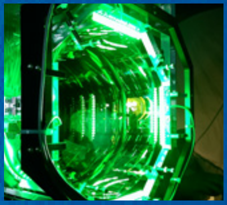
LSC LIGO Scientific Collaboration

LIGO MAGAZINE

issue 5 8/2014

Major milestone: First full lock achieved!

Life at the Louisiana site – LIGO Livingston:
A postdoc's experience p. 10



The Transmission Monitor Suspension Telescope
Auxiliary optics p. 20

... and a look at Life after LIGO!

Title image

The beam at the dark port of the Livingston interferometer as seen during the locking sequence. At this stage the interferometer is locked on radio-frequency signals; the transition to DC homodyne readout has yet to occur. At the time of writing the Livingston interferometer has achieved stable locks in excess of two hours with a sensitivity in excess of 15 Mpc. This milestone occurred after less than three months of commissioning activity after completion of the installation.
Credit: Joe Betzwieser

Image credits

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p. 3 Comic strip by Nutsinee Kijbunchoo
p. 5 Photo by Andreas Freise
p. 10 Photo by Alexander Montuschi
p. 13 Photos courtesy of Tobin Fricke
p. 15 Image credit: ePetri Inc
pp. 16-17 Photos by Andreas Freise
p. 18 Diagram from Patel et al. PLoS Comput Biol 9(7): e1003108
p. 23 Image courtesy of Benno Willke
p. 25 Stills from the film 'LIGO, A Passion for Understanding' by Kai Staats
p. 30 Images courtesy of Stefan Ballmer
p. 32 Illustration by Nutsinee Kijbunchoo

Upcoming Events (compiled by the editors)

DPG Physics School on General Relativity @ 99
14 – 19 September 2014,
Physikzentrum Bad Honnef, Germany
http://www.dpg-physik.de/dpg/pbh/aktuelles/S214.html

Recent Developments In Gravity (NEB 16)
17 – 20 September 2014, Mykonos, Greece
http://neb.hsrgc.gr/16/

Frontiers in Optics: The 98th OSA Annual Meeting and Exhibit/Laser Science XXX
19 – 23 October 2014, Tucson, Arizona
http://frontiersinoptics.org/

Workshop on Gravitational Wave Astronomy
1 – 5 December 2014, Jena, Germany
http://wwwsfb.tpi.uni-jena.de/Events/GWA2014/

225th Meeting of American Astronomical Society
4 – 8 January 2015, Seattle, Washington
https://aas.org/meetings/aas225

Eleventh Edoardo Amaldi Conference on Gravitational Waves
21 – 26 June 2015, Gwangju, Korea

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 available on ligo.org:
https://wiki.ligo.org/LSC/UpcomingConferencesAndMeetings

Contents

Antimatter

Nutsinee Kijbunchoo

Antimatter is a web-based comic strip by Nutsinee Kijbunchoo. Nutsinee is an undergraduate student at Louisiana State University and she recently joined the LSC in January, 2014 working under the supervision of Gabriela Gonzalez. School and research aside, Nutsinee spends half of her free time drawing and the other half on photography. She is also a part time gamer, and a forever cat lover. Look out for more comics by Nutsinee in future issues.

Welcome to the fifth issue of the LIGO Magazine!

Advanced LIGO is progressing with amazing speed. While in the previous issue we reported on the installation of the detectors, we can now already talk about sensitivity curves and detector ranges: The Advanced LIGO detector at LIGO Livingston was fully locked for the first time in May 2014 and much of this issue is dedicated to documenting the work and life at the detector in Louisiana. In `Major milestone: First full lock achieved!' we provide technical insights into the art of locking LIGO, while `Life at the Louisiana Site' offers a glimpse into the life of a commissioner in Livingston. More visual impressions of LIGO are available in the new documentary `LIGO, A Passion for Understanding' by Kai Staats, who talks about his experiences of making this movie in an interview with Marco Cavaglià. We also collect and share the experience of colleagues who have moved on to other activities in `Life after LIGO'. We would like to focus on the activities at the Hanford LIGO site in the next issue and are looking for your contributions. Please send your comments and suggestions to magazine@ligo.org.

Andreas Freise
for the Editors

LIGO Scientific Collaboration News

Gaby (Gabriela) González
LSC spokesperson

With the heat of the summer winding down (at least in the northern hemisphere!), it's time for yet another great issue of the LIGO Magazine. I hope you will enjoy, as we did, reading about life at the sites, the making of the new Advanced LIGO film documentaries, and many other nice stories. And this time we even welcome a comic strip!

Since the last LSC-Virgo meeting in Nice, we are much closer to the first Advanced LIGO observing run in 2015, "O1," thanks to the hard work of our colleagues in Livingston and Hanford. A milestone one-hour lock of the full interferometer in Livingston was achieved on May 27, with a DC readout lock a couple of days later. As we write, LLO is achieving stable locks with an estimated inspiral range of more than 10 Mpc! The installation of the Hanford interferometer is also nearing completion and commissioning with a full interferometer will begin soon.

Last year the LSC began a formal planning of our searches in the next observing runs, to ensure we have all the resources we need for their timely completion. This became even more important when funding agencies in the U.S. asked us to justify requested computing resources. We are now embarked on defining what our searches will need, and also in prioritizing those searches in a time of limited financial resources (computing and human). Please make sure you read and comment on any related communication: this is how we plan to detect gravitational waves!

Several LSC committees are busy with a range of science and service issues: blind injections in the Advanced LIGO era, the new Scientific Monitoring system, remote participation, ways of giving proper academic credit to collaboration members, and many others.

Beverly Berger (Caltech) has been appointed chair of the LIGO Open Science Center review committee. Eric Thrane (Caltech) and Adam Mullavey (LIGO Livingston) were appointed co-chairs of the LSC Hardware Injections Group, a sub-group of the Detector Characterization group. Brian Lantz (Stanford) was re-elected chair of the Suspension and Isolations Working Group. Eric Gustafson (Caltech) is taking over the co-chairmanship of the LVC Meetings Committee, with Erik Katsavounidis stepping down after several years of great service that brought better organized, more friendly and more collaborative meetings (thanks for the long breaks, Erik!), Laura Nuttall (UWM) took over the direction of the LSC Beginner's Guide project from Erin Macdonald (Cardiff) who left the LSC to pursue new career opportunities. Our deep gratitude goes to Erin for all her work on the first edition of the LSC Beginner's Guide, which is now widely used by many new (and old) LSC members.

The LSC is playing an ever more important role in physics organizations. Several LSC members are officers of the International Society of Relativity and Gravitation (with Beverly Berger as the Secretary and Treasurer, David McClelland representative to IUPAP, and several others being elected members). Also, several LSC members were elected this year to the GGR Executive Committee: Laura Cadonati (new Vice-Chair), Tiffany Summerscales (new member at large) and Sarah Gossan (new student member at large). Congratulations to all, as well as many thanks to Mike Landry and Ben Farr, who are retiring as Members at Large, and Beverly Berger, who this year assumes the GGR Chairpersonship. If you aren't yet, please consider becoming a member of these societies: GGR is very close to reaching division status in APS, your membership matters!

Thanks to the efforts of many of you, the LSC continued its strong tradition in public outreach. Our collaboration participated (again!) in the World Science Festival's Street Fest in New York, the U.S. Science and Engineering Expo in Washington D.C., and hosted a booth at the June AAS meeting in Boston with a press tour of the LIGO Lab at MIT. The thousand-square foot LIGO traveling exhibit "Astronomy's New Messengers", which first premiered at the 2010 World Science Festival in NYC is now on display at the Science Education Center in Livingston. A small, portable version of the exhibit continues to tour the U.S.. If you travel to Stanford for the August LSC-Virgo meeting, you can see it there. And remember that you can have it displayed at your institution. Ask us how!

The new film documentary "LIGO: A passion for understanding" was released to the public in April with a companion article and extensive coverage on space.com. Filming of the second film documentary, "LIGO: Generations," was completed by director Kai Staats at MIT and Livingston in June. You may read more about these films in Kai's feature interview in this issue.

As U.S. Presidents are wont to say, the "state of the [Collaboration] is strong." We welcomed two new groups in the LSC, West Virginia University and Whitman College, and we're ready to welcome a few more --all together, working in a collaborative spirit towards the upcoming detections of gravitational waves. Let's keep up the good work!

Gaby and Marco.

Victory! The winning team jump for joy at completing the LVC-trivia game at the recent collaboration meeting in Nice.

Major milestone: First full lock achieved!

After many years of planning, design, assembly and installation, Advanced LIGO is finally entering integrated testing, where all the subsystems have to be made to work together. This process can be separated into two phases: First, the systems that automatically bring the detector to its operating point and keep it there must be made to work – this is called "locking." Secondly, we must achieve low noise readout of the differential arm strain, to allow "science mode" data collection.

At the Livingston observatory we have progressed rapidly to the final stage of the first phase: full lock has been achieved! The final chamber install finished on April 1st with the closing of the Y-end station. As with previous Advanced LIGO commissioning efforts success came quickly; the Y-arm was locked by mid-April and the interferometer was

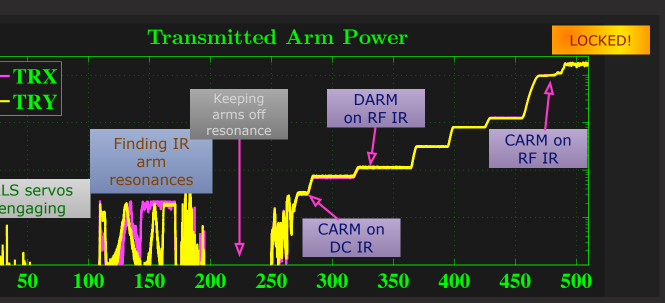
Ryan DeRosa

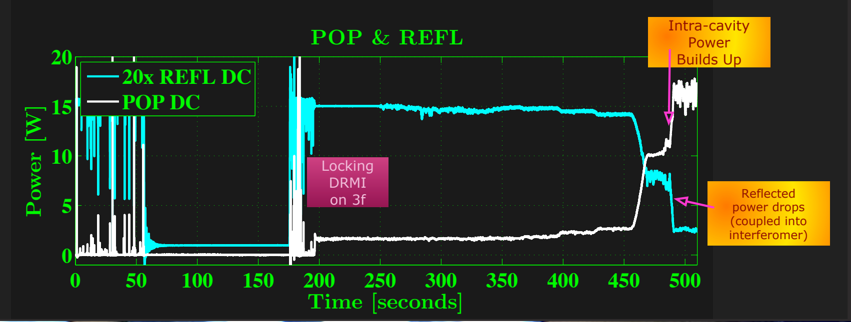
Ryan is an LSU grad student who has worked at the LIGO Livingston Observatory since 2009. He has dutifully served as chairman of the LLO nicknaming committee since 2012.

fully locked by the end of May. In Advanced LIGO, the locking process is quite different from Initial LIGO.

In the Initial LIGO interferometers the suspended mirrors formed four length degrees of freedom (DOF) to be sensed interferometrically and controlled actively with feedback: (1) the short Michelson interferometer ("MICH"), which keeps the dark port "dark", (2) the power recycling cavity (PRC), which filters laser noise and increases the circulating power, (3) the common mode arm length (CARM), used as a frequency reference, and (4) the differential arm length (DARM), used to catch those gravitational waves.

Before being locked, the mirrors swing randomly through interferometer fringes, driven by the residual seismic motion. In Initial LIGO, the locking strategy was to wait for the mirrors to swing through resonance by random chance. When resonance was momentarily and randomly obtained, the real-time digital signal processing code on the "front-end" computers would then quickly trigger the length control, attempting to stop the mirrors in place and hold them "locked" in position. The success of this process relied on careful tuning of a set of parameters including things like trigger thresholds, activation delays, filter switching, etc. This is referred to as "catching the fringe."





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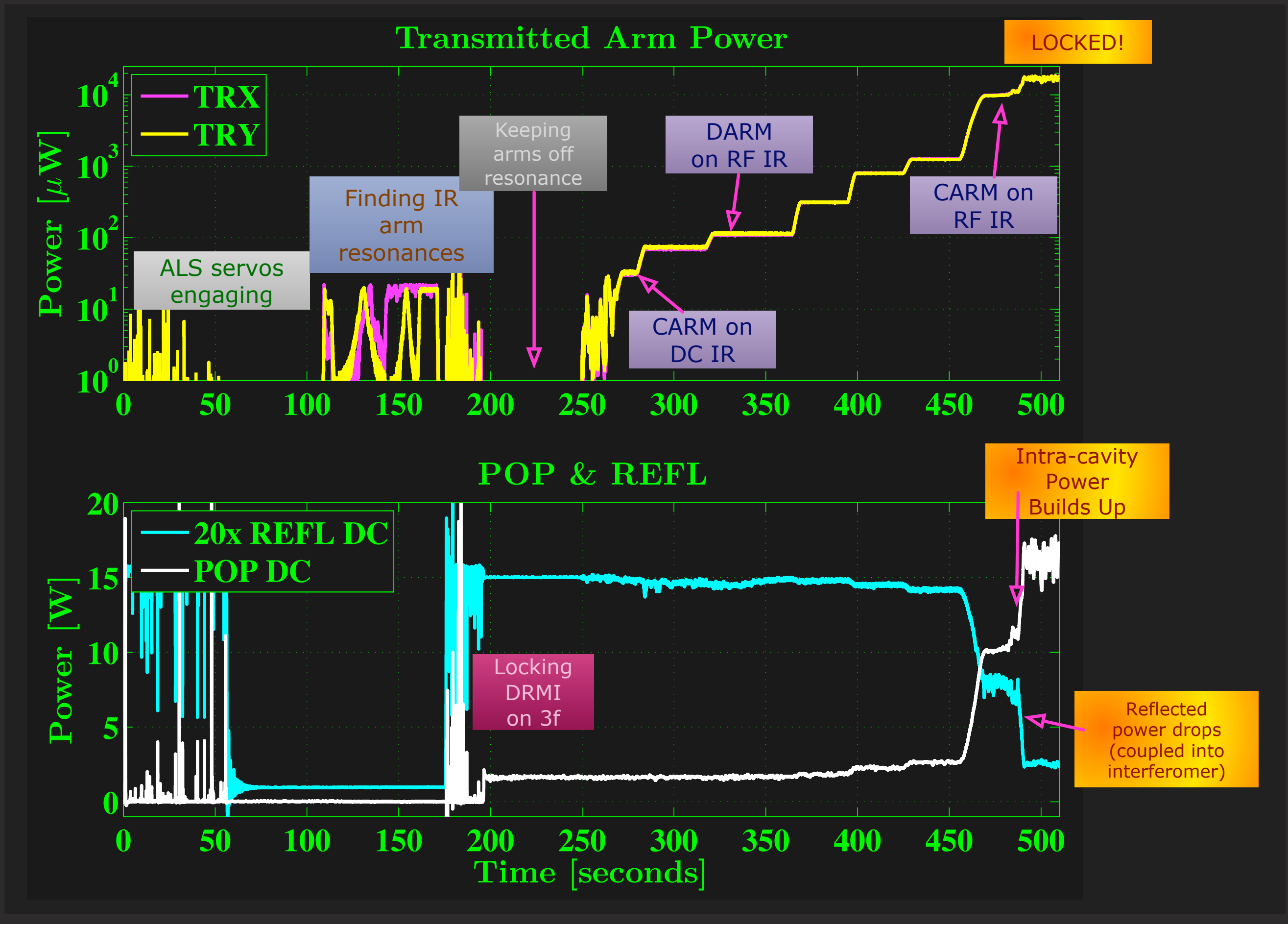
Commissioners at work in the LIGO Livingston Control Room. Large TV screens show the laser beam spots at many places in the interferometer, and the computer terminals are used to make measurements and tune interferometer parameters and control system settings.

In Advanced LIGO, the lock acquisition process is designed to a deterministic, step-by-step process, not relying so much on random motion. There are two main reasons for this: first, Advanced LIGO features another length degree of freedom created by the addition of a mirror between the dark port detection bench and the beamsplitter: this so-called signal recycling mirror forms the signal recycling cavity (SRC) used to manipulate the frequency response of the interferometer to differential strains (like gravitational waves). With five DOF needing to be simultaneously controlled, not only would the lock acquisition tuning be even more complicated than before, but the time in between coincident resonances in all cavities might be uncomfortably long.

The second reason for a new lock acquisition approach is the stringent noise performance goals. Initial LIGO was most sensitive between 100 and 300 Hz. At higher frequencies the sensitivity weakened with a slope proportional to frequency, due to the response of the interferometer. Below 100 Hz, the sensitivity degraded with a much more aggressive slope. This is commonly referred to as the “seismic wall” since the noise was due either to residual seismic motion or by noises associated with the controls (both length and angle) to overcome that seismic motion.

While Advanced LIGO is often marketed as being “ten times more sensitive than Initial LIGO”, this is the sensitivity at 100 Hz where the noise is lowest. Around 10 Hz the improvement factor is closer to seven orders of magnitude—that’s what all the new Advanced LIGO seismic isolation systems buy you! The actuator noise incurred by applying large control forces to the mirror (to catch the fringe during lock acquisition) could defeat the isolation chain. In Initial LIGO the peak force which could be applied to a 10 kg test mass was approximately 25 mN. In Advanced LIGO the peak force which we can apply to a 40 kg test mass is expected to be 150 μN. Stronger actuators exist at higher stages in the quadruple suspension chain, but the nature of the suspension limits those drives to actuation at low frequencies.

Not only is the DARM servo bandwidth now much smaller than before (20 Hz compared to 200 Hz), it should also be noted that the rms of the residual seismic motion has not



Time series of power monitors at different ports in the interferometer. The transmitted power of each end test mass shows the arm build-up as a function of CARM offset, achieving a maximum build-up of ~1000x more than the arm power when only one arm is locked at at time. In the corner, the intra-cavity power of the PRC increases and the power reflected by the interferometer decreases as more and more carrier is coupled into the detector.

been greatly reduced. This is because the ground motion is dominated by features below 0.5 Hz, the microseism and tilt, and the sensors we use now are the same type as those we had in the past (at least at Livingston, where an Advanced LIGO isolation system has been in use for 10 years). So, while at 1 Hz the suspension point motion has been decreased by more than two orders of magnitude from Initial LIGO to Advanced LIGO, at 10 or 100 mHz we are roughly in the same shape as we were then.

This is where the Arm Length Stabilization (ALS) system comes in, also known as "green locking." An auxiliary Nd:YAG[1] laser at each end station, frequency doubled to 532 nm, is locked to each freely swinging arm cavity independently. In the corner station, where the two arms come together, the green light transmitted by the X arm is interfered with a beam from the main laser, which is also frequency doubled to 532 nm. The green light from the Y arm is separately interfered with the green light from the X arm. Using these two green beat signals we lock the main laser to the X arm by tuning the laser frequency, and then control the differential arm lengths by moving the test masses. Once these two transitions have been made, the frequency tuning range of the "green interferometer" allows us to push the arm cavities onto the infrared resonance (or hold them away from the resonance, if we prefer). This is possible because the frequency noise of the green locking system is less than the linewidth of the arms, about 40 Hz. During all of these ALS activities the recycling cavities are not controlled, and maybe not even aligned.

A corner interferometer composed of the beam splitter, input test masses, Power Recycling and Signal Recycling mirrors is called the Dual-Recycled Michelson Interferometer (DRMI), and we have been working on it without the main interferometer arm cavities for approximately one year. While the frequency noise of the ALS system is low enough to allow control of the arms by themselves, when the power recycling cavity is also involved it forms a coupled cavity with the arms, which has a much narrower resonant range. This is good for noise filtering, but creates difficulties for the green locking system.

If the arms are moving around resonance the corner interferometer will not be controllable, since the radio-frequency (RF) sidebands used to sense MICH, PRC, and SRC are sensitive to the arms' motion as well,

[1]Nd:YAG (neodymium-doped yttrium aluminium garnet) is a crystal that is used as a lasing medium for solid-state lasers.

when they are close to the fringe. Therefore in order to lock the DRMI we use the green interferometer to hold the arm cavities away from their infrared resonances.

The figure on page 8 shows the locking sequence by tracking the transmitted power from each arm (TRX & TRY), the intra-cavity power circulating in the central interferometer (POP DC), and the amount of power at the reflection port (REFL DC). In the beginning of the plotted time series no cavities are under control, but the green lasers are locked to their arms individually.

The bottom traces during this stretch show that the corner mirrors are misaligned. Once the ALS servos are engaged we use them to find the infrared resonances in both arms. You can see that we have found them around three minutes into the process.

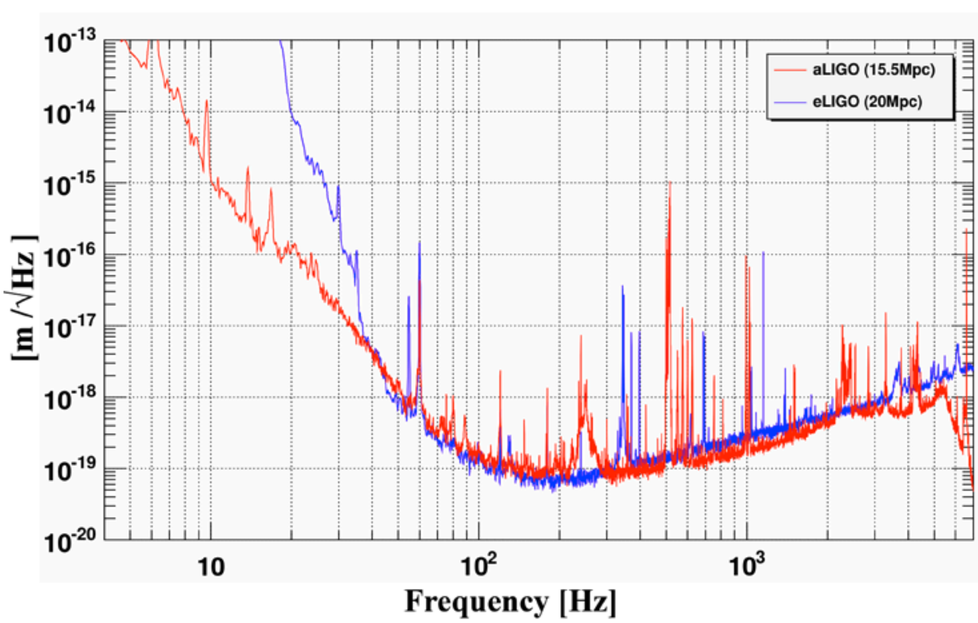
We then push the arm cavities off resonance (you can see TRX & TRY go to zero) and hold them there while the DRMI is locked by catching the fringe (in this case the mirrors we use for controls have strong actuators and we are only waiting for 3 DOFs to line up, instead of the full 5). There is some power in the central interferometer (POP DC) when the DRMI is locked, but most of the light is reflected in this configuration. The sensing of the corner lengths is then switched to a special set of sidebands which are insensitive to the conditions of the arms. This "3f locking" technique is based on the observation that third harmonics of the phase-modulated sidebands produce error signals which are to first order independent of the arm cavity resonance. With the DRMI locked on 3f signals, the arm cavities are ready to begin their march towards resonance ("CARM offset reduction"). You can see the arm transmitted power begin to rise around 4 minutes into the process.

Along the way, control of the arms is handed off from the now too-noisy ALS signals to infrared (IR) signals, these are the "CARM on DC IR" and "DARM on RF IR" steps around 4 or 5 minutes into the plot. As we push the arms further up the fringe the intra-cavity power begins to increase, and the reflected power begins to drop since it is being coupled into the interferometer now. Close to full lock we switch CARM from a DC to an RF IR signal, and take the last step to full build-up. Once at full build-up we get to measure the DARM spectrum, and start the next phase: noise hunting. A preliminary DARM graph from this July shows where we stand as of now. The commissioning process will lead to further improvements at high frequencies through increases in the laser light power, at low frequencies through tuning of control systems and electronics, and at all frequencies through hunting and eliminating coupling to environmental disturbances and scattered light.

LIGO 2014

Some references

- Initial LIGO locking: M. Evan's thesis (P020003) and the associated paper (P010015)
- 3f locking: K. Arai's thesis and associated paper (2002 Class. Quantum Grav. 19 (1843)
- DRMI and CARM offset reduction: R. Ward's thesis (P1000018)
- ALS: the design technical note (T0900144), and the paper Mullavey et. al, Optics Express, Vol. 20, Issue 1, pp 81-89 (2012)
- aLIGO lock acquisition write-ups/simulation studies: L. Barsotti & M. Evans (T1000294), also K. Izumi, S. Dwyer & L. Barsotti (T1400298), and a wiki page: https://awiki.ligo-wa.caltech.edu/aLIGO/LockAcquistionModeling



The L1 DARM displacement spectrum from July. For comparison, the DARM spectrum from Enhanced LIGO (eLIGO, S6) is also shown. The approximate distance to which one could see a 1.4-1.4 solar mass neutron-star inspiral event is 15.5 Mpc for the current aLIGO spectrum and 20 Mpc for eLIGO. The recent curve was taken with 2W of input power, while the S6 curve had 14W of input power. The sensitivity at high frequencies is similar despite this power difference, due to the change in detector frequency response between eLIGO and Advanced LIGO: the cavity pole has moved from 80 Hz up to 400 Hz. At 1 kHz and above the aLIGO curve shows some features of the digital down-sampling filter (the ripple and roll-off), and at all frequencies this calibration is preliminary.

Life at the Louisiana Site

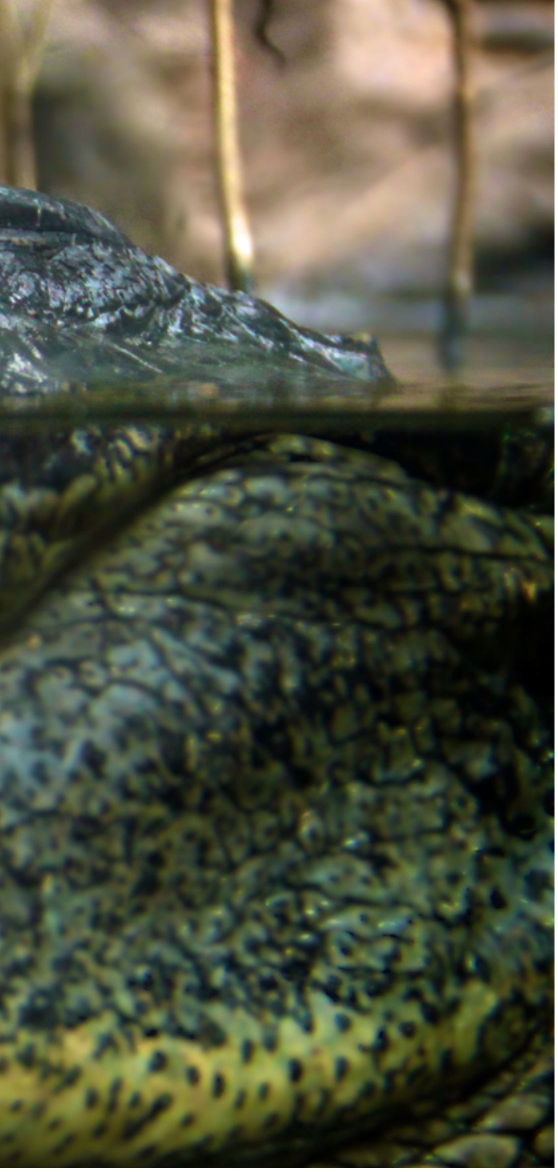
Keiko Kokeyama

Keiko Kokeyama is a postdoc in Louisiana State University working at LIGO Livingston. She has worked on both table top R&D as well as aLIGO commissioning. Outside the lab, she loves to visit art museums all over the world.

As a graduate student and at my first postdoc, I worked on table top research and development experiments for future generation detectors, and simulations for interferometer sensing and control. Crazy new ideas for the next generation were very fun to work on, but I also wanted to experience the real large-scale gravitational-wave detectors. The timing of the Advanced LIGO upgrade gave me the chance and the challenge to work on the detector in Livingston, Louisiand as a postdoc at LSU.

Before arriving, I had no idea what Louisiana would be like. I imagined Baton Rouge as just a typical American mid-size city, with a west-coast atmosphere, a stereotypical image of the US for Japanese. I was completely wrong. The first culture shock was Louisiana's car society. Being a city dweller for thirty years, I was really shocked by the fact that I could not walk anywhere, even to a supermarket or a coffee shop. After getting a driver's licence and a car, I started enjoying the life in Louisiana, especially the food and music! I was almost overwhelmed to discover the depth of Louisiana's uniqueness: swamps, spanish moss, gators, the Louisiana accent, and creole cuisines.

Louisiana has its own local and unique American cuisine, evolved from French and African American traditions from the colonial era. The typical ingredients are chicken broth, okra, catfish, corn, crawfish (crayfish!) and a lot of spices. Deep fried



Alligators are found in swamps all across south Louisiana, sometimes even including the ponds on the LIGO Livingston site! If you'd like to see one, the best way is to arrange a swamp tour… or order the fried alligator appetizer at a local restaurant - the dish is mostly popular with tourists. (This particular specimen was photographed by Alexander Montuschi at a zoo in the Canary Islands.)

chicken and seafood are very popular. Deep-fried foods piled onto a french roll make great "poboy" sandwich. Now I miss the flavor of Louisiana every time I travel to somewhere else!

At the lab, I am a member of the team of "commissioners," whose job it is to make the interferometer work. We work very hard to accomplish our goal: the full interferometer operation and achieving the design sensitivity. Although commissioners work on a bit of everything, our main responsibility and interest are in locking the interferometer. The lifestyle of commissioners is also a culture of its own.

The schedule of the day follows a certain pattern. In Livingston, we divide the day into time slots depending on work topics. From the early morning to lunch time, "noisy" work is done. Noisy work includes cabling, cleaning, transfer function measurements in which you have to excite the plants, hardware repairs, and everything for which you have to walk into the large vacuum equipment area (LVEA), where all the sensitive interferometer equipment is physically located. (Since the full interferometer was locked at the end of May, we changed the shift schedule: the noisy work is done between 6am to 10am, and the morning commissioning is from 10am to 6pm, then the night commissioning happens from 6pm to early morning.)

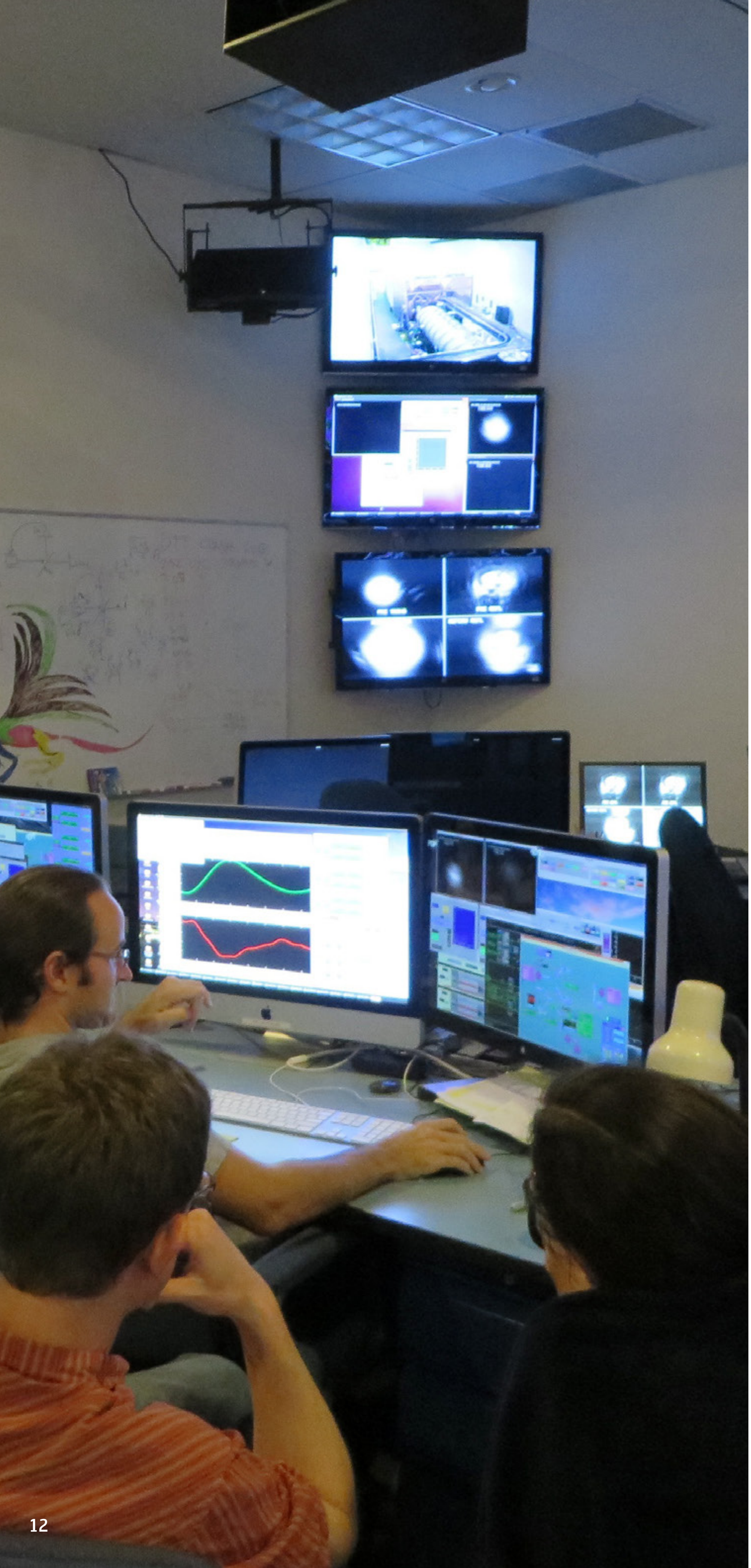
Commissioners come in to work after all the noisy work is done. We begin by discussing the goal of a day and making a strategy, and arrange "who does what." In the afternoon, the rough alignment work is conducted, including the related suspension, internal seismic isolation, and vacuum/air-conditioning system maintenance. If there are any issues on these (cables were found broken, for instance), we talk to the subsystem team so that they can take care of them in the next morning.

The middle of our workday is dinner time. Every Tuesday we get pizza, and on Thursdays we go to a Mexican restaurant. On pizza days, visiting scientists are honored to design their own pizza! I am thinking of proposing an evaluation system to score each custom pizza. Sometimes an earthquake hits the interferometer during pizza time. In such an evening, our efforts before dinner turn to be in vain. For a few hours, until the earthquake settles down, we have to wait. Most of the important measurements, such as arm length, contrast defect, sensing matrices, and so on, are done in the late night.

The commissioner's' job is to make the installed optics and subsystems work as an interferometer. It is a big team effort across the entire collaboration. Interferometers do not work as gravitational-wave detectors simply by just having optics and subsystems (such as the laser and suspensions) in place. To make the system work as an interferometer, all of its subsystems must be integrated. The other most important work in commissioning is modeling the noise coupling, compiling a noise budget, and hunting the noises toward the design sensitivity.

Throughout this commissioning effort, hundreds of colleagues help us both remotely and locally. Subsystem teams of ISC, PSL, SUS, ISI, HEPI, and all the other subsystems support us remotely or at the site. They offload the site tasks, help solving problems when we have any issues. Local engineers and operators help for various things, for instance cabling or circuit problems. When we need good vacuum environment, of when we want to open up an evacuated vacuum chamber, commissioners and vacuum specialists work together. Digital systems for interferometer controls and data acquisitions cannot work without the CDS specialists. A stable temperature control is also indispensable.

It is difficult for remote collaborators to follow the commissioning progress at the site. Because commissioning work is very specialized and intense, communication efforts, such as through the logbook and regular telecons, are very important for



us not to be isolated from the rest of the world. Lack of good communication might lead to issues at the site being partially misunderstood, which lead to lengthy delays or extra work. To prevent such an unfortunate situation, we often and closely speak with the entire collaboration.

After a long day (or night) of commissioning, it's time to go home. I live in a house in Denham Springs, which is between Livingston and Baton Rouge. I share a big house with two other commissioners, LIGO graduate students Anamaria Effler and Chris Mueller, and Anamaria's cat, Apple. We have a pool, wooden deck area, and a big back yard. Rabbits and squirrels live there, apparently. It is convenient to stop at our house if you live further towards Baton Rouge as many people do. We often hold pool parties to celebrate our commissioning progress after work. Sometimes a celebration starts at midnight, if we finish work "early." Apple does not appreciate the parties very much.

A Commissioning Story

The nature of commissioning work is perhaps best illustrated with an example. Here is one story of recent commissioning work.

Once we had the high power pre-stabilized laser, the optics on the suspensions, and the seismic isolation stages, each piece installed and commissioned by the subsystem team, we were ready to commission the "dual recycled Michelson interferometer," known in the control room as DRMI. The DRMI is the corner Michelson interferometer portion of the full interferometer, including the two input test masses (ITMs), power recycling mirror (PRMs) and signal-recycling mirrors (SRM), plus some other beam-directing optics. Establishing

A typical scene in the control room, where most commissioning activity takes place.

the DRMI operation was a significant milestone towards the full interferometer.

During the early phase of the DRMI commissioning, a number of unexpected things happened. We found that even a simple Michelson interferometer could not be locked without the optical lever damping in addition to the local damping loops of suspension actuators. This is because the second stage of beamsplitter suspension had too much force-to-angle coupling -- when you push on an optic, it also tilts, and this wasn't yet fully compensated. Also, at that time, we did not know that the ISI watchdog can be activated when the beamsplitter moves to try to control the Michelson degree of freedom. (The watchdog is a system that turns off the active control if the motion is too great, which prevents control systems from going out of control and causing damage.) Furthermore, with more than 3W of input laser power, the heat from the laser causes the interferometer alignment to drift away. The length of the suspension fibers seemed to change due to the heat, causing the mirrors to drift so that the interferometer could not be kept locked for a long time. At this time, the initial DRMI goal of 3f locking itself was accomplished, however, we realized that without stabilizing the alignment drift, the DRMI would not work stably for hours. To overcome the issue, we decided to install the alignment sensing and control system (ASC), which was not planned to be used in DRMI phase. These are the major unexpected things, and there are also tens of minor unexpected incidents every day. That is how it goes with commissioning.

LIGO 2014

Water and water related activities play an active part in Louisiana life - from a typical Louisiana swamp scene (top) to an unplanned boat trip in Old Mandeville during a storm surge from Hurricane Gustav (below). Sometimes the H_2O even freezes (middle, LIGO site, December 2008).

Life after LIGO

Lucía Santamaría

Lucía is a former gravitational-wave researcher turned data scientist, currently building recommender algorithms at outdoor planning start-up komoot. When she's not busy editing the LIGO magazine, she can be found on her bike or behind her laptop, but not yet both at the same time.

During the last decades, the LSC has seen many talented physicists start their careers, complete their PhDs, and go on to form research groups, all while contributing to the global quest for gravitational waves. Lifelong relationships ensue, the collaboration meetings being a great opportunity to catch up. Nonetheless, it is a fact that at the current PhD completion and tenure-track hiring rates, only a minority of all LIGO graduates and postdocs will remain in the academic pipeline and become university professors.

Fortunately, the opportunities to transition from GW research to other careers are plenty as well as truly fascinating. The unique set of skills that trained physicists, whether experimentalists or theorists, can offer to a variety of industries is in high demand. More often than not, however, LIGO members are only tangentially aware of the career paths of those with whom they once shared weekly teleconferences and face-to-face meetings.

In this issue of the LIGO Magazine, we showcase the experiences of former colleagues beyond their time spent researching in the LSC. Their success stories in many diverse fields, from medical physics to climate research to nanoelectronics, highlight not only their remarkable talents, but also the interdisciplinarity of the scientific method and the applicability of the skills acquired as a researcher. Through the following paragraphs Nick Fotopoulos, Phil Willems, Peter Kalmus, Pinkesh Patel, Lisa Goggin, and Diego Fazi share their experiences and thoughts about their Life After LIGO.

Nick Fotopoulos

For seven years, I searched for gravitational waves with you within the stochastic and CBC groups. I was particularly fortunate to have done a key part of the GRB 070201 analysis, and spent four months as an Astrowatcher. My life in academia was really sweet. But as I entered my postdoc years, I noticed the serious squeeze for faculty positions. Highly qualified, amazing colleagues were taking third postdocs and weren't happy about it.

After two years of postdoc at Caltech, I left for Synaptics where Antony Searle had blazed a trail. The company makes the chips in phones and laptops that drive touch screens, and has about as many employees as there are LVC members. My team defines the data analysis platform across many product lines. This involves understanding the customer requirements and physical and information theoretic constraints, then designing algorithms that will fit on a tiny microprocessor. Drew Keppel also followed from LIGO and now we are on the same team, making a difference that is felt across the company. It's thrilling to have our contributions in recent market hits like the Samsung Galaxy S5. And it's thrilling to have authored patents.

It might seem like gravitational-wave astrophysics has little in common with sensing fingers, but we are detecting signals amid diverse and horrible environmental and instrumental noise. We see glitches and broadband noise, we slowly drift into problematic configurations then drift out. With our proximity feature, we're trying our hardest to push out the detection horizon to 2 cm and beyond!

Physicists are particularly known for picking up whatever tool is necessary to answer a question. To search for CBC counterparts to GRBs, I needed math and computers, so I invested heavily in these areas. It turns out that to find fingers, you need math and computers too. But lots of bozos can code. What employers are actually looking for is someone who thinks and then can execute their concept from zero all the way to the end, either in analytical calculation, code, or hardware. They want someone who can understand, critique, and improve a whole system, and who works well with a team, whether leading or following. They want someone who has designed and commissioned a new system, either in hardware or software. LIGO produces many such rock stars and Silicon Valley wants them.

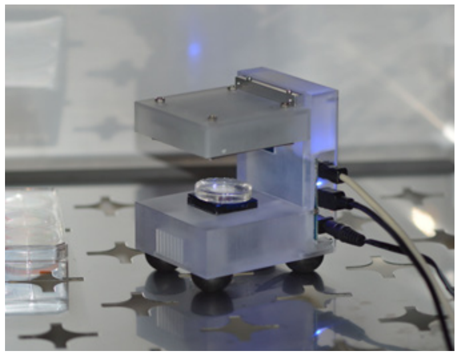
There is a great psychological barrier around leaving academia. Many PhDs have never contemplated a life outside and have made professorhood an integral part of their self-identity even before the degree is in hand. With this sort of conditioning it feels a lot like failure when you start taking the outside world seriously. Let me assure you that every element of academia can be found outside. There are interesting, challenging, and impactful problems, and opportunities to mentor colleagues and be mentored in turn. There are papers to write (though they might be secret) and conferences to attend. The step to a managerial role is optional, so you can continue spending most of your time on research. Finally, in Silicon Valley at least, the average starting compensation is over twice as high as the average starting professor positions. There is ample opportunity for a satisfying and rewarding career outside academia and your skills are in high demand. You just have to be brave enough to apply.

Nick Fotopoulos' work defines the core firmware data analysis platform across Synaptic's products, which translates into improved touch performance for your smartphone.

Phil Willems

I was part of LIGO from 1998 to 2011, always at Caltech except for 5 months at the University of Glasgow. I worked on a tabletop resonant sideband extraction experiment, tested Q factors of silica suspensions and mirror test materials, developed thermal noise models, demonstrated a mesa beam interferometer, and for the last years focused on thermal compensation.

After LIGO, I spent six months as a researcher at the Physical Optics Corporation before finding my new career commercializing new microscope technologies developed by Prof. Changhuei Yang's group in Caltech's Electrical Engineering department. I am now the CEO of ePetri Inc., a small start-up headquartered in Pasadena, currently working to commercialize Fourier Ptychographic Microscopy.



Willems's company commercializes ePetri microscopes such as the one in this image. Each device is its own lens-free microscope with 100x the field of view of conventional ones, allowing to image the entire cell culture at the same time. (Image Credit: ePetri Inc.)

The diversity of activities I pursued in LIGO is pretty typical of a GW researcher, and over the years I became something like a systems engineer, coordinating the efforts of a team of specialists in electronics, optics, mechanics, and software. This sort of background is valuable in a start-up environment—nearly everything technical that happens here I do myself, supervise directly, or personally outsource to consultants. Still, I jumped into this water without checking its depth first—it would have been useful to have some training in basic accounting and business management.

There is a lot about the LSC that I miss and would like to duplicate here at ePetri Inc. All the highly capable people, obviously. But also the culture of frequent seminars and documentation of results and code and design reviews. Yes, even the design reviews—they make us prove out our plans in an open forum. And I would love to get a central repository for documentation such as LIGO's DCC running here.

Following a decade-long career at LIGO, Phil Willems jumped into the start-up world and is now Chief Technology Officer at biological imaging company ePetri.

Peter Kalmus

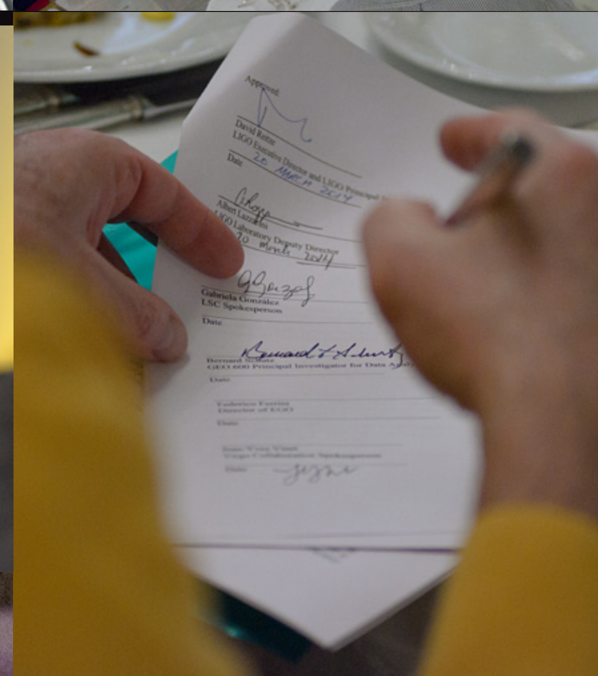
I worked in LIGO for about eight years, searching for externally-triggered signals from magnetars and supernovae. Since 2013 I'm a postdoc in the Climate Physics group at JPL, where I study low clouds and their interaction with the climate system, through both modeling and observation.

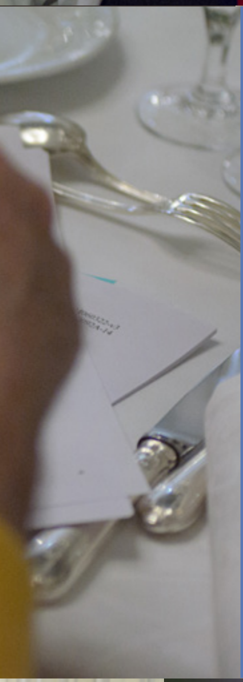
In LIGO, I learned how to eke every last bit of science out of a stream of data, and how to quantify the uncertainty in my results. Both of these skills have served me well. At some level data is data, and a good understanding of it is critical before any meaningful scientific statement can be made.

I gradually became passionately interested in the climate problem. It called to me, and as much as I loved doing astrophysics, I had to put it down and "take up the call." It came to the point where I couldn't justify spending my life thinking about gravitational waves any longer with global warming on the loose. I also felt that climate scientists were not doing the greatest job of communicating their findings to the public, and that eventually I might also be able to make a contribution there. Making the switch was a relief, because my life became more aligned with my deeper principles.

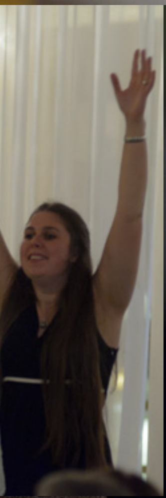
continued on page 18

LSC-VIRGO COLLABORATION MEETING March 2014, NICE





These images were taken at the latest LVC meeting in beautiful Nice. We had fun not only discussing science, but also renewing the LSC-Virgo agreement (see the spokesperson's appropriate headwear) and playing an LVC-trivia game that a young and enthusiastic team won (and not the team with the spokespersons and the directors...).



A switch from physics or astrophysics into climate science isn't unheard of, but it's unusual. The first few months were a little stressful. My colleagues had PhDs in atmospheric science, and there were a lot of new concepts, jargon and acronyms to learn. But slowly it began to coalesce, and now it's fine.

I don't miss the lack of signal in LIGO, but hopefully that will change for you soon. I found it tough doing science without a signal. The signal in climate science is only getting stronger with time. Also, searching for that mythical tenure-track job year after year as a LIGO postdoc was discouraging. It's a relief having a position in science in which, if I do good work, I can be confident of a good career.

A postdoc at JPL, Peter Kalmus studies low clouds and their interaction with climate. At LIGO he used to search for externally-triggered signals from magnetars and supernovae.

Pinkesh Patel

I did my PhD at Caltech from 2005 to 2010 with Alan Weinstein. I worked in the CW group on the implementation of barycentric resampling, operated the two-kilometer detector at Hanford as Astrowatcher and ran a search for GW from Calvera, a suspected neutron star. The hopes of publishing this result, however, were scuppered by the publication of pulsations from the object which would preclude emission of any detectable GWs.

After I left the LSC, I did a postdoc at Stanford working with Dr. Kerwyn Huang on mitochondria and aging research, wrote simulations of mitochondrial dynamics in cells and analyzed yeast mitochondrial genomic data. I really fell in love with the field, but then realized that I would be trapped in the same tenure process in biology. Since January of 2013, I work as Data Scientist at Facebook, helping decide what position the company is in, and how to get to where we want to be. I am mostly concerned about the user experience of Facebook.

I use a lot of skills I learned as a graduate student from coding to critical thinking. However the main skill required is the ability to ask the right questions. It is quite easy to sit and code, but to code what? To take a holistic approach to problems and to ask what you can infer from relevant data is a highly valued skill in my current job. I must say that whilst the LSC was helpful in this regard, I learned it above all else in my postdoc.

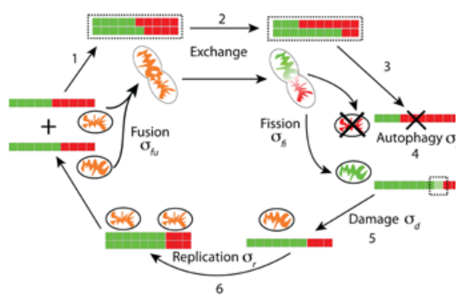


Figure from a publication from Patel et al. on mitochondrial dynamics. Each mitochondrion is represented as a set of discrete health units either in a healthy (green) or damaged (red) state. A cycle of fusion, fission, and autophagy contribute to quality control of mitochondrial health. Patel PK, Shirihai O, Huang KC (2013) Optimal Dynamics for Quality Control in Spatially Distributed Mitochondrial Networks. PLoS Comput Biol 9(7): e1003108. doi:10.1371/journal.pcbi.1003108

That being said, I miss the LSC for the enthusiastic people and the general sense of grandeur of the endeavor. We really did think that gravitational waves are the best thing since sliced bread. We need such dedication to keep going under such long odds and I appreciate all the people who continue to do so. However I left because I felt that science and overall human endeavors do not start and end at gravitational waves and I wanted to be a part of other things. I still love all of what I did and would gladly do it again, but new adventures are fun as well.

After Astrowatching during his PhD and doing research on mitochondria, Pinkesh Patel now works as Data Scientist at Facebook, helping shape the company's strategic position.

Lisa M. Goggin

I read about LIGO as an undergrad and was immediately enthralled by it. I got a spot in Caltech's SURF program and had a fantastic summer working for Alan Weinstein at the 40m lab. A year later I was back at Caltech as a graduate student, first at the 40 m lab and then in the CBC group. After graduation I took a postdoc at UWM.

Afterwards I transitioned to medical physics. I first completed a brief informal internship at a hospital then started a formal two-year residency program in medical physics at UCSF. This is a clinical program in therapeutic radiation therapy which trains the physicist in treating patients and managing treatment delivery machines. On completion of the program I was hired into the R&D group of Accuray, a medical device company. We design two radiation therapy machines, CyberKnife and Tomotherapy, which deliver targeted high energy photons to the patient to control or eradicate their disease.

My wish was to stay working in pure

physics but I wanted to use my skills in an area that directly impacted people's lives. Unfortunately cancer has touched most of us either directly or indirectly, and so I thought that given my skill set, radiation therapy was an area in which I could make the most impactful contribution. During my clinical training I had a direct influence on patients' treatment, which was very rewarding. In my current position I have the opportunity to influence the design and scope of the upcoming technology, and it is my hope that patients will benefit through improved treatments.

While at LIGO I developed many useful skills for my current job, such as the ability to approach a problem in a methodical way, plan and execute experiments, interpret data, and present the results and conclusions in a concise manner. Also, programming. From the LSC I miss interacting with such a diverse group of impressive and dedicated scientists.

As a R&D research physicist at a medical devices company, Lisa Goggin designs radiation therapy machines to help cure diseases with high-energy photons.

Diego Fazi

I worked in the LSC for seven years within the Spinning Binaries and Parameter Estimation subgroups. I was a visiting graduate student at Caltech from the University of Bologna, and later a postdoctoral fellow at Northwestern University. My research focused on new data analysis algorithms to search for GWs from spinning black-hole/neutron-star binaries and estimate their intrinsic and extrinsic parameters. I implemented a data-analysis strategy for detecting GWs from compact binaries with one significantly spinning component.

About two years ago I left the LSC to follow my passion for renewable energies and joined the Solar Conversion Group at Argonne National Laboratory. I study novel materials (catalysts) that use solar energy to convert water into hydrogen fuel; my research focuses on the characterization of their molecular structure to better understand their catalytic activity and improve their efficiency in producing hydrogen.

Even though my current research is very different from what I did at the LSC, there are conceptual and practical similarities to GW research. At a very basic level, the problem to solve is the same: there is a signal which needs to be extracted from noisy data and compared to theoretical models. The expertise developed at the LSC allowed me to bring a valuable contribution to my research team at Argonne, since I am the only group member who can integrate theoretical modeling with a rigorous and systematic data analysis. Of course there are many things I miss from the LSC, first and foremost the many great colleagues and friends I left behind; LSC meetings were a great occasion not only to strengthen collaborations and work synergies, but also to establish enriching relationships that still last, even after two years and many miles of distance.

Diego Fazi followed his passion for renewable energies and took a postdoctoral appointment at Argonne National Laboratory to conduct research on hydrogen-producing catalysts.

Contributions compiled by Lucía Santamaría

Virgo collaboration news

The Advanced Virgo input mode cleaner was locked for the first time on June 19th. Thus, the first top level project milestone has been met on schedule and the first complex integration effort has been completed successfully. Beside the main activity on the input optics preparation itself, work on many other subsystems was required for this achievement: the acoustically isolated clean room, the laser, the vacuum system, the superattenuator suspensions, the optics, the active isolation optical bench, the baffles, the electronics, and the data acquisition system. A suspended cavity is now available for detailed commissioning and student-training activities. This is important to build up a solid commissioning team and prepare the ground for a faster improvement of the sensitivity of the full detector.

Giovanni Losurdo for the Virgo Collaboration and EGO

The Transmission Monitor Suspension Telescope

Of all the fancy suspensions in LIGO, the Transmission Monitor Suspension, or TMS for short, is an odd ball. It is not nice and square looking, like the triple suspensions (used for the mode-cleaner mirrors, beam splitter and the recycling cavity mirrors). Nor is it as complicated and shiny as the quadruple suspensions (used for the large transparent test masses in the arm cavities). During assembly and installation the TMS looks hideous and over-complicated. But when installed in the vacuum and illuminated by the green laser, it looks rather snazzy and spectacular indeed.

So, where are these snazzy TMSs? There are two Transmission Monitor Suspensions per interferometer, furthest away from the beamsplitter, at the end of the 4 km long arm cavities. They are several centimeters behind each End Test Mass (ETM). The TMS is, as its name suggests, a suspended telescope, which captures the light transmitted through the end test mass, focused down and directed on various photodetectors. This light is used to help bring the full interferometer to its operating point. In addition, the TMSs are used to inject green lasers, located in the end-stations, into the arm cavities. Green lasers used in the Arm Length Stabilization system are also employed to help bring the interferometer to its operating point.

The suspension component of the Transmission Monitor is a double pendulum suspension (interestingly, LIGO uses single, dual, triple and quadruple stage suspensions!). There are two sets of blade springs to provide vertical isolation. The top mass is suspended from the support by a set of blades, and the telescope is suspended from the top mass by a second set of blades. The top mass has 6 sensors and actuators to control and damp the motion of the telescope. The TMS is bolted onto the test mass vacuum chamber (BSC) seismic isolation platform, just behind the end-test-mass quadruple suspension (see figure 1).

The telescope is an all-reflective off-axis telescope (or a 'Schiefspiegler' used in astronomical telescopes), with a primary mirror diameter of 9" and a focal length of 2m. The light beam entering the telescope has a diameter of about 12cm (size of the beam spot on the ETM), and is diverging. The beam is focused on the secondary mirror, down to about 6mm in diameter.

Unfortunately, there is no 'autofocus' option in the telescope, so prior to installation, the telescope needs to be 'focused'. Focusing is done in the lab using an appropriately shaped laser beam (e.g. a few mm in diameter) and a machine which can measure the shape and size of the reflected laser beam (this is a commercial machine called 'Modemaster'). Once the telescope is focused, we lock it into place so the focus cannot change.

Bram Slagmolen

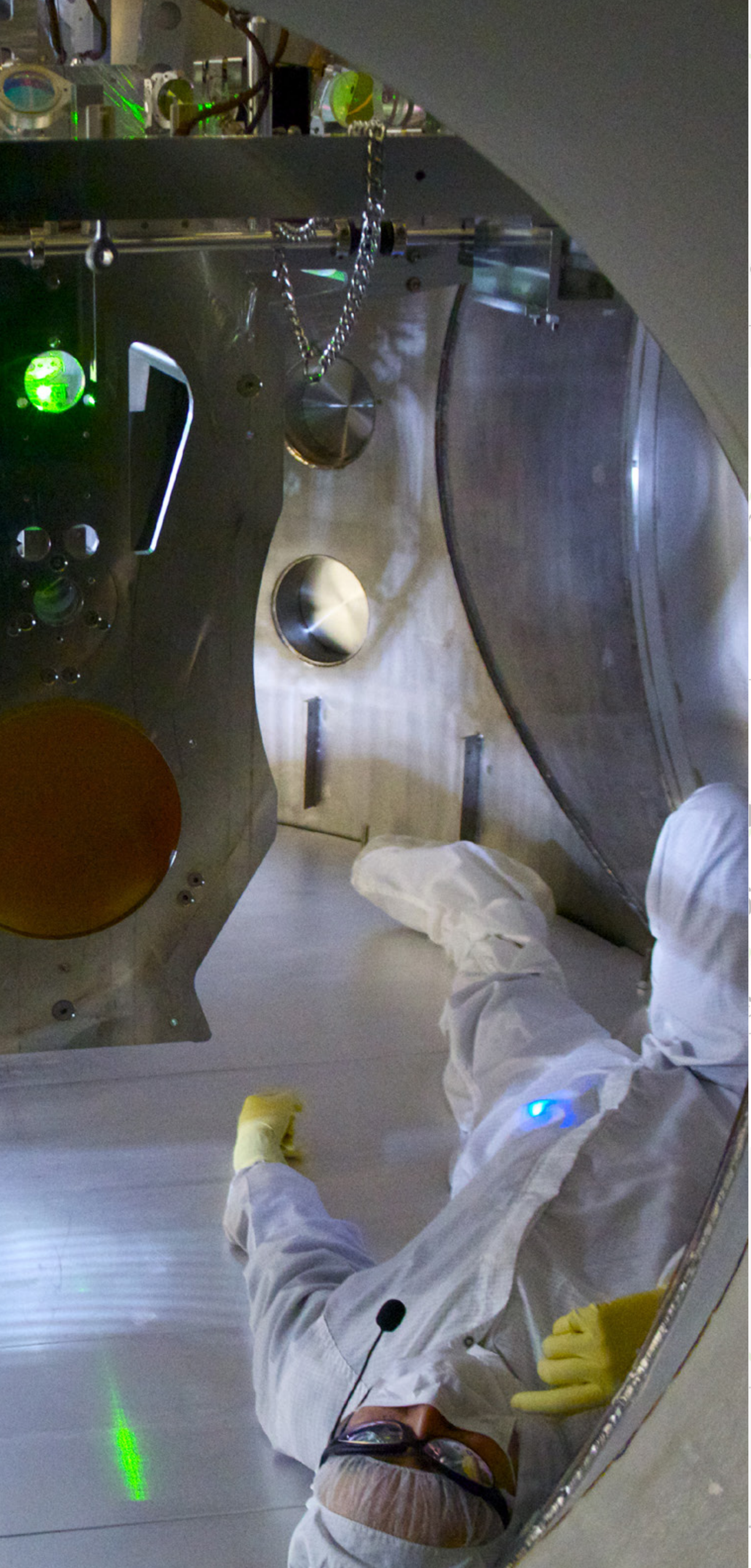
Bram Slagmolen is a researcher at the Australian National University in Canberra, where among other things, he is building a low-frequency gravitational-force sensor. A keen amateur astrophotographer, he routinely braves the (not so) dark, cold nights.

Other technical jabber is, that a breadboard with more optics and some photodetectors is bolted on top of the telescope. A little periscope is used to pop the beam out of the telescope on top of this breadboard. The optics on the breadboard will steer the light onto a pair of quadrant photodetectors. The alignment of the optics and photodetectors is done in the lab, prior the full assembly.

The quadrant photodetectors are used for the alignment of the input and end test masses. (Technically it will be a combination of the alignment of the light beam entering the interferometer at the input; at the input of the arm cavities and the suspended optics, but that is beyond the scope of this article).

During 2011, I visited the LIGO Hanford Observatory and during this time I helped build and assemble the first version of the Transmission Monitor Suspension, which is currently referred to as the H1 TMS EY (after a previous life as H2 TMS EY).

Keita Kawabe takes a respite from working on the Transmission monitor (TMS) in the end station of the X-arm at LIGO Hanford Observatory. ▶



Inception of an event

I hear it, I hear it", alerted Alan
"Freaking loud!", screamed Stephen
It is a dog, big and black"
Echoed Tom from his shack
"This is no mongrel terrestrial
A Canis Major quite monumental"

"Why did she arrive at the stroke of ten?
How does she know six from seven?
Not at half-past or quarter to eight
Pondered Jolien by day and night

Drew measured the background with care
Collin showed it to be a hound quite rare
This is for me a direct proof"
Pleaded Saulson "It is no goof"
"Hello! we disagree", demanded Stan
"It is only an evidence" concurred Shawhan

"No matter how loud and chirpy
It's only a lone voice", urged Gaby
Alas our analysis is but shabby
Even so we vouch it's a doggy

John and Viven, Vicki and Christian
They all came with good old Bayesian
To measure that beast, to see if she spun
By hook or crook to get her location
Was she near or far from us
Black or star, it turned onerous

People travelled by day and by night
To get to the mass on foot or by flight
No wonder this was the sight
Not to be missed whatever the plight

Jay was patient, he knew the answer
Hough was tense, for he had a wager
I'd bear no more and rolled my top
It spun and spun, failed to stop

by B.S. Sathyaprakash

A Humboldt Fellow at Stanford

Benno Willke

Benno Wilke is a faculty member at the Leibniz Universität Hannover and a senior scientist at the Albert Einstein Institute Hannover. He likes running and skiing and regrets that the "Aspen meeting" is no longer held in Aspen.

When I heard that the Fall 2014 LVC meeting would be held at Stanford I immediately began looking forward to it. For me an LVC meeting at Stanford means not only attending exciting talks, posters, and break discussions, but also diving into a very happy memory of a one year postdoc time that I spent at Stanford University. I would like to invite you to join me on a journey back in time that, as you will see, comes close to an advertisement for a postdoc time abroad.

Several years ago, 1996 to be precise, when I was a young postdoc in the German GEO600 group in Hannover, Karsten Danzmann came to me and suggested to spend a postdoc year abroad. I had heard senior people before praising the postdoc time abroad as "very important," "essential to become a mature scientist," "almost unavoidable for a career in academia," and as "really important for your personal development."

There was, however, my internal voice that said: "They are exaggerating. You can as well become a good scientist if you stay in Germany," or "Those advantages can not be worth the effort of moving with your wife and two small kids to a foreign country and leave parents, relatives, and all the good friends behind." But there was as well this voice saying: "You can not miss this opportunity, such a chance might never come again". And guess what, the second voice won.

Karsten suggested Stanford as a good place to go. I contacted Bob Byer and after an phone call with Eric Gustafson it was decided that I would write a proposal to apply for a fellowship of the German Humboldt foundation to go to Stanford and work on lasers and gravitational wave detection. It might sound strange, but all the uneasiness about this year abroad disappeared as soon as the application letter was in the mailbox. From then on I was only looking forward to first winning the award and then going to California.

I was lucky and found myself in February 1997 in a plane towards the US. I still remember that I read "Gebrauchsanleitung Amerika" on the plane, which means something like "Users' Guide to America," with many useful tips what to do, and what to avoid in the US.

The first few weeks were a mixture of settling in at work and getting life organized. The work part was easy as I was warmly welcome by the Stanford Galileo group. (The LSC did not exist at that time, but a collaboration of several groups at Stanford had just handed in the Galileo proposal to prepare for a kilometer scale Sagnac type GW detector). The topics of discussion at work were related to physics and the required lab skills in Hannover and Stanford were very similar.

Organizing my private life and preparing for the arrival of my family was a little more tricky. I needed a social security number, a bank account, a flat, a car, and furniture. Fortunately former Stanford postdocs had prepared a document that clearly described the not arbitrary order of how and where to get all this. After six weeks I was well prepared to pick up my family at the airport, drive them with our new minivan to our just-rented flat on Wilkie Way (funny, almost a copy of our family name Willke) and put the kids to rest on the new futon mattresses.

By that time I had clearly learned the first lesson of a postdoc year abroad: Don't be shy and ask, ask, ask. At work I got a very interesting project: Nob Uehara had just finished the design and the construction of the first pre-mode-cleaner (PMC) for initial LIGO and my job was to continue his experiments and to integrate it into the pre-stabilized laser system (PSL) that was set up at Caltech. I learned how to build, align, stabilize, and characterize optical ring resonators and had a lot of fun with the Galileo graduate students and post-docs. The offices of the senior scientists Eric Gustafson and Roger Route were always open and I got a lot of good advice from them. And once in a while Prof. Byer stopped by at the lab for a chat.

What was completely new to me was the close collaboration between several departments at Stanford. Already after half a year I found myself involved in a photodiode design project with the electrical engineering department, a cavity ring-down experiment with the chemistry department, and in two projects beside my own in the physics department. This was the second lesson I learned: don't try to solve all your problems alone but ask for help and collaborate. If there is a wheel maker next door, do not try to invent the wheel yourself! Unfortunately such a regular and easy collaboration over department borders is not normal in Hannover and I sometimes still miss the Stanford situation.

What I miss as well is the nice weather in California. Already after several weeks we had a complete set of camping equipment and understood that the most popular State Parks and National Parks required early reservations. Hence we made a plan and booked campgrounds for many weekends of the year to come: Yosemite National Park, Lake Tahoe, and Big Sur, just to name a few. When we weren't away camping, we spend days in San Francisco, in Santa Cruz at the beach or in local parks. During the week the pool in our apartment complex was the favorite place for our kids.

Workwise, things moved forward at an enormous speed. I made good progress in the lab, spent several weeks at Caltech to work on the PSL, attended the first LIGO collaboration meetings and my first Aspen conference. And suddenly I realized that it was already time to wrap up. Even though I would had loved to stay for a second year, we decided to go back to Germany as it was time for our son to start school. Furthermore the GEO600 infrastructure and vacuum system was ready and I did not want to miss the optics installation and first operation of the mode-cleaners.

Due to the extremely nice working environment in the Byer/Fejer group and the strong interdisciplinary connections I left Stanford after one year with five scientific papers and several new lab skills. I learned a lot about physics and collaboration and grew as physicist and as a person. Furthermore I made many new friends in Stanford and in the LSC. The postdoc time in Stanford was clearly an important milestone in my scientific career and laid the foundation for my future role as the Lasers Working Group chair in the LSC and as subsystem lead of the Advanced LIGO pre-stabilized laser (PSL).

I now belong to the "converted" and joined the chorus of those saying how useful and beneficial a postdoc year abroad is. Looking back, I am very happy that I didn't pass up the opportunity to experience a year as a Humboldt fellow at Stanford.

Benno and his family enjoying a spot of sightseeing at the Golden Gate bridge in San Francisco ▶

LIGO: A passion for understanding - An interview with

Kai Staats

Kai Staats is a jack-of-all-trades / master-of-none professional writer and film maker. In 2011 he put his house on the market and sold everything he owned in order to capture life on film. His film projects have taken him from Mauna Kea to Africa, from Idaho to Palestine, and... from Hanford to Livingston.

Marco Cavaglià: Who is Kai Staats? Why do you make science films?

Kai Staats: I am, in simplest terms, a recovering entrepreneur reinventing myself as a storyteller. My story telling takes form in writing and film making. Sometimes I tell a story simply to entertain, but usually, my stories are a means by which I may share my raw enthusiasm for learning, to stimulate the thinking of the members of my audience.

I am inquisitive by nature. I want to know how everything works. Not only mechanical things, old clocks, CPUs, and jet engines, but the inner workings of human beings too.

To learn what makes us tick, we look to biology, psychology, and sociology. But to truly understand what is happening inside each individual, we must ask questions and then embrace the unfolding stories.

Through twenty years of world travel I have received myriad stories, around camp fires, in cafes, and at unexpected intersections where two people happen to meet. In these stories, I have discovered a pattern to what people seek. From an orphanage in Kenya to the West Bank of Palestine; from the rim of the crater of Mauna Loa to the largest telescope in Africa, at the heart of each personal story people seem to be asking the same question, Why?

As an inquisitive species we seek to answer this question through various means. However, each avenue of inquiry does not provide the same answer. Some warn us to stop asking. Some give us a dead-end answer. But when we gain deep understanding through the language and process of science, in such a way that people connect to the real world around them, then that first question "Why?" leads to "How?", "Where?" and "When?"

When someone wants to learn more, when their eyes light up and the gears start turning – that, to me, is incredibly exciting. If my work in film can in any way be a catalyst for this kind of transformation, then I will have accomplished something.

Two years after the sale of my Linux OS and HPC systems design company in 2008-09, I was missing the stimulation of working with scientists and researchers for those previous ten years. Further motivated by a growing intellectual angst in response to popular documentaries which began with legitimate intent but slide into the realm of pseudo-science and feel-good new-age magic, I set out to make a documentary film which told the passion of real science.

"The Explorers" took form as the story of how astronomy invokes a passion for science.

I recall an ah-hah! moment while filming at NASA Ames when I realized I could, if successful, travel the world, work with the most intelligent, driven minds this planet has to offer, absorb a broad smattering of science (more than any university classes could provide) and share what I learned to help others carry that first question Why? to a much, much deeper level.

M: How did "LIGO, A Passion for Understanding" unfold?

K: By the spring of 2013, I had produced a variety of short, educational videos and a short, Hollywood-quality sci-fi. In Tanzania and South Africa I had conducted interviews with professional astronomers, teachers, and learners to complete principal footage for The Explorers.

Upon my return to the U.S. a former client and good friend Gaurav Khanna, astrophysicist at U Mass, Dartmouth introduced me to Gabriela González at LIGO. Gaurav believed my growing skills in film making coupled with a drive to tell the stories of modern science was a good match for Advanced LIGO, whose story had not yet been told on film.

Gabriela González, Marco Cavaglià and I co-authored the proposal to the NSF, which was intercepted by the LIGO Collaboration at Caltech and immediately funded. "LIGO, A Passion for Understanding" was given the green light and ten days later I was on-site at the LIGO Hanford Observatory, Washington.

M: What was your experience at LIGO Hanford?

K: From the moment I walked on-site I was made to feel at home. Michael Landry was my host, and an exceptional host at that. I was amazed by his ability to juggle such an intense daily schedule with a smile, to help coordinate the daily interviews.

I was given an empty cubicle to claim as my desk, where I configured my camera rig each morning (some assembly required) and repacked my gear each night.

Immediately, I noted that each office door was fitted with a small whiteboard, where anyone walking by could stop to diagram, write formula, or make a note. There was no ownership of these mental spaces, rather, they were posted to make certain that all ideas had opportunity to take form.

It was my observation that no one had two or three letters following their names, not on office placards nor business cards. In fact, most LIGO staff struggled to provide a title when I insisted I needed something to put on screen.

This flew in the face of traditional academia or corporate America where the higher degree or well paid position earned some kind of note worthy seniority. I learned some of the staff held Master degrees while others a Ph.D., yet some were originally working with the construction crew and became a permanent part of the science team. Everyone was an important part of the team. Refreshing!

This kind of all-for-one and one-for-all collaboration is in my mind at the core of research and investigation. While publication is certainly a motivating factor in academia, the overarching goal is to work with a team to discover the fundamental principals by which the world operates, and then share those discoveries with the world. LIGO seems to embody this, at its core.

M: What were some of your most memorable moments in making the film?

K: When I had finished filming a segment with Alexa Staley at the "X" end-station, I had free time and offered to help. We ran a fibre optic cable and adjusted angles on a half dozen instruments on the optics table. In the process, we discovered a reflection caused by a misaligned mirror which could have proved harmful to the experiment. While I did little more than hold things, tighten bolts, and ask a lot of questions (Why? How? Where?), I felt I was a part of LIGO, even for just one hour.

The humor and energy of Betsy Weaver was contagious. We conducted her proper interview and then shot a spoof in the style of the old spaghetti westerns. Once edited, I shared it with the LIGO team, but told them it was the final film. They soon realized the joke, but liked it so much, they are now using it for student recruitment.

Bubba Gateley was incredibly generous with his time, dedicating a half day to taking me up and down and around and around in the cherry-picker to obtain key, opening shots.

If Daniel Sigg were to ever leave science to open a restaurant, I would be his first patron. His home-cooked, Wednesday dinners are outstanding.

Personally, I felt the most kinship with Robert Schofield, for the way he sees the world is not unlike my own. He wakes, eats, breathes trouble-shooting and problem solving, chasing the ghosts out of the machine. So much to learn from him.

Jamie Rollins is … intense. Need I say more!? (smiling)

I thoroughly enjoyed my time with Michael in writing the animation sequence script. We started at his house one evening, sketching storyboards in chalk on his dining room chalk board. Filming the animation sequence with Jamie and Michael in the auditorium a few days later was a departure from standard interviews, with dialogue we had to get just right.

Finally, flying with Alexa during her training session at the local airstrip was surprisingly relaxing. She perfectly executed a half dozen take-off and landings and what's more, we got the perfect shot for the opening sequence of the film as we flew over the observatory.

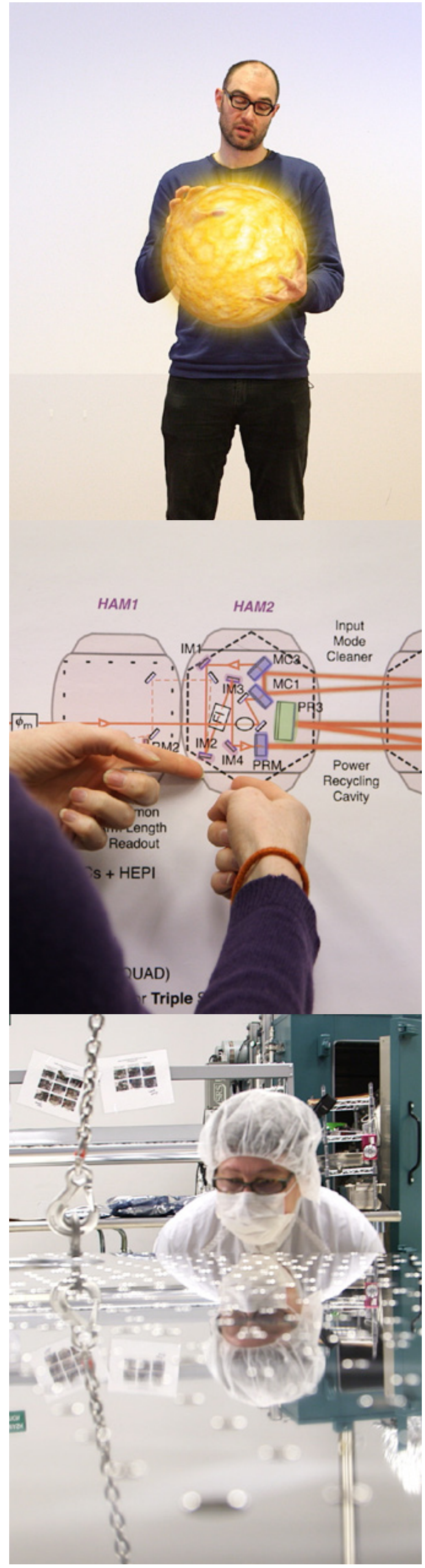
There are many more stories, for certain, but the summary is this – I recognize that all teams struggle in more than one way, shape, and form. But not since I spent a similar amount of time installing HPC systems at NASA JPL have I witnessed that kind of team spirit and unity.

The sense of urgency, of total focus after more than twenty years toward a single goal is to me incredible. Can you imagine if all of corporate America stayed that course? Or if the US government worked with that level of efficiency? What a world that would be.

M: Tell us about the post-production process, and how the final version took form.

K: Our target audience was students 15-22 years of age who may be considering a career in science. We kept coming back to: How do we share the science? How do we tell the story of those who have dedicated their lives to this tremendous undertaking?

In a documentary, you can certainly script the entire film to a degree of control similar to a proper Hollywood film. But my style



Movie stills

is that I prefer to just let the stories unfold, even if it means more time editing and a film whose dialog is not quite as polished.

I need only count the hours, nearly 200 in the edit of this 20 minute film, to emphasize the detail which is given to every frame on screen. Attention is given to the context and tone of each interview. The beats of the musical score sometimes drive the visual edits. The way each transition is executed works to carry the audience from one segment to the next. In this kind of film, we must entertain and educate at the same time.

There were sticking points, total sections re-worked as an attempted edit met a dead-end. We had to remove an entire section due to the BICEP2 results mid-edit. Not because what we had shot was wrong, but because it needed further explanation to differentiate the kind of gravitational waves observed by BICEP2 and what will be observed by LIGO.

Gaby, Szabi, Mike, and you [Marco] were fundamental in the edit process as each contributed valuable feedback. Never did I feel you focused too heavy on the details, but always maintained solid science as the guiding principal. We worked well as a team, each bringing to the table our own area of expertise. I could not have asked for a better first effort. I look forward to the next film (and the next, if all goes well).

Most important for me, as a film maker in the realm of science, is to remain connected to our humanity. We are exceptional story tellers, each one of us, using our hands and arms, face and total body to share complex subject matter. I wanted to build upon that, to augment our natural story telling with computer generated animations that work to build upon what we do naturally, not replace it.

Hollywood has spent twenty years working to perfect Visual FX. Now, I believe, it is time to bring the humans back to the screen. We may be momentarily in awe of a computer generated, visual effect, but in the end, we will remember what we connect to the most deeply, another human being..

We were very fortunate to have at our disposal Space.com as a launch vehicle for the premiere. Former National Science Foundation employee Josh Chamot and his team of science savvy editors and publicists were instrumental in the successful launch of "LIGO, A Passion for Understanding" mid-April, with more than 10,000 views in the first week alone. We hope to have the opportunity to work with them again.

M: What will the next movie be about and what will you do differently?

K: The next film, "LIGO Generations" is our attempt to tell the story of the three, unfolding four generations of scientists, researchers, and engineers who have worked to make gravitational wave astronomy a reality. On the brink of success, these past 30+ years represent one of the longest running scientific experiments in the history of human kind. That is a story worth telling.

We will also share more science. We want to dive deeper into the explanation of gravitational waves, their origin, frequency domain, and how LIGO works to detect them.

For me, the challenge will be finding continuity from the first to second film without simply duplicating the structure and inserting new content. I want to experience the Livingston Observatory as I did Hanford, for the first time. I want to walk on-campus in total awe, capture it, and then present it on screen.

If I can accomplish that, than as with the first film, I believe we will carry our audience into a deeper understanding of gravitational wave observation and what it means to the world.

Thank you for this opportunity to tell this story. I am eager to work with the LIGO family again!

LIGO 2014

Can you solve our unique LIGO sudoku puzzle?

LIGOku grid

$\times$			h		$+$			f
	G			L			$\times$	
			η		f			
	L						$\mathcal{M}$	
f		$\mathcal{M}$		$+$		$\times$		G
	η						L	
			$\times$		G			
	f			η			G	
G			$+$		h			c

Standard Sudoku rules apply!

Each row, column and 3 x 3 box should contain exactly one of the nine symbols commonly used in gravitational wave physics: c: The speed of light; h: The gravitational-wave strain; f: The frequency of the gravitational wave; η: The Minkowski metric; G: The gravitational constant; +: The "plus" polarization; $\times$: The "cross" polarization; L: The length of one LIGO arm; $\mathcal{M}$: The chirp mass. – by Martin Hendry

We Hear That ...

Recent Graduations

Thomas Adams defended his PhD thesis in May and will join the Virgo group at Annecy in August. His work will focus on the low-latency MBTA CBC search.

Cristoph Affeldt defended his PhD thesis titled "Laser power increase for GEO 600 – Commissioning aspects towards an operation of GEO 600 at high laser power" at the Albert Einstein Institute in Hannover in March.

Heather Audley defended her PhD thesis, "Preparing for LISA Pathfinder operations: characterisation of the optical metrology system," at the Albert Einstein Institute on July 11th.

Charlotte Bond defended her PhD thesis titled "How to stay in shape: Overcoming beam and mirror distortions in advanced gravitational wave interferometers" at the University of Birmingham in May. She will continue her work on modelling Advanced LIGO in Birmingham until this fall.

Tara Chalermsongsak defended his thesis, "High Fidelity Probe and Mitigation of Mirror Thermal Fluctuations" and will be taking up a teaching position in Thailand this fall.

Mark Edwards graduated from Cardiff University this July. He has since moved into the local high-tech industry in Cardiff, including part-time work at the Newport patent office.

Ben Farr defended his PhD thesis entitled "Extracting Astrophysical Information from the Gravitational Waves of Compact Binary Mergers and Their Electromagnetic Counterparts" and moved to the University of Chicago in July to continue his work on parameter estimation in gravitational wave and electromagnetic astronomy.

Justin Garofoli, an Operator at LIGO Hanford Observatory during Initial LIGO, defended his dissertation, titled "Measurement of CP Observables in B→DKππ decays," at Syracuse University in March.

Kari Hodge, defended her thesis in gravitational-wave data analysis entitled "The Search for Gravitational Waves from the Coalescence of Black Hole Binary Systems in Data from the LIGO and Virgo Detectors; Or: A Dark Walk through a Random Forest". She plans on staying in Los Angeles and has accepted a job at Malachiarts as a junior developer in technical consulting.

Stephen Privitera, defended his PhD thesis entitled "The importance of spin for observing gravitational waves from coalescing compact binaries with LIGO and Virgo" in May and is moving to AEI-Potsdam this fall.

Patricia Schmidt defended her thesis titled "Studying and Modelling the Complete Gravitational-Wave Signal from Precessing Black Hole Binaries" in June and is moving on to a postdoc position at Caltech this fall.

Darren White, previously a graduate student at Sheffield, successfully defended his PhD thesis in December 2013. This spring he moved on to a postdoc position at the University of Warwick working on the development of the Gravitational-wave Optical Transient Observatory (GOTO), built specifically for follow-up observations during the upcoming advanced detector era.

Career updates

Berit Behnke, previously a postdoc at AEI Hannover, started a postdoc position at the Federal Institute for Physics and Technology (PTB), Germany, in the field of radiation physics.

Collin Capano will be leaving Maryland and moving to AEI Hannover this Fall as a postdoc. He will continue work on developing the binary-black hole search for advanced LIGO and Virgo with the CBC data-analysis group at Hannover.

Kate Dooley, currently a post-doc working on GEO600 at the Albert Einstein Institute, has accepted a tenure-track faculty position at the University of Mississippi, to begin in the fall of next year. In the meantime, she will begin a new postdoc at Caltech LIGO Lab.

Tobin Fricke, currently a post-doc at AEI in Hannover, will move from commissioning laser interferometers to commissioning airborne wind turbines, at Makani Power, part of Google[x].

Oliver Gerberding, currently working on phase readout systems as a post-doc at the Albert Einstein Institute in Hannover, has accepted a new post-doc position at the U.S. National Institute of Standards and Technology (NIST) near Washington DC, starting in July 2014. He will work on opto-mechanical accelerometers.

Ian Harry, previously a postdoc at Syracuse University is moving to start a new post-doc at the AEI Golm this summer.

Jeff Kline, after three years of working with the LSC at UWM, left the collaboration to become a Senior Data Analyst for MdotLabs in Madison, WI.

Erin Macdonald, recently left the world of academic research to focus on making a documentary about postdocs and to develop her voice acting experience. Additionally, she is working at the Denver Museum of Nature and Science and is teaching astronomy at the local community college.

We Hear That ...

Evan Ochsner accepted an associate scientist position at the University of Wisconsin-Milwaukee (where he was previously a postdoc) to work on improving LIGO data analysis software

Greg Ogin will start a tenure-track position at Whitman College as assistant professor of physics this Fall. He was previously a visiting professor there.

Richard O'Shaughnessy moved to the Rochester Institute of Technology, as tenure-track faculty affiliated with the astrophysics program and the Center for Computational Relativity and Gravitation. He will extend his work on modeling and interpreting compact binary sources of gravitational waves.

Margot Phelps will be leaving the COC/SUS group, based at Caltech, after five years to start graduate school at the University of Glasgow's Institute for Gravitational Research this coming fall.

Valeriu Predoi returned to Cardiff University in April to begin a postdoc working on the all-sky burst search with the spherical radiometer pipeline. He previously completed a postdoc in computational virology in Toronto.

Vivien Raymond will finish his appointment as Richard Chase Tolman Prize Postdoctoral Fellow at Caltech and move across the Atlantic in fall 2014 to work as a Senior Post-Doc at the AEI Golm.

Christopher Wipf will move from LIGO MIT to a postdoctoral position at Caltech's LIGO Laboratory this fall.

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**.

News

The University of Texas at Brownsville and the University of Mississippi were selected as 2015 sites for the Conference for Undergraduate Women in Physics.

The University of Texas at Brownsville was selected to host the Rio Grande Science and Arts Festival (RiSA), as part of the Science Festival Alliance, this November. This is a large city wide festival which will focus heavily on astronomy.

The filming of the second new Advanced LIGO documentary took place in Livingston and Cambridge, MA, in May/June. The documentary is scheduled for release by the end of the year.

Sarah Gossan, a third year graduate student in the Caltech Relativity and Theory group (CaRT), was elected as the student representative for the APS Topical Group on Gravitation (GGR). She is working to augment the social media presence of GGR in order to attract many new members and consequently help GGR to become an APS Division. In anticipation for the GR centennial next year, she would like to ask readers to please join GGR!

Awards

Berit Behnke was one of the awardees of the Otto Hahn Medaille 2013 for her PhD thesis "A Directed Search for Continuous Gravitational Waves from Unknown Isolated Neutron Stars at the Galactic Center".

Sheon Chua was awarded the 2013 GWIC Thesis prize for his thesis titled "Quantum Enhancement of a 4km Laser Interferometer Gravitational-Wave Detector".

Tjonnie Li, now a postdoc at Caltech, was awarded the 2013 Stefano Braccini Thesis Prize for his thesis entitled "Extracting Physics from Gravitational Waves: Testing the Strong-field Dynamics of General Relativity and Inferring the Large-scale Structure of the Universe".

LSC Elections

Graham Woan was re-elected as co chair of the continuous waves group for a 2 year term in March 2014.

Iain Martin became the chair of the optics working group in March for the next two years, replacing **Gregg Harry**.

Duncan Brown was re-elected as co chair of the CBC group in March 2014 for a 2 year term.

Brian Lantz was re-elected as chair of the Suspension and Isolations Working Group in March. He will serve a two year term.

Recent papers

The LIGO and Virgo collaborations continue to prepare for the first observing runs of Advanced LIGO and Advanced Virgo. The 6 months since the last issue of the LIGO Magazine has seen many new papers submitted to journals and become publicly available on the preprint ArXiv server. These papers are some of the last that will analyse initial LIGO and Virgo data and many of the techniques used will be directly applicable in the Advanced detector era.

One of the great open questions in astrophysics is the origin of gamma-ray bursts (GRBs). GRBs are intense flashes of high-energy photons; they are some of the brightest electromagnetic events in our universe, typically releasing more energy in a few seconds than the Sun will in its lifetime. GRBs occur approximately once per day and are usually classified according to their duration and spectral hardness as 'long' or 'short' GRBs. Short GRBs typically last less than 2 seconds and have a "harder" (more energetic) gamma-ray spectrum whereas long GRBs last more than 2 seconds and have a "softer" (less energetic) gamma-ray spectrum. The source of long GRBs is generally thought to be the collapse of very massive, rapidly spinning stars resulting in a supernova; these make up the majority of the GRB population. The source of short GRBs is not yet understood, but the current favored hypothesis is that they are caused by the collision of a neutron star with either another neutron star or a black hole. The first of this issue's papers describes a "Search for gravitational waves associated with gamma-ray bursts detected by the InterPlanetary Network" (http://arxiv.org/abs/1403.6639). This paper searches for gravitational-wave signatures from both long and short GRBs that were observed with the InterPlanetary Network of satellites during LIGO's fifth and sixth science runs. No gravitational wave signatures were detected but from this non-observation it is possible to put lower limits on the distance to each progenitor and place a lower limit on the cumulative distribution of short and long GRBs in the Universe. At this point these bounds are not of great astrophysical interest, but with Advanced detector sensitivity LIGO will help to better understand the nature of GRBs.

Our second paper discusses "Methods and results of a search for gravitational waves associated with gamma-ray bursts using the GEO600, LIGO, and Virgo detectors" (http://arxiv.org/abs/1405.1053). This paper searches for gravitational-waves in coincidence with GRBs that were observed by one of the LIGO and Virgo detectors and the GEO600 detector in Germany. As this detector has significantly lower sensitivity than the LIGO and Virgo detectors below 500Hz the focus of this search is supernovae signals at frequencies around 500 - 1000Hz. As with the first paper, no gravitational-wave signals were observed but again lower limits on the distance to the GRBs are placed.

Another focus in recent papers is searching for so-called "intermediate" mass black holes (IMBHs). Observations have revealed the existence of two classes of black holes: those with masses up to a few tens of times that of the Sun and black holes with masses of millions of times that of the Sun. The black holes that belong to the first class are the remnants of the most massive stars and are called stellar-mass black holes, while the black holes belonging to the second class are located in the centers of galaxies and are referred to as supermassive black holes. Observations also suggest that a third class of black holes could exist - with masses that are between those of stellar-mass and supermassive black holes, these are called intermediate mass black holes. The gravitational radiation emitted by such systems will predominantly be below the sensitive band of the first-generation LIGO and Virgo observatories. Only the final merger and post-merger "ringdown" might be visible. The paper "Search for gravitational radiation from intermediate mass black hole binaries in data from the second LIGO-Virgo joint science run" (http://arxiv.org/abs/1404.2199) describes the result of a search for unmodelled gravitational-wave signals focusing on merging IMBHs. This is complemented by the paper "Search for gravitational wave ringdowns from perturbed intermediate mass black holes in LIGO-Virgo data from 2005-2010" (http://arxiv.org/abs/1403.5306), which describes the result of a modelled search for the post-merger ringdown of an IMBH merger. Neither work detected any gravitational-wave signature, but both were able to place limits on the rates of IMBH mergers in the Universe. With the increased low-frequency sensitivity expected in Advanced LIGO, IMBH sources will be an interesting target for gravitational-wave observations in the coming years.

Our fifth paper, "The NINJA-2 project: Detecting and characterizing gravitational waveforms modelled using numerical binary black hole simulations" (http://arxiv.org/abs/1401.0939), carries out a systematic study of our ability to observe stellar-mass binary black hole mergers in 2015. This work draws heavily from our numerical relativity colleagues to provide us with highly accurate binary black hole merger waveforms, generated from large-scale numerical simulations. These numerically-generated waveforms are used to obtain the best estimates of how far we could observe real binary black hole mergers in the first observing runs with Advanced LIGO.

In our last issue we focused heavily on searches for rapidly spinning neutron stars. Our final paper "Implementation of an F-statistic all-sky search for continuous gravitational waves in Virgo VSR1 data" (http://arxiv.org/abs/1402.4974) continues in this vein, supplementing the papers described in the last issue by running over data from Virgo's first science run in place of LIGO data. As with other works, no gravitational-wave signature was observed, but limits on "continuous" gravitational-wave signals, such as spinning neutron stars, was able to be placed. The knowledge gained from running these searches will greatly facilitate similar searches with the much more sensitive Advanced LIGO and Virgo.

Congratulations to everyone who has worked hard to get these papers finished and published!

Our World is Three-dimensional

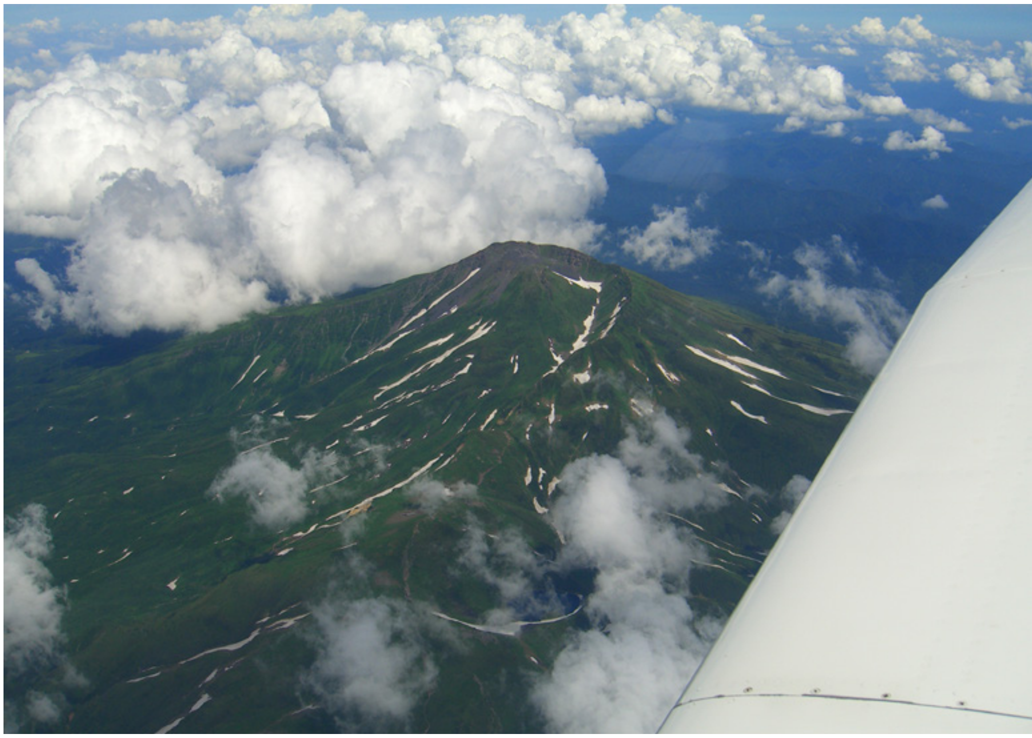
Stefan Ballmer

is an assistant professor of Physics at Syracuse University. When not working or flying, he is trying hard to brush up his Japanese skills before he falls too much behind his three year old son.

When I get tired of exploring four-dimensional space-time, I like to completely detach from the planet for a while, enjoying space-time’s third dimension and the vistas it provides. I have been fascinated with flight since my childhood, starting with radio-controlled (RC) aircraft. Getting my pilot’s license and then my instructor certificate has provided me with some unique experiences.

There was the flight in a star-lit, moonless night, with only the faint distant glow of the LA basin and overcast cloud layer below me. There were flights to the Pacific islands of Oshima, Nishima, on Hawaii, and over New Zealand’s Hauraki gulf. And there were the low flights over the waters of the Prince William Sound and the Susitna river in Alaska.

If you suffer from a similar addiction, I can recommend http://www.aopa.org/letsgo-flying/ as a good starting place. You may find that more LSC members than you think are already pilots.



I keep some of those memories in the form of pictures at http://tinyurl.com/ligoflights. It includes a series of aerial shots of both LIGO observatories. Feel free to use them if you are in the need of artwork for a talk!

LIGO Crossword #3: Crossfire

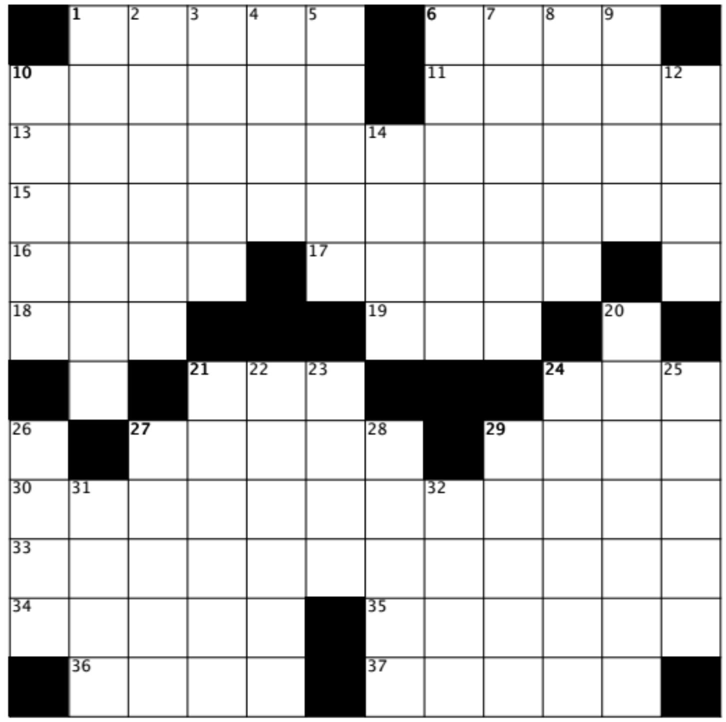
Crossword Clues

ACROSS

1. well know in Buffalo
6. higher means less red skin
10. John Wayne was there often
11. American Poet
13. you are one of a kind
15. you might find it at the road
16. very special style sheets
17. this results in bang
18. employ for something
19. I might arrive at this time 21. UTC - 6 hours
24. add an I and it is still not a sea lion
27. a farmer in England would have used it a long time ago
29. this sounds better than mono
30. carved, not printed
33. Walt Disney: If you can dream it, you can do it.
34. his sword was used
35. in a cell
36. there is actually only one
37. multiple good buys

DOWN

1. life would be boring without it
2. a simple sweetener
3. take the word 'lions' and swap two letters
4. some say this is all you need
5. snaps makes a funny sound
6. a French painter
7. this was hot at the beginning
8. an amount needed to occupy all the space
9. often at the bottom of an ocean or a shoe
10. town in Lahaul Valley
12. 100 of it is equal to 1 sum
14. you would know this name, if you like NASCAR racing
20. against the purpose
21. teeth or optical things may have it
22. water runs through it
23. it is an adaptor, around 85 nucleotides long
24. Some LIGO folks searching for them
25. in-between both sides
26. Orson Scott Card's
27. Blast from the past kind of T-Shirt
28. bright
29. a plant not very well known outside middle Persian
31. Regional Ocean Modeling System
32. not yours



Created by Hans-Peter Bischof

The LIGO Magazine

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How to lock an interferometer:

A chicken and egg problem

The core of Advanced LIGO is a large laser interferometer with several suspended mirrors. To bring this interferometer to the point where it can measure gravitational waves is a complex and difficult task, which we call lock acquisition. During lock acquisition we want to bring swinging mirrors which move uncontrolled relative to each other (unlocked state) to a situation where most of the mirror positions are controlled with respect to each other to very high precision (locked state). We need to reach and maintain the locked state to allow the laser light to fully resonate in all the optical cavities.

The interferometer itself can provide nice signals that tell us how to keep the mirrors at the correct places, but these signals exist only for a small fraction of each mirrors' possible positions, and worse, often depend on the position of several mirrors in a complicated way.

This is a chicken and egg problem: once the interferometer is locked, we have signals that tell us how to keep it locked. But how do we get there in the first place? We could just wait until all mirrors are in the correct position just by chance (which we call stochastic locking). For the 5 mirrors that need to be controlled, we would need to wait very very long. But there are other ideas: firstly, we generate some extra signals only for lock acquisition which have a large range (at the price of higher noise), and secondly, we break down the lock acquisition into individual steps.

For Advanced LIGO, the idea for lock acquisition was to do the locking of the long interferometer arm cavities first, with the help of a pair of extra green-light lasers. The green light provides correct signals for the mirror positions over a large range, and makes it possible to split up the whole lock acquisition into individual steps. Locking the two interferometer arms with the help of green light is the first. Once this is done, the other mirrors can be locked more easily!

Hartmut Grote