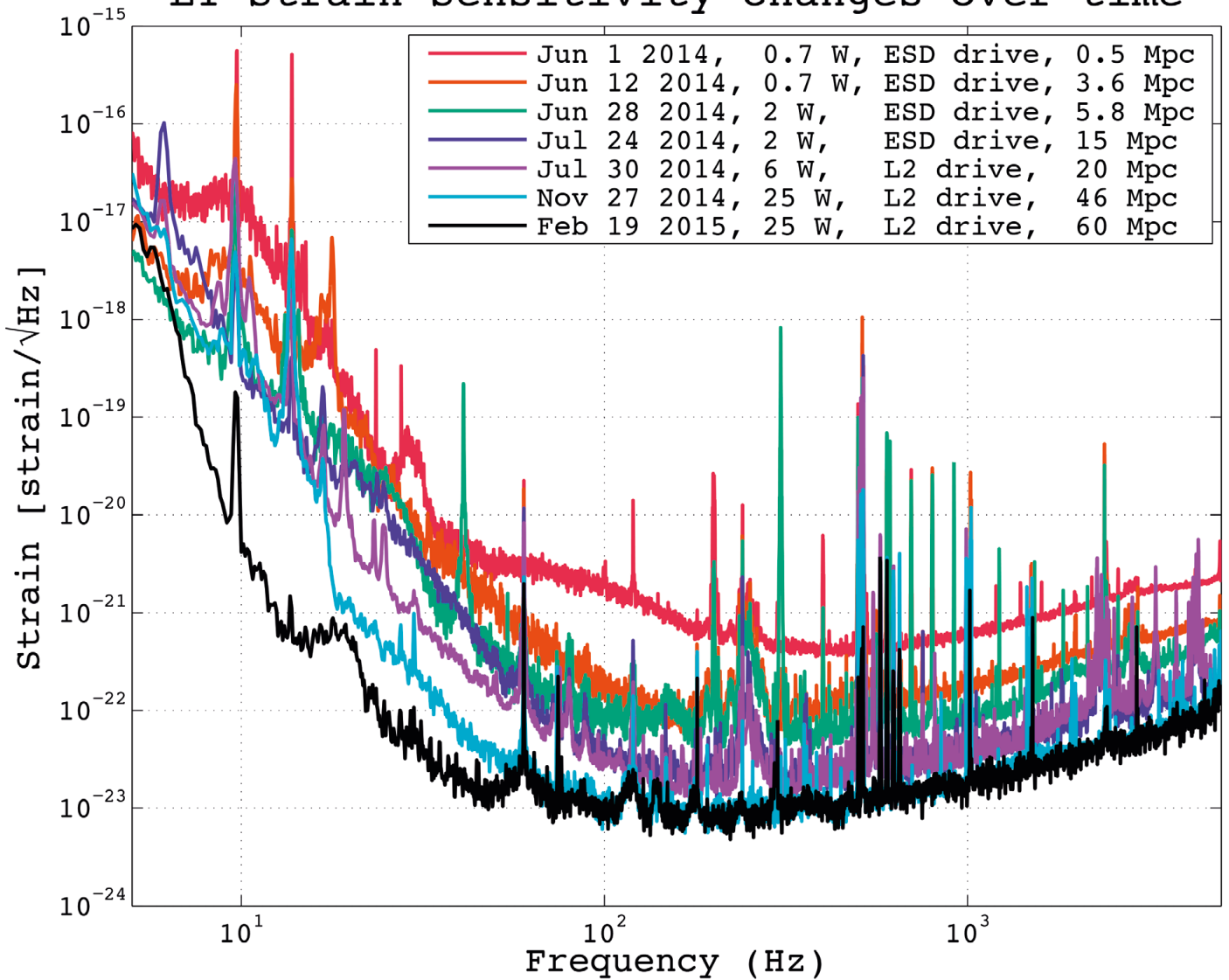


Fig. 4: Pre-construction planning and feasibility studies (FY1988-1991) ▶



GV5

L1 Strain Sensitivity changes over time

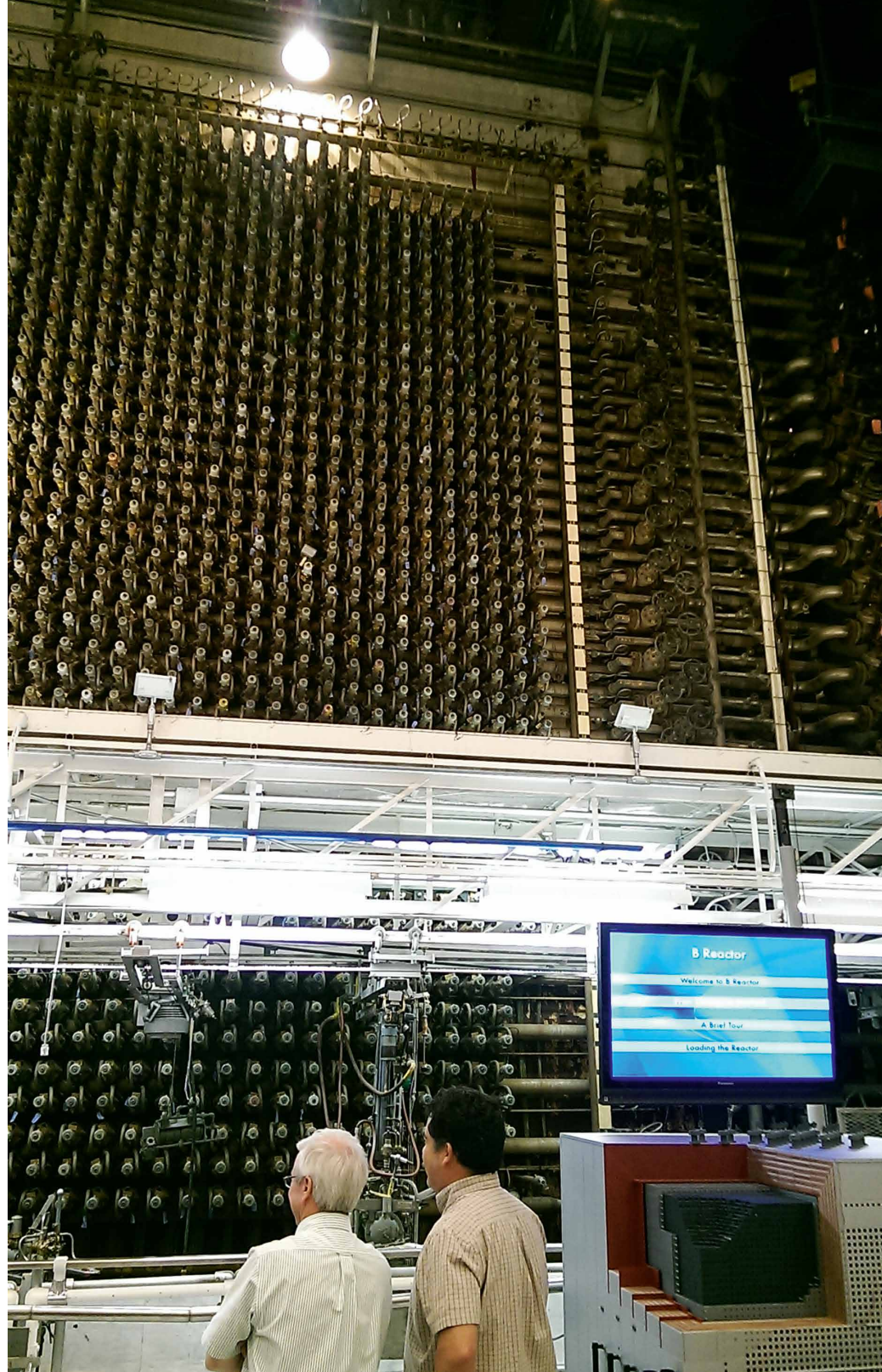


This plot shows the improvements in strain sensitivity of the LIGO Livingston detector. The legend indicates date of the spectrum, the power input to the mode cleaner at that time, the actuation method used to drive the end test masses and the range we could detect a standard binary neutron star inspiral. The two actuation methods are the electrostatic drive (ESD) pushing directly on the test mass and alternatively, using coils to push on magnets on the penultimate (L2) mass. The range estimation is based on a preliminary, unofficial calibration.

LIGO Field Trip: A Visit to the Hanford Site and the B Reactor

At the invitation of the Department of Energy's (DOE) Richland Operations Office, LIGO Hanford Observatory (LHO) personnel broke away for a hosted four-hour tour of the Hanford site and the historic B Reactor on September 30, 2014. In part the tour was reciprocity for a LIGO tour that we provided for about 70 DOE staff members in June of 2013. The Hanford bus tour helped the LIGO crew better understand occasional site-related seismic noise in H1; those of us touring the site for the first time appreciated the opportunity to learn some of the history of the facilities we can see from LHO's back patio.

As the bus traveled across some of the site's 640 square miles, we passed the ghost towns of Hanford and White Bluffs. Once home to hundreds of residents, these towns were razed in 1943 to secure the site and to make way for more than 50,000 workers, a number of whom would build B Reactor in just thirteen months. Little is left of the original towns except the foundation of a school and a few trees that stand out on the treeless landscape. Our guide pointed out that every tree was planted by a resident of these vanished communities. I began to think about those



silent sentinels and how many kids played under their shade, how many first kisses were kissed there, and on the difficulty of giving up one's home for a secret.

The B Reactor looks like many other mid-20th century industrial sites – square, cold, and gray. Inside we found cinder-block walls painted in gray and drab

green bands. As we walked into the reactor room, coming face-to-face with rows of ports for the process tubes that penetrated into the reactor's core, the historical significance of the room came into focus. I was standing in the actual spot and looking at the actual structure where industrial nuclear technology became a reality.

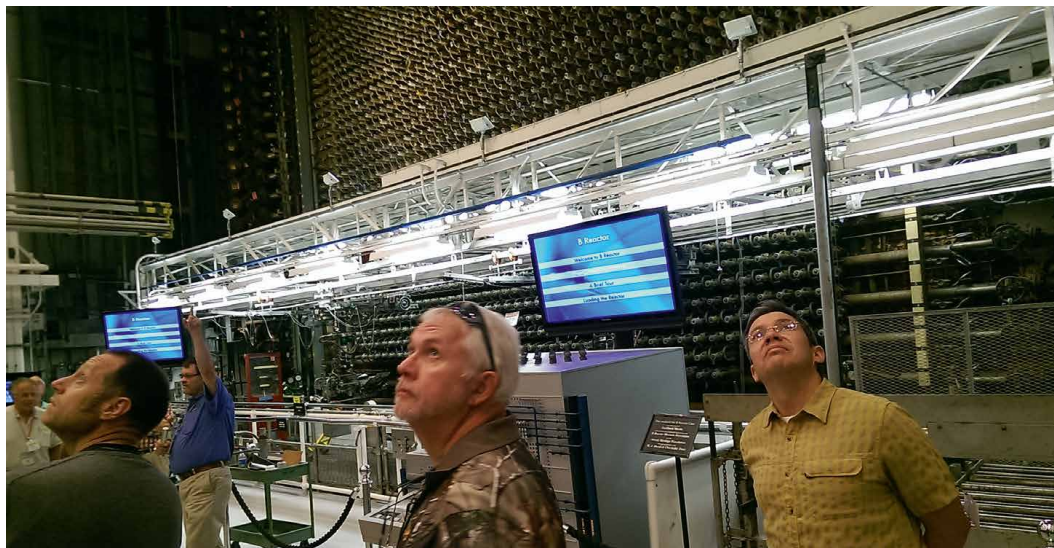
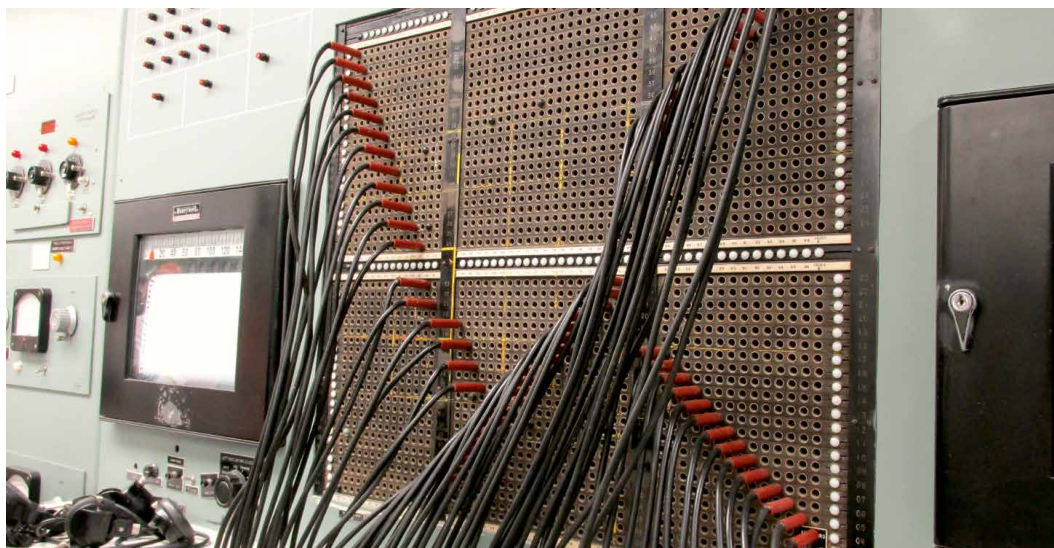


Jeff Bartlett

When he's not sailing his Flying Scot #2127 "Squark," Jeff Bartlett serves as an operations specialist and the contamination control czar (or coordinator) at LIGO Hanford.

From the reactor room we moved to the control room, a relatively small space with a small operator console flanked by walls of mechanical gauges and monitoring equipment. In 1944, control systems were mechanical and analog; Hanford was no exception. The operating temperature of the individual process tubes, a critical safety factor in operating the reactor, was monitored by a phone system-type switchboard that appears in old movies. To select a particular process tube, the operator would connect one of several hard-wired gauges to the process tube by connecting a wired plug. 1944 B Reactor control room staff might have seen Enrico Fermi or John Wheeler peering over their shoulders on a given day.

As we concluded the tour, our guide opened one of the monitoring panels. Inside was a tidy maze of wires and contactors. In one corner of this panel was a Cub Scout blue/yellow Ray-O-Vac D cell battery, which powered some portion of the instrument. Looking at that panel and marveling that this largely untried experiment worked at all, I wondered – did the fate of millions in 1944 rest upon a D cell battery?



◀ *Overleaf: LHO's Vern Sandberg and Gerardo Moreno stand in front of the B Reactor process tube array.*

Top: the B Reactor operator station in a condition that's close to original. The reactor building sat empty for a number of years before it was refurbished for tours.

Middle: B Reactor's switchboard-style communications board. Reactor controls were pneumatic. Bottom: LHO personnel inspect the B Reactor main hall, a large space dominated by process tube ports on the rear wall. ▶

Undergrads Conducting Research for LIGO

Nelson Christensen



Nelson Christensen is the George H. and Marjorie F. Dixon Professor of Physics at Carleton College. He started gravitational wave detection research as a junior at

Stanford in 1983. Be careful what you choose to do for undergraduate research as it can last a lifetime!

Many people from highly diverse backgrounds conduct LIGO research. The complexity of our experiment creates the need for different research projects in various scientific areas, and at differing levels of sophistication. LIGO's research environment definitely holds a place for undergraduate students who want to contribute to this effort.

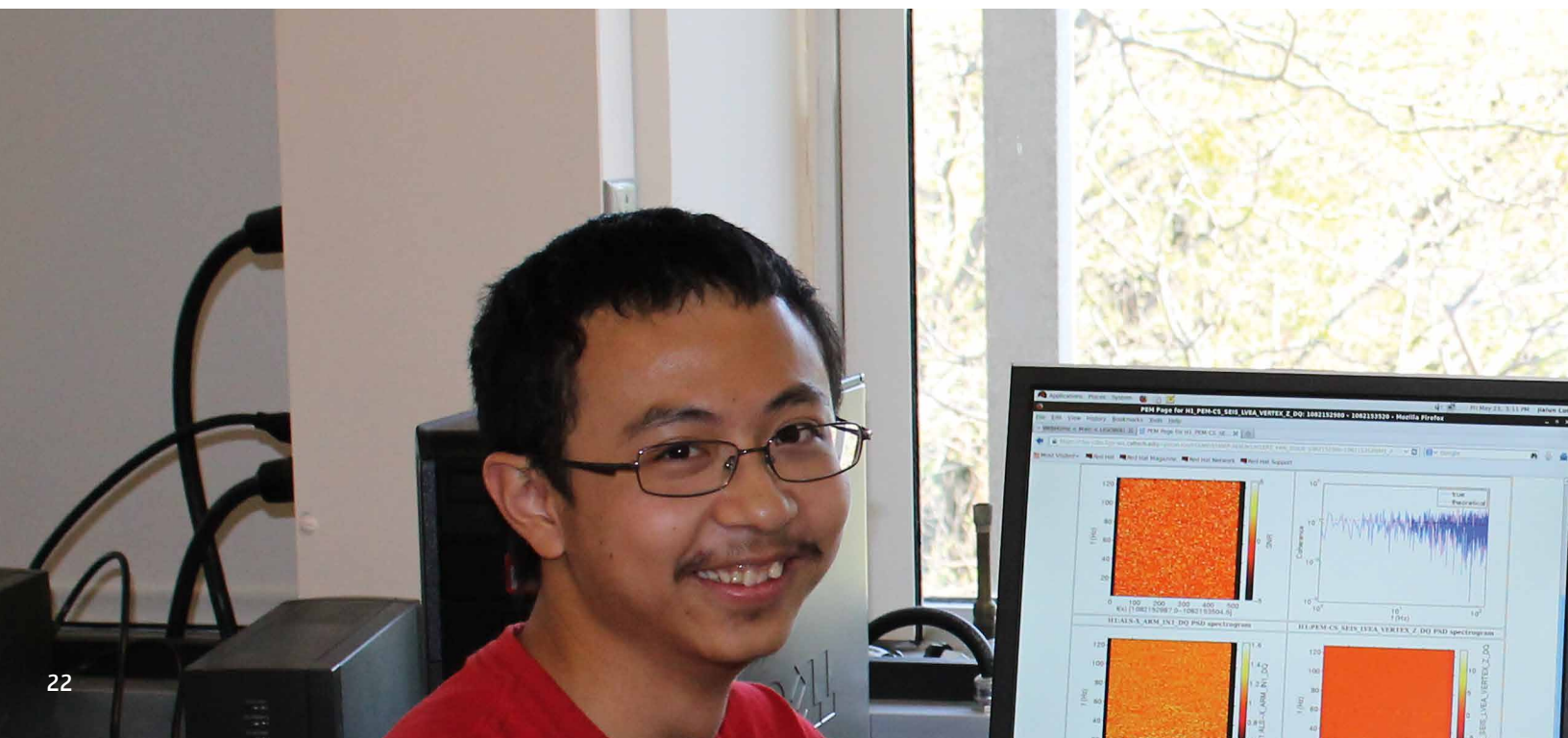
The American Physical Society recently reported that 62% of undergraduate physics majors now expect to conduct research as part of their degree program. LIGO offers a wonderful opportunity for undergraduates to experience the joys of physics research. With guidance, students across the undergraduate physics spectrum can find a project suited to their level and their interests.

Over the years at Carleton College I have had the thrill of seeing many students make real and significant contributions to LIGO's research efforts. You have probably interacted with some of these students, especially since a number of them have gone on to graduate school and postdocs, and are still in the LSC! But it should be noted that research is not a sure success for all undergraduate physics majors. I have seen "A" students who could never make the connection to the independent and original work required with a research project; that's okay, research is not for everyone. On the other hand, I have worked with students who earned B's and C's in their physics classes, yet exploded with the opportunity of research; the applied nature of the physics motivated them, and consequently, often encouraged them to become bet-

ter students in the classroom as well.

So how do you start a new research project? I typically point the students to the resources linked to ligo.org. It is important that the students understand what LIGO is and what we are trying to accomplish. Knowledge of general relativity is not required in order to undertake LIGO science, but certainly good lab or programming skills can allow a student to quickly build momentum on a project. Much of my own research concerns detector characterization and I find this to be a good entry point for undergraduates. Quite often I would sit a student down in front of a computer, show them how to access data, point out a particular noise problem and ask them to look for other time segments during which similar noise was occurring: undergrad-mon! Soon the students grow weary of data analysis by eye, and will report to me later that they have written their own program to find these events. Little do they realize that they have just taken their first steps in independent initiative and creativity. The research die has been cast!

Undergraduates are motivated to participate in the front lines of science, but they



are certainly terrified as they begin. Fortunately we have a very kind and generous collaboration with respect to students. I tell my students that interesting results will need to be reported at an appropriate telecon. Fearfully they present their first results, but always the response from our LSC colleagues is positive while giving recommendations and advice. The students seem to thrive on this positive feedback. Certainly they are even further motivated by the prospect of having their name on a LIGO publication. I also emphasize that an established research record will assure them of getting into graduate school. In the end, it is the actual ability to contribute to LIGO's science that makes the students work harder and harder. Even small research accomplishments can have a tremendous motivating effect on the students; when a voice on the telecon tells them that their presentation was interesting and helpful, they beam with pride. And so begins the career of a new scientist.

My research students have heard the lore from former students, and consequently strive to maximize their research options by taking advantage of other research avenues available to them in the LSC. The

International REU, run by the University of Florida, is an extremely attractive opportunity. With this REU an undergraduate can have both an overseas experience plus an intensive research opportunity for the summer. The other popular summer research program is LIGO Lab's Summer SURF. A number of Carleton students have participated in the SURF program and they always return raving about the positive experience. My students have been particularly impressed with the high level of science that they were expected to conduct. Both the Florida International REU and the LIGO Lab summer SURF programs serve as major motivators for my students; they want to do well with their work so that they can have a potential exciting summer of research with LIGO Lab, or at some interesting location outside of the US.

Carleton is not the only LSC group with effective undergraduate researchers. We see these great students at many LSC colleges and universities. Big and small schools are providing important undergraduate research opportunities. This valuable educational experience for the students is also part of the lifeblood of the collaboration. These are our future graduate students,



postdocs, and collaboration leaders. I'm gratified to see numerous research opportunities across the LSC available to undergraduate students.

I encourage all of you to find ways to involve undergraduates in your research. It has been a joy for me to see these students grow into scientists. But I must selfishly admit that my undergraduate researchers are the ones who help me get real work done. I have no choice, that's all I have at my little liberal arts college. Many times I have been paid a high compliment - "Nelson, that graduate student of yours is really doing great work." I love to then reply, "No, that's my undergraduate!" Good luck with your undergraduate researchers!

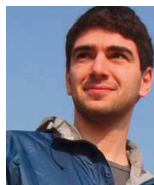
LIGO₂₀₁₅



Lower photo: Carleton juniors Jialun Luo (left) and Nathaniel Strauss (right) are both working on detector characterization projects in search of noise lines. **Upper photo:** Carleton senior Kenny Harvey (left) and sophomore Isabelle Hu (right) calibrating an antenna built to measure the magnetic field from the Schumann resonances. These antennae will monitor correlated magnetic field noise between the LIGO and Virgo sites.

A word of advice

Where Should I Apply for Grad School?



Ilya Mandel

is a Senior Lecturer in astrophysics at the University of Birmingham, UK. He strives

to seek out, and occasionally

finds, interesting astrophysical problems that yield to a mixture of back-of-the-envelope analysis and sophisticated statistics.

Where should I apply for grad school? What should I look for when visiting a potential university / research group? What factors do I weigh to reach a decision? And how much of this is still relevant when searching for a postdoc? Ilya Mandel, a LIGO member on the faculty at the University of Birmingham, UK, where he oversees graduate admissions in astrophysics, tries to address some of these questions in this article. In future issues, he will look at selecting a PhD project, and at maximizing what you get out of your PhD experience.

The decision on where to go for grad school is an important one: after all, you will likely be spending 3 to 6 years of your life there, depending on the country, university, and specialization area, and the skills you learn and connections you make during these years will lay the foundations of your future career. The decision is very much an individual one, and I won't pretend to know what's best for you; instead, I will suggest some questions that you may want to ask yourself.

First, what I won't address: the location-specific questions. There are many reasons why these might be important, from the need to be close to family (or a desire for space away from them) to preferences for large vs. small cities, or particular climates. These are all significant, and, depending on your personal circumstances, could be critical. Don't listen to people who tell you that you shouldn't pay attention to such things since your primary focus should be science: if you are miserable because, say, you are on the wrong side of the world from your partner, you won't be able to do good science, either.

At the same time, do beware of going to grad school just because it's an opportunity to live in a nice place for a few years or

because you can't think of anything better to do just now. This applies particularly to staying at your undergraduate university. It's usually not the best idea in general (it reduces your exposure to other ways of doing things), but you should be particularly wary if the reason you are staying is that you already have a nice place to live, your mates are there, you can't be bothered to apply for real jobs, and you are good at academics. You may discover that grad school isn't nearly as much fun as you thought – you could be making a lot more money and getting a good start on a career by doing other things – and after your friends move even though you didn't, you'll wonder why you decided to waste a few years of your life.

So what is a good place to start? Let's begin with the university. Reputation matters. You can have a lousy experience at a world-famous university or get a fantastic mentor at a middling one – but, on average, the quality of fellow students and the research environment will be better at the former. Plus, having that fancy name on your resume can help. However, if you are a sensitive soul, do watch out – faculty at top universities are often very competitive, and some will view graduate students as an investment; that means that until you've proven your worth to them, you may be treated as dispensable, so don't expect to be loved and cherished from the moment you step through the door.

What about the department? Again, reputation is telling – and here, if you can't judge for yourself, don't be shy in asking for opinions of people with more experience – but one of the basic things to look for is the flow of visitors. Check the calendar of seminars in the department; if the leading lights in the field you are considering are regularly passing through, you will

have the advantage of exciting interactions with them while a graduate student (and do take advantage of those interactions once you arrive – more on this in the third article).

Finally, if you already know exactly what you want to do in grad school (and in some countries, you have to apply for a position in a specific research group), how do you evaluate the group quality? Of course, a big-name advisor might sound impressive, perhaps someone whose popular-science articles in Scientific American you read when you were younger. But this famous person might be quite busy and not have too much time to spend on you. So talk to the current students in the group. Are they

happy? Are they getting enough attention? Do they find it easy to schedule meetings with their advisor, and if not, are there senior postdocs around who can help?

Don't be shy to check on practical details, such as finances. Are students in the research group getting the resources they need? Do they have enough money to order equipment, or get laptops and necessary software? Do they get to travel to conferences to present their results? Do students have to teach in addition to doing research, and if so, how much time do other obligations take? If the PhD program is funded for a limited duration, are there resources available to extend the stay if you'll need just a few more weeks to get

out that very exciting result from an experiment you have spent several years developing?

And what happens to students when they graduate? If you are possibly interested in an industry job, does your advisor have connections that helped previous students land the jobs they wanted? And if you think you might want to stay in academia, did previous students of your potential advisor go on to prestigious postdocs and eventual faculty jobs? Keep in mind that it's not just about the quality of the research in the group, but also about your advisor's willingness to promote their students and help you forge those key connections.

APPLICATION	LETTERS				SCHOOL	NOTE
	ESSAY	1	2	3		
<input checked="" type="checkbox"/>	✓	✓	✓	✓	STANFORD	↑ LOWER YOUR <u>EXPECTATIONS</u> ↓
<input checked="" type="checkbox"/>	✓	✓	✓		MIT	
<input checked="" type="checkbox"/>	✓	✓	✓		CALTECH	
<input type="checkbox"/>					U. OF FLORIDA	EVERYDAY IS A HOLIDAY!
<input type="checkbox"/>					SYRACUSE	SNOW ♥
<input type="checkbox"/>					LSU	LLO IS HERE!

We Hear That ...

Recent Graduations

Chris Bell successfully defended his thesis entitled “Mechanical Loss of Fused Silica Fibres for use in Gravitational Wave Detectors” at the University of Glasgow in May 2014. He is now at DNV GL, working in asset integrity management.

Thilina Dayanga successfully defended his thesis entitled “Searching for gravitational-waves from compact binary coalescences while dealing with challenges of real data and simulated waveforms” in December 2013 at Washington State University. He is now a yield analysis engineer at Intel Corporation in Portland, Oregon.

Ryan DeRosa successfully defended his thesis entitled “Performance of Active Vibration Isolation in the Advanced LIGO Detectors” in November 2014 at Louisiana State University. He has since taken a postdoc at LIGO Livingston Observatory.

Anamaria Effler successfully defended her thesis entitled “Characterization of the dual-recycled Michelson interferometer in Advanced LIGO” in December 2014 at Louisiana State University. She has since accepted a postdoc at LIGO Livingston Observatory.

Ashikuzzaman Idrisy successfully defended his PhD thesis, “Searching for gravitational waves from neutron stars,” at Penn State last Fall. He has taken up a position with Thompson-Reuters, the company that runs the Science Citation Index.

David Keitel successfully defended his PhD thesis in November 2014 entitled “Improving robustness of continuous-gravitational-wave searches against signal-like instrumental artefacts, and a concept for an octahedral gravitational-wave detector in

space”. He will continue to work at the AEI-Hannover as a postdoc.

Nutsinee Kijbunchoo, previously an undergraduate at Louisiana State University working with Gaby Gonzalez, started as an operator at LIGO Hanford Observatory in January 2015.

Prayush Kumar successfully defended his PhD thesis entitled “Compact Binaries in Gravitational Wave Astrophysics” at Syracuse University in August 2014. He moved to CITA last Fall to work as a postdoctoral fellow.

Josh Logue successfully defended his thesis entitled “Bayesian Model Selection with Gravitational Waves from Supernovae” at the University of Glasgow in December 2014. He is now working at British Telecom.

Jim Lough successfully defended his thesis entitled “Optical Spring Stabilization” last Fall. He is now a postdoc at the AEI-Hannover.

John Macarthur successfully defended his thesis entitled “Towards Surpassing the Standard Quantum Limit Using Optical Springs” in November 2014 at the University of Glasgow. He is now working at Fraunhofer Institute for Photonics in Glasgow.

Grant Meadors successfully defended his thesis entitled “Directed searches for continuous gravitational waves from spinning neutron stars in binary systems” in October 2014 at the University of Michigan. He started a postdoc position at AEI-Hannover in January 2015.

Ignacio Prieto successfully defended his thesis entitled “Transient Gravitational Waves at r-mode Frequencies from Neutron Stars” at the University of Glasgow in August 2014. He is now working at the Universidad Iberoamericana, Mexico.

Leo Singer successfully defended his thesis entitled “The needle in the hundred square degree haystack / The hunt for binary neutron star mergers with LIGO and Palomar Transient Factory” in November 2014. He moved to Goddard Space Flight Center in January 2015 as a NASA Postdoctoral Program Fellow.

Career Updates

Laura Cadonati, previously an associate professor at the University of Massachusetts Amherst, moved to Georgia Institute of Technology in January 2015.

James Clark, previously a postdoc at the University of Massachusetts, moved to Georgia Institute of Technology in October 2014 to take up a postdoc position in Professor Deirdre Shoemaker’s group in the Center for Relativistic Astrophysics

David Feldbaum, previously a scientist at LIGO Livingston Observatory, has joined the faculty at Southeastern Louisiana University.

Alexander Khalaidovski, previously at the AEI-Hannover, left LIGO after 8 years to head in to the world of industry.

Keiko Kokeyama, previously a postdoc at Louisiana State University, moved to the University of Tokyo as a Project Assistant Professor, working on KAGRA.

Conor Mow-Lowry, previously a postdoc in the 10m Prototype group at the AEI-Hannover, will begin a faculty position at the University of Birmingham in the UK.

Jamie Rollins has accepted a staff scientist position at LIGO Caltech, where he was

previously a postdoc, followed by a one-year tenure as Interferometer Automation Scientist. Among other things, he will continue working on making the interferometers self-sufficient.

Alberto Stochino, previously a postdoc at Stanford University, is now a Senior Technologies Development Engineer at Apple.

Eric Thrane, previously a Senior Postdoctoral Scholar at Caltech, is now a Lecturer at Monash University in Melbourne, Australia.

Awards

Duncan Brown, Syracuse University, was elected a fellow of the APS “for leadership in all aspects of the search for gravitational wave signals from compact binary coalescences, including algorithms, waveform templates, pipelines, statistical interpretation, and connection with general relativity and astrophysics.”

Juan Calderon Bustillo and **Francisco Jimenez-Forteza**, both of UIB, were awarded the Max Planck Prince of Asturias Mobility Award, from the Max Planck Society in October 2014.

Lynn Cominsky, Sonoma St. University, received the 2014 Aerospace Awareness Award for her excellent leadership and sustained dedication to aerospace education and for her tenacious advocacy for girls and young women in aerospace.

Evan Hall, Caltech, and **Sudarshan Karki**, University of Oregon, received the 2014-2015 LIGO Student Fellowships. Evan will focus his attention on automating the alignment of the Advanced LIGO optics, whilst Sudarshan will work on commissioning and calibrating the various environmental monitoring sensors, measure environmental couplings, and possibly also on the photon calibrator system.

Martin Hendry, University of Glasgow, was made a “Member of the Order of the British Empire” (MBE) for services to public engagement in science in the Queen’s New Years Honours List.

Bala Iyer, Raman Research Institute, was awarded the Beller Lectureship from the APS. He has also been selected for the Vaidya-Raychaudhuri Endowment Award for the 28th meeting of the Indian Association for General Relativity and Gravitation at RRI, in March 2015

Stephen McGuire, Southern University, has received the honor of having his oral history interview made a permanent part of the inaugural History Makers Collection within the United States Library of Congress.

Richard Middlemiss, a postgraduate at University of Glasgow, was the winner of the UK-wide “3 Minute Thesis” public engagement competition. His £3k prize money will be used to film a documentary in the Faroe Islands on experimental verification of general relativity during the solar eclipse on 20th March 2015.

Guido Mueller, University of Florida, was elected a fellow of the APS “for innovative and inventive research in instrument science and experimental methods for terrestrial and space-based gravitational-wave detection.”

M. Alessandra Papa, Max Planck Institute, was elected a fellow of the APS “for numerous key contributions to gravitational-wave astronomy, including devising new data analysis methods for gravitational waves from pulsars and coordinating the worldwide exchange and analysis of data.”

Dave Reitze, Caltech, was named a Fellow of the Optical Society of America.

Sheila Rowan, Director of the IGR at the University of Glasgow, was selected as the

2014 “Women in Physics” prize lecturer by the Australian Institute of Physics (AIP) and gave a multi-state lecture tour around Australia in November/December 2014.

Robert Schofield, University of Oregon, was elected a fellow of the APS “for leadership in identifying and mitigating environmental factors which impact on the sensitivity of terrestrial gravitational wave detectors and elimination of spurious noise sources in LIGO.”

LSC Elections

Warren Anderson was elected as the LAAC senior member in December 2014.

Stefan Ballmer was elected to serve as the Technical Adviser to the LIGO Oversight Committee in January 2015.

Laura Nuttall was elected as the LAAC postdoc representative in December 2014.

Amber Stuver was elected as co-chair for the LAAC in December 2014.

John Veitch was elected co-chair of the CBC group in January 2015.

Marissa Walker was elected as LAAC student representative in December 2014.

General

Membership in the Topical Group in Gravitation of the American Physical Society reached 3% of total APS membership in January 2014. The Gravitation Group can petition to become an APS Division after January 2015 if membership remains above the 3% threshold.

The new LIGO film documentary “LIGO:Generations” was released on Space.com in January 2015.

Recent LIGO Papers

LIGO/Virgo Publications

As in every edition of the LIGO magazine we like to spend some time to discuss recent LIGO and Virgo publications to give our readers a sense of the scientific output of our collaborations. In the last 6 months, 9 papers from the LIGO and Virgo collaborations have been posted to the free-to-view ArXiv preprint server and submitted to peer-review journals. Please remember that you can view brief science summaries of all the publications we discuss in these articles at <http://www.ligo.org/science/outreach.php>.

Two of the papers that appeared in the last 6 months, <http://arxiv.org/abs/1406.4556> and <http://arxiv.org/abs/1410.6211> focus on searches for stochastic gravitational-wave background signals. Our science summaries describe this background as being similar to being in a crowded room. You can hear clearly the words of the loudest people and of those closest to you, but the other conversations just blend together. There are murmurs of other conversations, but you cannot tell them apart. Gravitational-wave backgrounds are produced by large numbers of astrophysical or cosmological sources, that individually would not be observable above the instrumental and environmental noise sources, but collectively might produce a noticeable noise source. There are a few ways a gravitational-wave background might be produced, for example by large numbers of distant mergers of compact objects (black holes or neutron stars). A gravitational-wave background might also have been made in the inflationary era of the early Universe. Either way, observing a gravitational-wave background will allow us to better understand

whatever contributes to it, be it from the first moments of our Universe's formation, or much later on. The first of the two papers searched for a background in data from LIGO's sixth science run and Virgo's second and third science runs. The second searched in data from the two Hanford detectors in LIGO's fifth science run, using the co-location of these detectors to search for a correlated background signal. Neither of these analyses detected any evidence of a gravitational-wave background; measurements were consistent with environmental and instrumental noise in the observatories. This was not an unexpected result, however it did enable LIGO and Virgo scientists to place upper limits on the gravitational-wave background in the frequency band of 40-1700 Hz. It will be exciting to see how well such searches perform in the significantly more sensitive data expected from Advanced LIGO and Advanced Virgo.

In this article we often talk about the sensitivity of searches. This sensitivity depends on the noise level in the LIGO instruments. Lower noise levels means higher sensitivity to gravitational-wave signals. An important effort while operating the LIGO instruments is to characterise noise sources in the instruments, both transient and long-lived. If unexpected sources of noise can be understand, commissioners on site are often able to fix potential problems within the instrument. These "detector characterization" efforts are extremely important for achieving optimal sensitivity for astrophysical sources and this effort during LIGO's sixth science run is documented in the paper which can be read here <http://arxiv.org/abs/1410.7764>. Of course, before a LIGO instrument can be characterized, it must first be built and commissioned. The paper that can be found here <http://arxiv.org/abs/1411.4547> de-

scribes the design and optical layout of the Advanced LIGO detectors that will start taking data later this year.

One of the main targets for LIGO and Virgo is the search for continuous gravitational-wave emission from rapidly-rotating, asymmetric neutron stars. In the last 6 months LIGO and Virgo scientists have published 4 papers looking for gravitational-wave emission from such sources in data from the initial LIGO instruments. None of these works were able to find any gravitational-wave signatures, but we are still able to make some astrophysically interesting inferences from the lack of observations. The first of these papers, <http://arxiv.org/abs/1405.7904>, describes a search for gravitational wave emission from asymmetric neutron stars in orbit around a companion star, as well as a directed search for the known neutron star in the Scorpius-X1 X-ray binary. This work used data from LIGO's sixth science run and Virgo's second and third science runs and was able to place limits on gravitational-wave emission from unknown galactic neutron stars in binary systems as well as limits on emission from Scorpius-X1. The second paper, <http://arxiv.org/abs/1410.8310> covers a search for gravitational-wave emission from the Crab and Vela pulsars using data from Virgo's fourth science run. This work was able to constrain, for both pulsars, the fraction of the pulsar's rotational energy loss that is due to emission of gravitational waves. The third paper, <http://arxiv.org/abs/1412.0605> describes the results of a new search technique applied to 10 days of data from initial LIGO for gravitational-wave emission from Scorpius-X1. It will be interesting to see how this method performs on longer stretches of Advanced LIGO data. The final paper, <http://arxiv.org/abs/1412.5942>, focused on observing

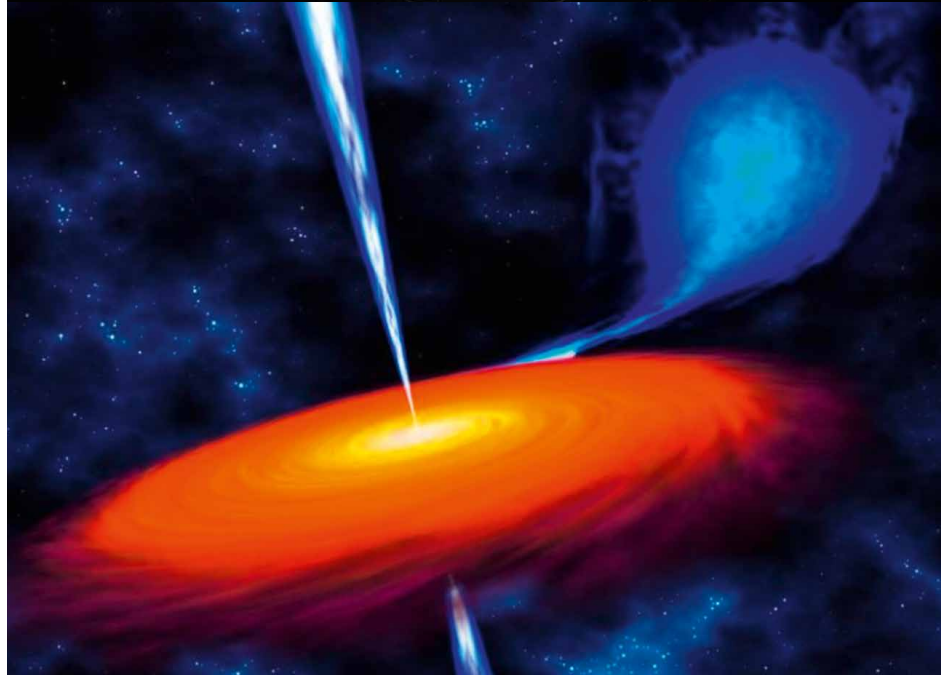
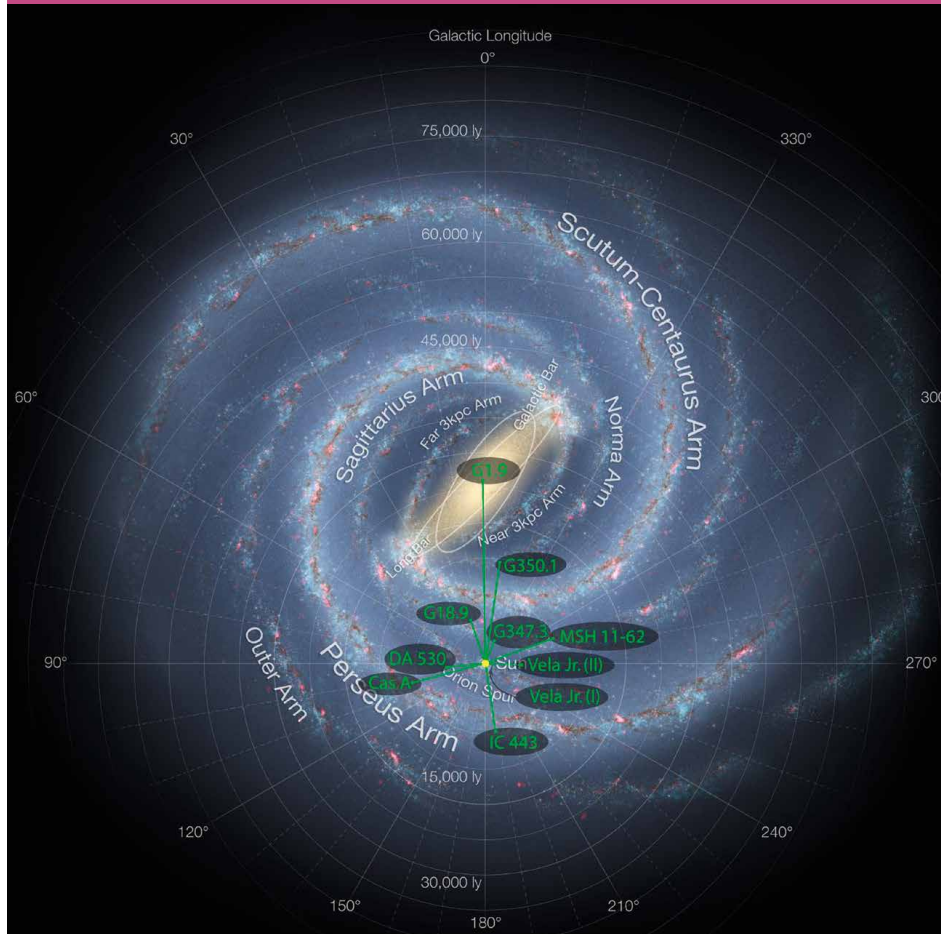
gravitational-wave emission from 9 young, nearby neutron stars in our galaxy. These neutron stars have known sky locations but have not been observed as pulsars, so the rotation frequencies are not known. Again, the lack of detection enabled LIGO and Virgo researchers to place upper limits on the gravitational-wave emission from these 9 sources.

Finally, the last of our papers describes the results of a coincident search for gravitational-waves and neutrinos. It is believed that cosmic explosions, such as gamma-ray bursts, can emit both gravitational-waves and neutrinos, which might be observed by existing gravitational-wave and neutrino observatories. The paper, which can be found here, <http://arxiv.org/abs/1407.1042>, describes a search for gravitational-wave signatures in initial LIGO data in coincidence with 20,000 separate neutrinos observed by the IceCube neutrino observatory in this time frame. Unfortunately no gravitational-wave signatures were observed in the data, but the paper is able to place upper limits on the event rate of joint emission of gravitational-waves and high-energy neutrinos.

As always, congratulations to everyone who worked on these papers. We can't wait to see how the variety of searches described above will do with Advanced LIGO data!

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Galactic positions of the 9 supernova remnants, believed to contain young neutron stars, that were searched for in <http://arxiv.org/abs/1412.5942>. All of these supernova remnants are very close to the galactic plane. The yellow dot represents the Solar System. Two possible locations for Vela Jr. were used. (Image modified with permission from NASA/JPL-Caltech/ESO/R. Hurt.)



An artist's impression of the Scorpius X-1 LMXB system, courtesy of Ralf Schoofs www.ralf-schoofs.de

When We're Not Doing Science

... We're Hiking!

LIGO Hanford Observatory (LHO) offers a number of comfortable conference rooms of various sizes for meetings and telecons. From time to time, however, we prefer to meet in spaces a little more wild.

One summer afternoon in 2014, for instance, various personnel from the Advanced LIGO suspensions (SUS), pre-stabilized laser (PSL), auxiliary optics (AOS) and interferometer sensing and control (ISC) groups met on a nice little fly fishing-only lake in the Blue Mountains. LHO operators have conducted meetings at an elevation of 12,280 feet, on a volcano and on hiking trails along beautiful Lake Chelan. Commissioners and operators have been known to hold face-to-face meetings atop the daunting Aasgard Pass (7,800 feet) in the stunning Alpine Lakes Wilderness as well!

The Pacific Northwest is home to beautiful backcountry destinations, many of which lie near the Cascade Mountains. This north-south range offers dormant volcanoes, a portion of the 2700-mile Pacific Crest Trail, and several national parks. Luckily LHO sits only a short drive away from the Cascades. If you're looking to explore rain forests, subalpine zones, snowy slopes or deserts, you'll find them all nearby.



LHO's Daniel Sigg shares a rock with mountain goat against a backdrop of snow. A day in the Cascades often provides views of wildlife of various sizes. While deer and elk appear frequently near sea level in the Northwest, a person must climb to view the white shaggy pictured here.

Backpackers from around the globe come to the Enchantments in the Alpine Lakes Wilderness. Camping permits for this area are distributed via an annual lottery because this area is so popular and access is limited for preservation. I've applied for three years and have yet to win a permit. LHO staff scientist Daniel Sigg scored a permit during the summer of 2012 and I was lucky enough to tag along with him for my first experience in this area. Amazing sunrises and sunsets, frolicking mountain goats, crystal clear waters and stunning mountainscapes will call you to take photos, but make sure to carry extra batteries and memory cards!

Will your science or engineering duties bring you to LHO? Be sure to check with us about our "expanded list" of meeting locations. And consider inviting me to your meeting!

Corey Gray

has worked at LIGO Hanford Observatory (LHO) since the late 1990s and now serves as a wily old Senior Operations Specialist. Outside of LHO you might find him kicking dust on a mountain trail, salsa dancing in the "509", or traveling elsewhere around the globe.



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The LIGO Magazine

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How does it Work? Signal Liberation

Gravitational wave interferometers are incredibly complicated machines with multitudes of possible configurations. The sheer number of parameters necessary to describe a particular configuration is daunting. Despite the high dimensionality of the configuration space, the peak strain sensitivity of the interferometer related to the optical system depends on just three parameters: the laser wavelength, the detection bandwidth of the interferometer, and the total light energy stored in the system. Collectively known as the Mizuno limit, these factors motivate our choice of optical parameters in order to optimize the interferometer's sensitivity to gravitational waves.

The Fabry-Perot arms of LIGO's interferometers consist of a partially transmissive input test mass (ITM) and a highly reflective end test mass. The arms enhance the gravitational wave signal by forcing the light to circulate many times before detection (see How does it work? An optical cavity, LIGO Magazine Issue 1). From the point of view of the Mizuno limit, a change in ITM reflectivity modifies both the amount of stored light energy and the detection bandwidth. However with the use of additional partially transmissive optics at the input and output ports of the interferometer, it is possible to adjust the stored energy and detection bandwidth independently. A power recycling mirror located between the beam splitter and the laser can increase the stored energy by recycling light that would normally be reflected by the interferom-

eter and lost. A mirror located between the beam splitter and the output port will either decrease or increase the detection bandwidth, depending on the reflectivity and microscopic position of the mirror. Signal recycling refers to a decrease in detection bandwidth and an increase in peak sensitivity. Resonant sideband extraction (RSE), on the other hand, makes the detector more broadband at the expense of peak sensitivity.

Resonant sideband extraction facilitates high stored arm power with only minimal power recycling. This reduces power absorption of the beam splitter and input test masses. The narrow-band arm cavities then accomplish most of the power recycling, and RSE allows the detection bandwidth to remain broad.

In a 1993 publication, Mizuno and coauthors warn the reader against confusion of RSE with signal recycling. This warning was not heeded when the Advanced LIGO subsystems were being named! It may come as a surprise to some members of the collaboration to learn that the technique used in Advanced LIGO is RSE, not signal recycling. In combination with each other, recycling and extraction techniques provide designers of gravitational wave interferometers with several independent knobs to tune the interferometer's optical sensitivity.

Nicolas Smith

