LIGO Scientific Collaboration

issue 3 9/2013

LIGO MAGAZINE

squeezed light

from inspiration to application

Squeezing at the Australian National University

A brief history p. 6

LIGO H1 Squeezing

Technology p. 12

... and more!

Title image

The title page shows a photo by JD Hancock called `Neon Wavelength'.

Upcoming Events (compiled by the editors)

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

Frontiers in Optics: The 97th OSA Annual Meeting and Exhibit/Laser Science XXIX
6-10 October 2013,
Hilton Orlando Bonnet Creek,
Orlando, Florida, USA
http://www.frontiersinoptics.com/

28th Annual Meeting of the American Society for Precision Engineering
20-25 October 2013,
Crowne Plaza St. Paul – Riverfront,
Saint Paul, Minnesota
http://aspe.net/

Gravitational-Wave Physics and Astronomy Workshop (formerly the Gravitational Wave Data Analysis Workshop)
17-20 December 2013, Pune, India
http://www.iucaa.ernet.in/~gwpaw/

27th Texas Symposium on Relativistic Astrophysics
8-13 December 2013, Dallas, TX

223rd American Astronomical Society meeting
5-9 January 2014, Washington, DC

APS March Meeting 2014
3-7 March 2014, Denver, CO
http://www.aps.org/meetings/march/index.cfm

APS April Meeting 2014
5-8 April 2014, Savannah, GA
http://www.aps.org/meetings/april/index.cfm

10th International LISA Symposium (LISA Symposium X)
18-23 May 2014, Gainesville, Florida
http://www.phys.ufl.edu/lisasymposiumx/

Gravitational-Wave Advanced Detector Workshop 2014
GWADW 2014, 25-30 May 2014,
Takayama, Japan

11th Edoardo Amaldi Conference on Gravitational Waves
Gwangju, Korea, Summer 2015

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

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Image credits

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Welcome to the third issue of the LIGO Magazine!

Andreas Freise
for the Editors

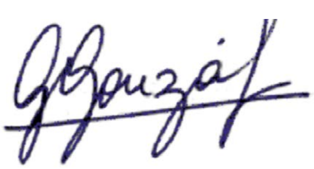
It has been one year already since we presented the first issue of the LIGO magazine, who would have thought? The last year has been exciting and fun, with many excellent contributions and feedback from you, the LSC members. Thank you!

In this issue we bring you stories about the squeezing of light. During my first years in gravitational wave science signal, recycling was still new and an actively debated topic. At first glance it seemed strange that you could increase the optical signal by putting a highly reflecting mirror in front of the optical (photo) detector. Since then we have moved on and some of our detectors have implemented not only signal recycling but also squeezed light. However, the introduction of quantum optics has rendered interferometry even less intuitive for some of us. Hopefully the stories in the magazine will help to make squeezed light a little bit less strange.

Our aim for the coming years is to deliver a new issue, including printed copies, at each main collaboration meeting. We can only achieve this with your help. Editing and layouting each issue typically takes more than eight weeks. Therefore we are looking for suggestions and articles for issues four and five now! Please send comments, suggestions, and contributions to **magazine@ligo.org.**

LIGO Scientific Collaboration News

Gaby (Gabriela) González
LSC spokesperson

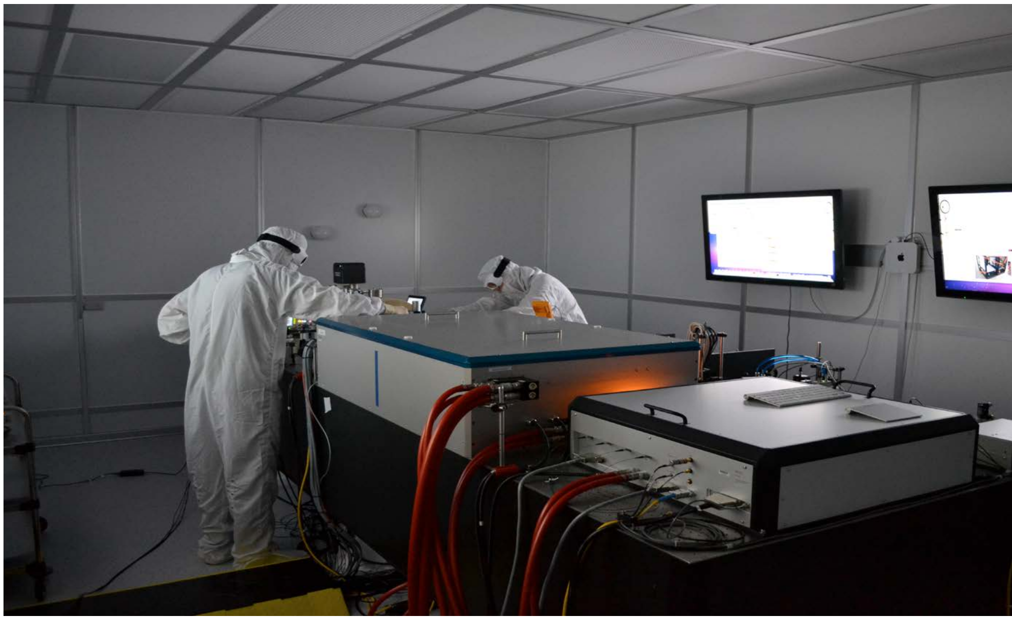


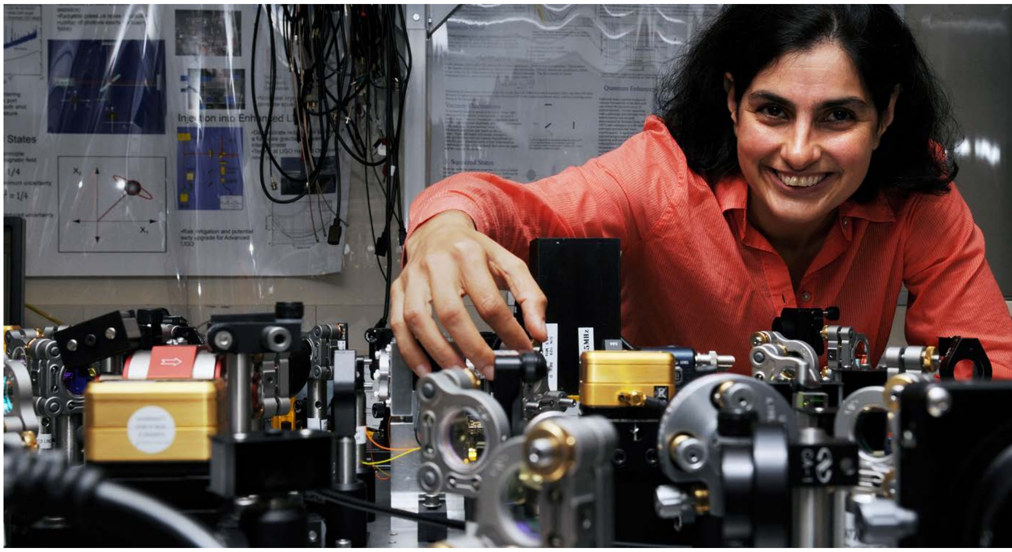
Hello again – it's a pleasure to see that *LIGO Magazine* is now a regular feature to better communicate our activities. Join me in thanking Andreas Freise and all the editors for this great initiative!

In the last issue, I mentioned there was an LSC spokesperson election being held in March. I am very honored to have been elected again by the Collaboration to lead it. You will also be glad to know that Marco Cavaglià was confirmed as Assistant Spokesperson. As before, I am confident we will continue to do very good gravitational wave science and prepare for the upcoming Advanced LIGO detector runs because we count on the help of so many highly motivated and capable scientists – we are true collaborators in this enterprise.

This issue of the magazine has a focus on "squeezed light" which is very appropriate given the recent publication of the article with the exciting results in the H1 LIGO detector (Nature Photonics 7, 613, 2013). We also posted online (arXiv:1304.0670) an article on "Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories" which will be published soon in Living Reviews in Relativity, and you

Experts from Hannover working on the installation of the Pre-Stabilized Laser at the Advanced LIGO detectors (top). Nergis Mavalvala checks the alignment of a laser-optics experiment in her lab at MIT (middle).





should read it if you haven't already. We estimate that advanced detector binary neutron star (BNS) ranges approaching 200 Mpc should give at least ~1 BNS detection per year even under pessimistic predictions of event rates. This will happen in 2019, but it's likely we'll have detections much earlier. We are indeed working hard on this goal, and we are making very good progress. The installation of the Advanced LIGO detectors is going very well, and we are preparing for a first science run in 2015.

We are also very excited about the interest in the astronomical community to "follow up" gravitational wave candidates looking for an electromagnetic counterpart. We had a call for "letters of interest" and we received more than 60 responses. By the time your read this, we will have met with most of the interested parties and will be getting ready to sign agreements for this initiative to start with the first science run in 2015 – again, signs of a very exciting era that is starting now!

Not all the activities were on gravitational wave science and collaborations. LSC members also had a very good time talking about LIGO in the "Innovation Alley" at the at the 6th annual World Science Festival in New York City in June. Also, the touring version of the "Astronomy's New Messengers" exhibit delighted hundreds of children and adults alike at the 2013 Aspen Science Festival Science Street Fair. I hope you have fun with similar activities, and join the Educational and Public Outreach group to share your experiences.

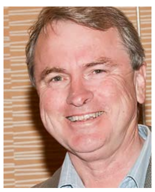
Keep up the good work, and let me know if you have any questions!

Gaby.

Harald Lück, Henning Vahlbruch, Volker Kringel,and Michael Weinert, just before lowering an 80kg steel pre-isolation plate into the vacuum chamber of the GEO 600 output mode-cleaner(bottom).

A brief history

Squeezing at the Australian National University



David McClelland

David McClelland is Director of the Centre for Gravitational Physics at the Australian National University. He has worked on gravitational wave detection for as long as he can remember (at least a week).

In 1985, the Bell group successfully produced squeezed light experimentally using four-wave mixing in sodium atoms [1]. Four years later, in 1989, the ANU quantum optics group was formed. Young ANU faculty members Hans Bachor and David McClelland, with post-doctoral fellows Peter Manson and Peter Fisk and PhD student Deborah Hope, set out to reproduce, (and hopefully better) the Bell experiment using barium atoms. We spent many long hours observing phase dependent amplified noise, but the de-amplification below shot noise that signifies squeezing did not appear. Finally, we opted to try a simpler optical cavity experiment and search for squeezing using optical bi-stability, depicted in Figure 1.

In the dead of night

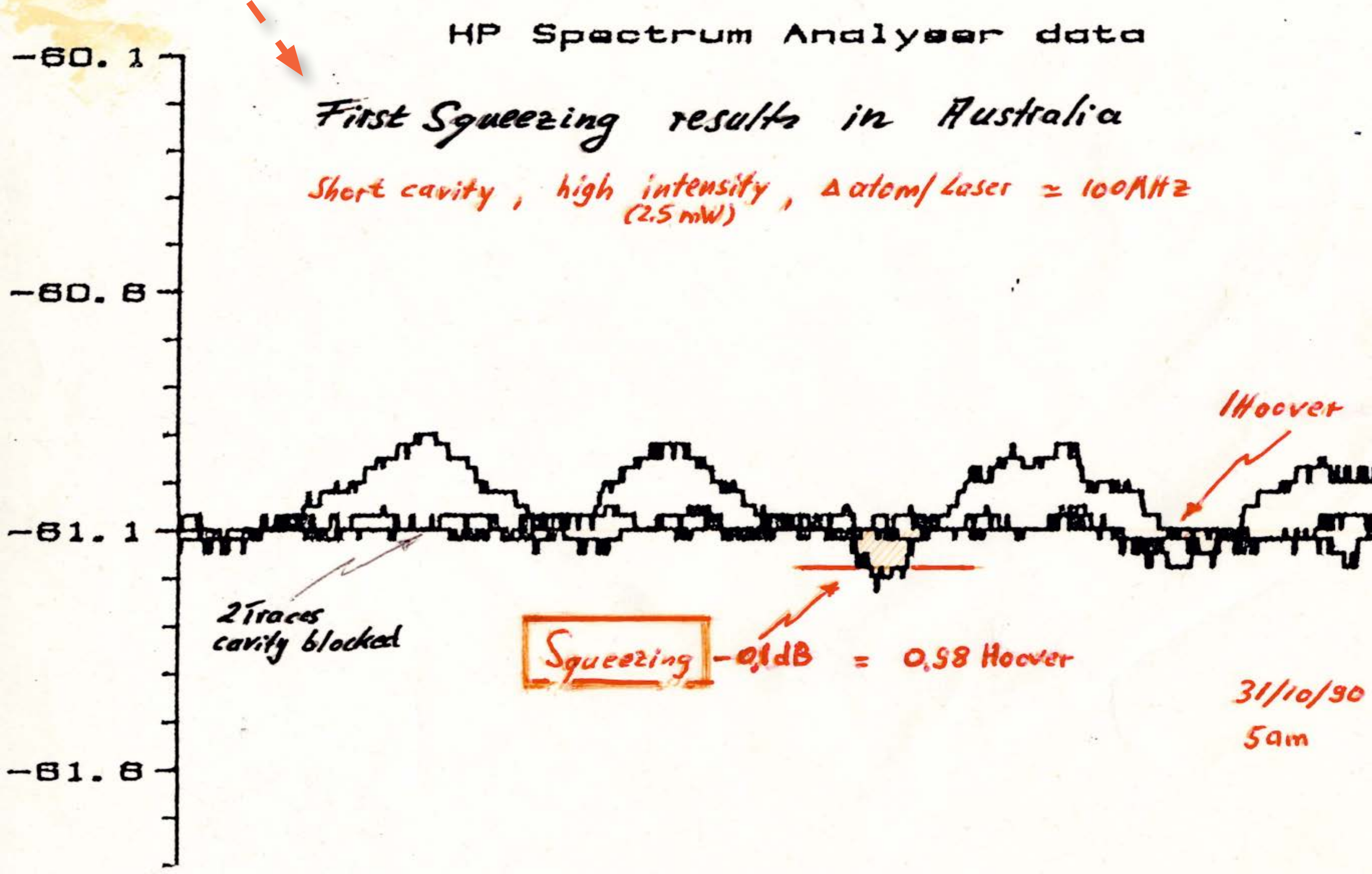
We had to do these sensitive experiments in the dead of night, as the lab was on the second floor of an old building and mounted on a concrete optical bench without the benefits of modern isolation systems. The nights grew longer and colder but we still had no success.

As spring drew near, the nights grew shorter and warmer. Finally on October 31, 1990, at 5 a.m. we produced the scan shown in the graph above: -0.1 dB of squeezing! We labelled it 0.98 Hoover, using a squeezing unit named after the Hoover vacuum cleaner, but the unit didn't catch on. The proud team, looking like a Swedish Pop band (see Figure 2 overleaf and let David dream – have you ever been to Karaoke with him?) retired deliriously to the nearest 5-star hotel to enjoy a sumptuous celebratory breakfast. It was only in the broad light of the next afternoon that we realised how delirious we must have been, and thought that perhaps we had been a tad bit hasty. But that first data point gave us something to optimise. The final outcome of that experiment was -0.8 dB [2] at a few hundred MHz detection frequency and we didn't bother to quote the losses.

Momentous results

That October 1990 result was momentous for us in two ways. Firstly, we realised that some time in the future such states would be used in the way Carlton Caves envisaged (see interview with Carlton Caves) – to enhance gravitational wave detectors. David McClelland contacted David Blair at the University of Western Australia to propose a collaboration on laser interferometry for GW detection, the beginning of the Australian Consortium for Interferometric Gravitational Astronomy (ACIGA). Secondly, we realised that -0.8 dB would not be good enough! We needed systems with much higher non-linearities and much lower losses to produce larger squeezing – it would be another decade before the penny dropped and we realized we also needed audio frequencies.

To get the improvements started, Hans Bachor embarked on a sabbatical to learn about squeezing using second order non-linearities in crystals. He spent time with Byer at Stanford and Mlynek at Konstanz where they worked on squeezing using second harmonic generation (SHG), with cavity mirrors coated onto the crystal to form a monolithic bright squeezer [3].



Spectrum analyser 'M' arches from the Ba experiment. Any noise below shot noise (here -61.1 dB) is squeezed! (see also page 15)

The measured squeezing was again around 1 dB with 63% detection efficiency, but the idea had potential. In the meantime, David McClelland began research on control and signal extraction for GW detectors.

Hans was a native Hannovarian and former graduate student with Karsten Danzmann, and he brought back to ANU a special, pure SHG crystal made by Laser Zentrum Hannover in Germany. The ANU–German collaboration had begun in earnest. It was from this crystal that PhD students Matthew Taubman, Andrew White and Tim Ralph (Figure 2b overleaf), made the first Australian monolithic crystal squeezer [4], with up to -0.6 dB observed at 20 MHz.

The project profile

A more detailed analysis convinced us and others that the reverse of SHG, optical parametric oscillation (OPO), would be a much better process for producing large amounts of squeezing. Armed with some of the best crystals in the word and improvements in detection efficiencies (and some pretty good students – Ping Koy Lam

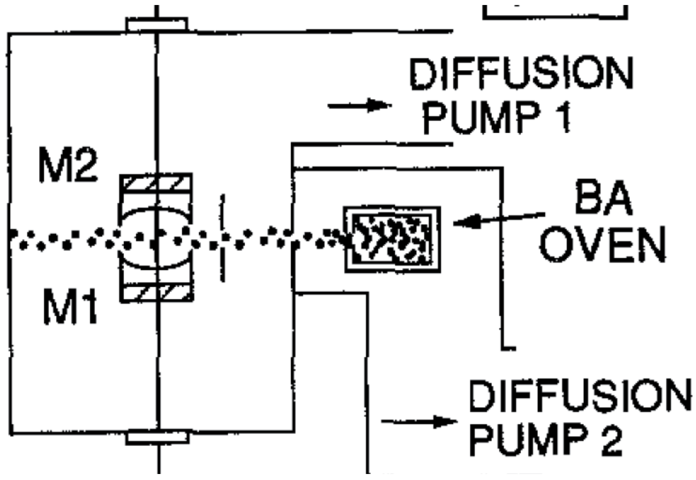


Figure 1: The layout of the barium beam optical experiment. Light from a ring dye laser (not shown) was conditioned and shone (from below) into an optical cavity through which a beam of barium atoms was passed. Barium is a nonlinear, bi-stable medium which squeezed the phase of the laser beam whilst making the amplitude noisier.

and Ben Buchler, and postdoc Gao), we claimed the then-world record for continuous-wave squeezing using a monolithic, singly resonant OPO, -7 dB measured in the MHz band [5]. Taking into account a propagation loss of 12%, the squeezing leaving the OPO was -10 dB.

The early 2000s saw the quantum optics world abuzz with teleportation following Kimble's work in setting the criterion. Key to teleporting a state with high fidelity are the size and purity of the squeezed sources [6]. The ANU quantum optics group was well positioned to make an impact, and Lam and Bachor, along with new PhD student Warwick Bowen, seized the opportunity. Roman Schnabel, a Feodor Lynen post-doctoral fellow from the plasma group at Hannover, also joined the team, keen to learn about teleportation (Figure 3). With Nicolas Treps, a PhD student from Claude Fabre's group in France, the group teleported a photon state with a fidelity of 0.64 [7]. From this beginning the ANU developed a thriving quantum communications group, hosting a node of the ARC Centre of Excellence in Quantum Computing and Communications and a start-up company [8], Quintessence Laboratories.

Schnabel's time at the ANU came to an end in 2002. Knowing that he and his family were returning to Hannover, the home of GEO600, he asked Hans Bachor and David McClelland for any suggestions. Both advised Schnabel to propose to Karsten Danzmann that he would build a quantum optics group for GEO, knowing it was an idea Danzmann would (and did) enthusiastically approve.

At about this time the gravitational-wave world, whilst not yet having brought initial LIGO to design sensitivity, was already looking to the next generation of detectors, when signal recycling would be used and the interferometers limited by quantum noise across the audio-frequency band. Suddenly the need for a squeezed source to enhance GW detectors was no longer decades away and we only had squeezing at MHz frequencies in our arsenal. It was time to focus.

It was 2003, the global financial crisis had not hit, no one had heard of 'The Big Bang Theory' or 'Twilight', and anything seemed possible, including 10 dB of squeezing at 10 Hz! McClelland, Lam (now ANU faculty), Nergis Mavalvala and Schnabel formed the '10 dB consortium' with that goal. Over the next 10 years these groups worked together to share ideas, equipment and students; source low loss, high nonlinearity crystals and high quantum efficiency photodiodes; and inject squeezing into gravitational wave detectors.

The first shot at lower frequency squeezing came from a joint effort by Hannover and ANU [9] which produced squeezing down to 220 kHz. The major breakthrough happened at ANU. One morning at tea in late 2003, McClelland, Lam and then graduate student Kirk McKenzie decided that the optical parametric amplification process should be producing squeezed vacuum from 0 Hz. Perhaps it was the environment around the squeezer that messed with the process? The decision was made to go into the lab, remove all optical fields that were not essential to the vacuum parametric process and see what happened. 'Captain' Kirk, who had previously demonstrated quantum enhancement of a Michelson interferometer at MHz frequencies [10], boldly headed for the lab with his trusted sidekick, 'Bones' Bowen. The rest is history.

Using a monolithic resonant squeezer and removing the control beam used for locking the squeeze angle, squeezing was seen down to a few kHz. By adding extra isolators between the homodyne and the squeezer and reducing other stray light as far as was possible in these early days, McKenzie observed squeezing down to a few Hundred Hz [11]. After sage advice from Stan 'Spock' Whitcomb and discussions with Mal 'Scotty' Gray (OK, enough of the Star Trek analogy), the quantum noise locking technique, which uses the phase dependence of squeezed quantum noise to lock the squeeze angle [14], was employed. Over the next few years, Schnabel and his team at the Albert Einstein Institute introduced a clever coherent control locking scheme [13], and superbly engineered the

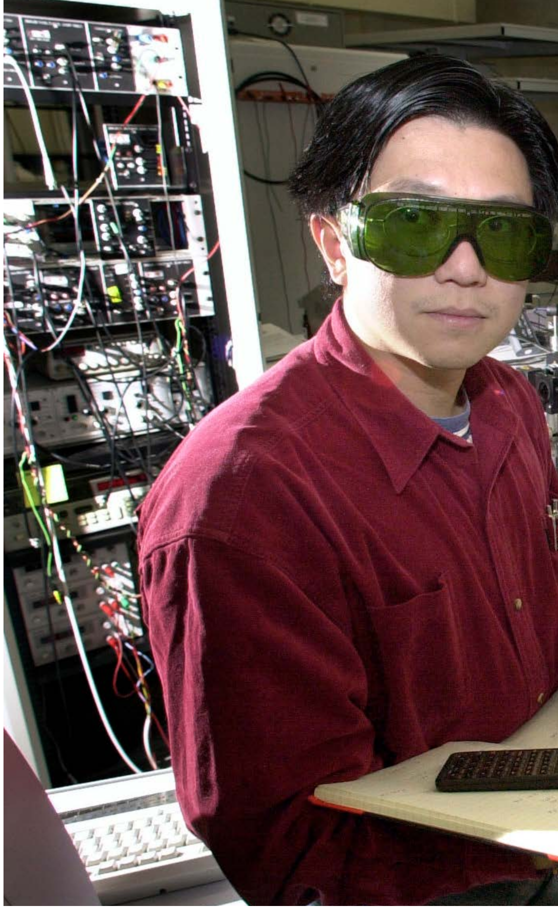
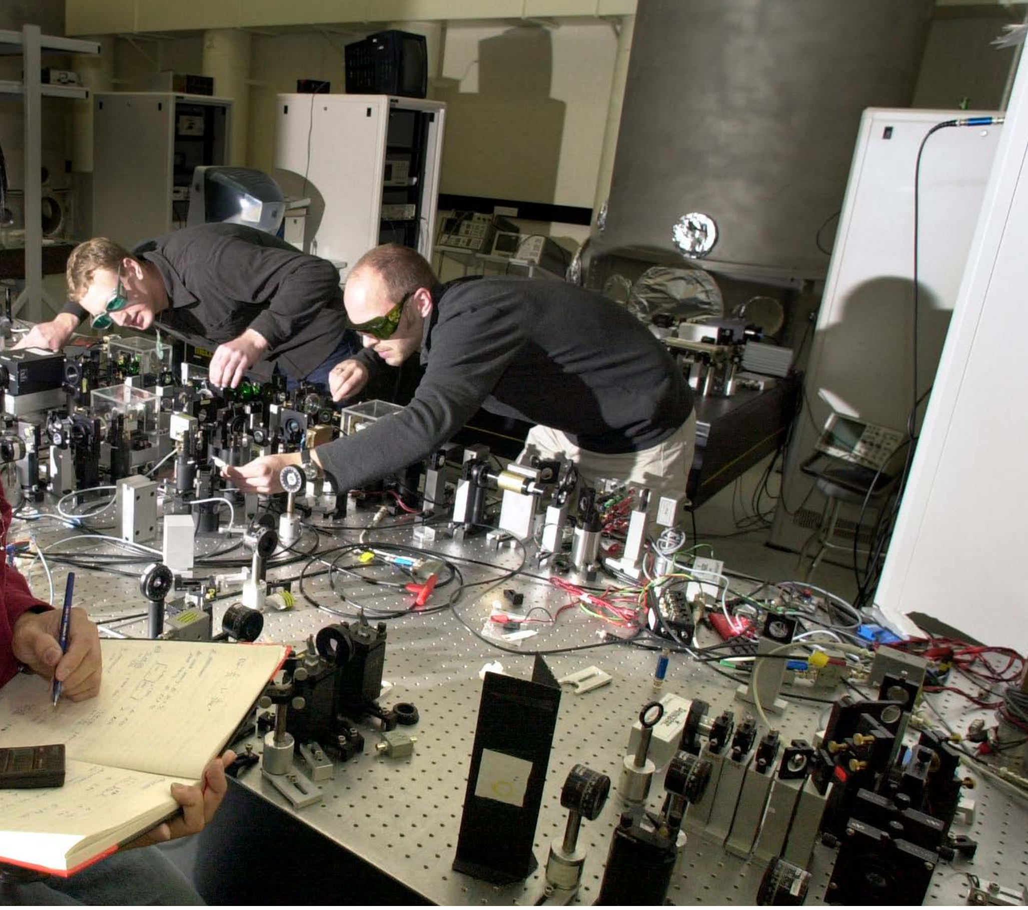


Figure 2 :

The ANU Quantum "Swedish Pop band" celebrating their success. From left to right: David McClelland, Peter Manson, Deborah Hope and Hans Bachor.

Figure 2b (far right):

The new "Swedish Pop band" trying to emulate their supervisors. From left to right: Wiseman, White and Taubman with the SHG.



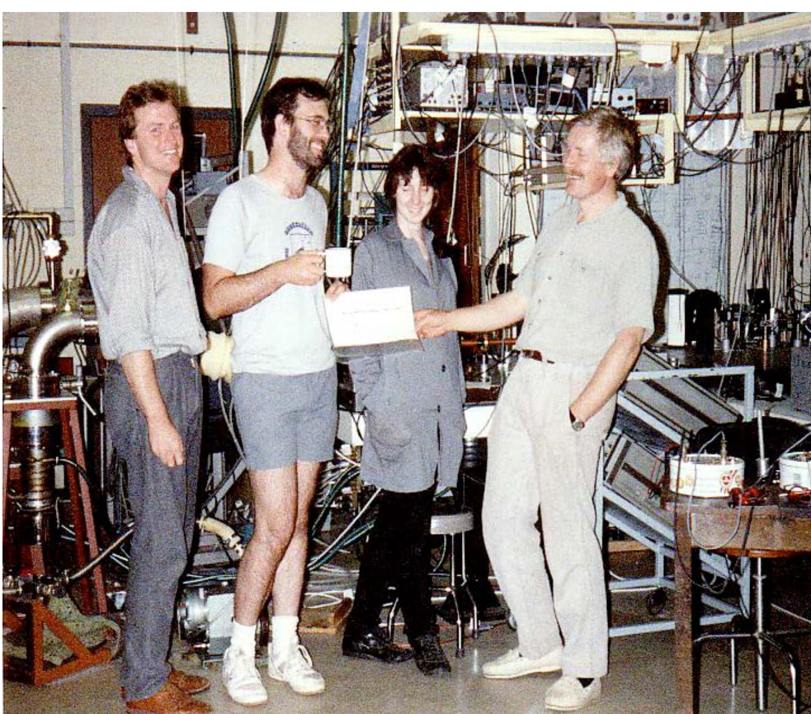
What is a **dB?**

A decibel (dB) is a unit describing a ratio of powers or signal levels. The formula is $[db] = 20 \log_{10} [\text{amplitude ratio}]$, or $[\text{amplitude ratio}] = 10^{([dB]/20)}$. So if we say that "the noise went down by 6 dB," we mean that it improved to about half its old value, since $10^{(-6/20)} \approx 0.5$.

Figure 3: 'DJ' Ping Koy Lam makes the play list whilst Warwick Bowen and Roman Schnabel setup the optics for the teleporter.

singly resonant linear system to produce more than 9 dB across the audio frequency band from 10 Hz, a squeezer that is now integrated into GEO600 [14,15] (see p. 18). At the ANU, we decided to go down another path. Knowing that the squeezer would be coupled to an interferometer, and given issues with stray light affecting the performance of both the squeezer and the interferometer, we opted for a bow-tie travelling wave squeezer, doubly resonant at both the pump frequency (532nm) and the squeezing frequency (1064nm). The bow-tie design gives immunity against backscattered light [16], and 6 dB squeezing at 100 Hz was quickly reached [17]. MIT dispatched graduate students Keisuke Goda (2004) and Sheila Dwyer (2008) to ANU to learn the art of squeezing.

LIGO elected to demonstrate the bow-tie system in a quantum enhancement of the H1 (4km) interferometer at Hanford. This demonstration experiment was jointly led by MIT and ANU, and all three '10 dB consortium' groups deployed graduate students to the site – Sheon Chua, Michael Stefszky and Conor Mow-Lowry from ANU, Sheila from MIT, and Alexander Khalaidovski from AEI. The experiment was an outstanding success and the results have recently been published in Nature Photonics [18] (see p. 12).



By mid-2011, however, we had not yet observed -10 dB at 10 Hz at ANU. Michael and Sheon were resolute in their efforts (Fig. 4, Fig. 4b). Corbitt from LSU pondered whether artifacts in the spectrum were caused by kangaroos hopping (Fig. 7 overleaf). Archie Wheeler, an undergraduate visitor from Andrews University, was just 'EMUsed' by the whole idea. (Fig. 6 overleaf).

Finally, in late 2011, ten years after the 10 dB consortium was formed, -10 dB squeezing from 10 Hz was measured, with -11.6 dB from 100 Hz [19]. After correcting for propagation loss and phase noise, this corresponds to 17 dB of squeezing available after the OPO.

The audio band squeezers have been such a success that a -10 dB squeezer is a certainty for installation as an early upgrade on advanced detectors. The Einstein Telescope and Third Generation LIGO include squeezed state injection in all of their design variations. Our near-term focus now is to do the hard work needed to enable the injection of squeezed light into Advanced LIGO. For Advanced LIGO we need to reduce total losses to less than 10%, and we need to be able to control the squeezing ellipse as a function of detection frequency to optimise the signal-to-noise.

But we still dream. We dream of -20 dB squeezing, quantum non-demolition and speed meters, of quantum opto-mechanical noise manipulation, human-scale mechanics in quantum ground states, and – who knows – maybe even teleportation of that state from one GW detector to another.

Acknowledgements

I count myself so lucky that I have been able to spend 20 years doing what I love whilst working with such a great bunch of colleagues and students. Many from my quantum research have been mentioned here; many from other areas who are equally important have not, yet. In particular: Daniel Shaddock who is always a source of ideas and solutions and a great leader in his own right; Andrew Wade, "Dr LIGO ANU" Bram Slagmolen; sensor(tive) man Jong Chow; Ben Sheard who now graces AEI; the "deVine" Dr. Glenn at JPL; Adam Mullavey, Daaf Rabeling, Danielle Wuchenich, Timothy Lam, Thanh Nguyen, Andrew Sutton, Elanor Huntington, Charles Harb, John Miller, Robert Ward and the list goes on.

This year I accepted on your behalf, my share of the American Physical Society Joseph F Keithley Award for Advances in Measurement Science. Let's celebrate in the traditional way (Figure 5)!

Figure 5: David piping with Bram, Conor and Daaf.

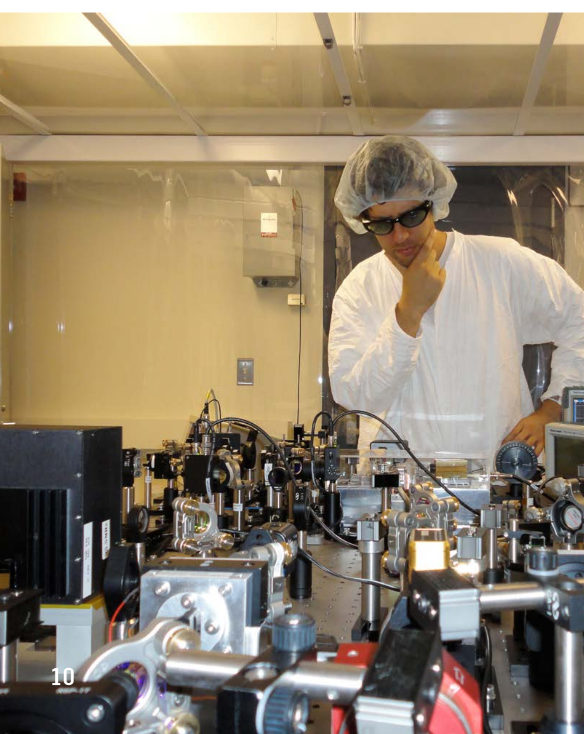


Figure 4 (on the left):

Michael in deep thought.

Figure 4b (on the right):

Sheon's glowing approval of squeezing.

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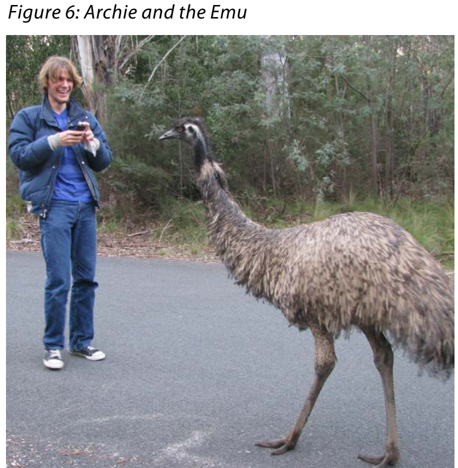
Figure 6: Archie and the Emu



Glossary of terms

Four-wave mixing: the interaction of 3 optical fields in a nonlinear medium to generate a fourth optical field.

Optical losses: removal of photons from a laser beam by absorption or scattering.

Optical bi-stability: two stable output states for a given input state.

Second order nonlinearity: a medium whose optical response is proportional to the square of the amplitude of the input.

Second harmonic generation (SHG): an input beam of frequency f interacts with a second order nonlinear medium to generate a new field at frequency 2f.

Monolithic squeezer: reflective coatings are deposited directly onto the faces of the nonlinear crystal to produce a squeezer made from a single optical element.

Singly resonant: when photons of a given frequency bounce around in an optical cavity so that they add in phase with new photons entering the cavity.

Doubly resonant: a system configured to enable 2 laser fields at different frequencies to build up in the same optical cavity.

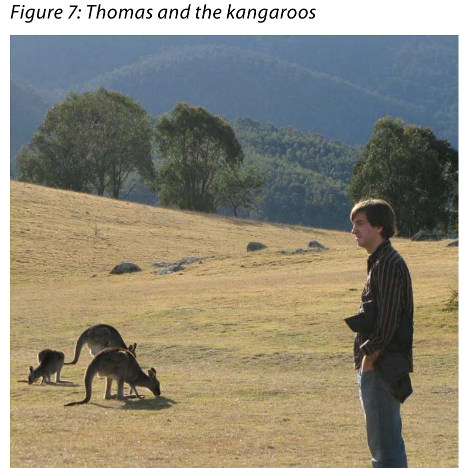
Optical parametric oscillation (OPO): the inverse of second harmonic generation. An input beam at frequency f interacts in with a second order nonlinear system to generate a new field at half the 'pump frequency'.

Teleportation fidelity: a measure of the "closeness" of two quantum states.

Bow-tie: a cavity in which the path light takes around the cavity resembles the shape of a bow tie.

Travelling wave: a light beam which never reflects back on itself.

Figure 7: Thomas and the kangaroos



H1 Squeezing Experiment at LIGO

Sheila Dwyer

is now a postdoc working on interferometer sensing and control at LIGO's Hanford Observatory. In the summer she gets away from the heat at Hanford by going to the mountains.

Lisa Barsotti

is a Research Scientist at MIT working on Advanced LIGO instrument science. She uses the airline miles earned flying between MIT and the LIGO sites to vacation in exotic locations. The H1 squeezing experiment took her to Chile, Bolivia and Peru!

The H1 Squeezing experiment began in a very humble way at MIT. We used a small crowded cleanroom, a laser leftover from initial LIGO with a temperamental chiller, and whatever optics we could find around the lab. We eventually got things working in a somewhat reliable way: Lisa Barsotti obtained super-polished optics through heroic efforts, Daniel Sigg brought nice new electronics from Hanford, we got a more reliable chiller, and we finally built something we could call a squeezer. The first time that we saw locked squeezing on our diagnostic homodyne detector was rather exciting for me. We first measured the shot noise, the level of noise when the squeezed beam entering the homodyne detector is blocked and only the local oscillator enters. As I normally expect, the level of noise increased when we sent a beam into the detector. As we tuned the squeezing angle, the level of noise slowly decreased until it reached the shot noise level, then amazingly dropped below. Even though we had been planning on this for years, and I had seen plots in many papers and even witnessed this myself in the lab at ANU, I was somehow still a little surprised that it actually worked. We had produced a beam with less noise than the vacuum fluctuations; in a sense we had produced something with less noise than nothing at all. The squeezer still had a lot of room for improvement at this point. In those first few days Michael Stefszky (from ANU) and I tried to stand very still while making measurements to avoid creating air currents.By the time we

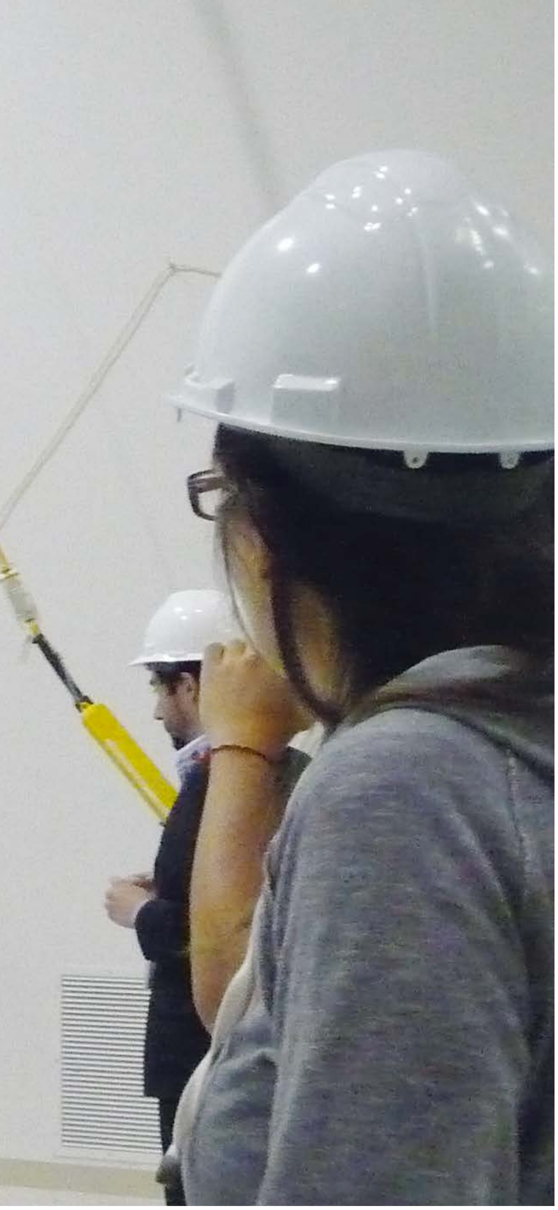


Figure 1: After triple checking that everything was securely bolted down, the squeezer team watches anxiously as the Apollo crew lifts the table off the ground for its journey from a temporary optics lab in the corner to its final position at the interferometer anti-symmetric port.

Nergis Mavalvala

is a professor of physics at the Massachusetts Institute of Technology (MIT) in Cambridge.

installed the squeezer at Hanford measuring squeezing was simply a matter of pushing a button from the control room on an extremely slick MEDM screen designed by Max Factorovich.

Soon enough in October 2010 it was time to document every last thing on the table, and take it all apart! With help from Conor Mow-Lowry (from ANU) we un-mounted all 115 of our optics and their mounts, disconnected and bundled up all of our cables, and packed everything into 42 boxes to ship across the continent to Hanford. There we reconstructed the squeezer, joined by Alexander Khalaidovski (AEI) and later Sheon Chua (ANU). As we worked on recovering the performance we had at MIT, improving the stability and automating some parts of the squeezer, we anxiously watched the Advanced LIGO schedule. We were hoping to run a parasitic experiment, to inject squeezing into the enhanced LIGO interferometer (H1) while decommissioning of the H2 interferometer and installation of Advanced LIGO began. Of course Advanced LIGO was the highest priority on site, and schedule delays or changes threatened to shorten the time available for a squeezing experiment or even to take us out of the schedule completely. Thanks to careful coordination by the installation team we were able to work with the corner Michelson while Advanced LIGO work was taking place on the arms in the early summer of 2011. We once again moved the squeezer, not as far this time but still nerve wracking as we watched the squeezer lifted high in the air and craned into place at the anti-symmetric port. The Apollo crew delivered it safely to its new home, and we were able to install the in-vacuum parts needed to inject squeezing. We saw some small amount of squeezing (0.75 dB!) for the first time in LIGO with a short Michelson interferometer. The Michelson was not shot-noise limited, but working with it allowed us to work on our control scheme in the interferometer, begin to figure out how to align and mode match our squeezer to the interferometer, and most importantly, realize that the losses were much higher than we had expected them to be.

It turned out that the output mode cleaner (OMC) losses were much higher than expected, almost 40%. This would limit the amount of squeezing we could observe to around 1 dB, once other losses were taken into account. The difficult decision was made to try swapping the OMC with the Livingston one, which would allow us to measure more squeezing but could also cause delays putting our narrow window of opportunity in the Advanced LIGO installation schedule at risk.

The installation team was able to fit in a window of time for squeezing in late September, before we had a chance to replace the OMC. The first part of the window was used to recover the interferometer to a reasonably good sensitivity, and on October 3rd we got to inject squeezing into the full interferometer for the first time. We were really making the sensitivity worse, but in a “quantum” way... One would have

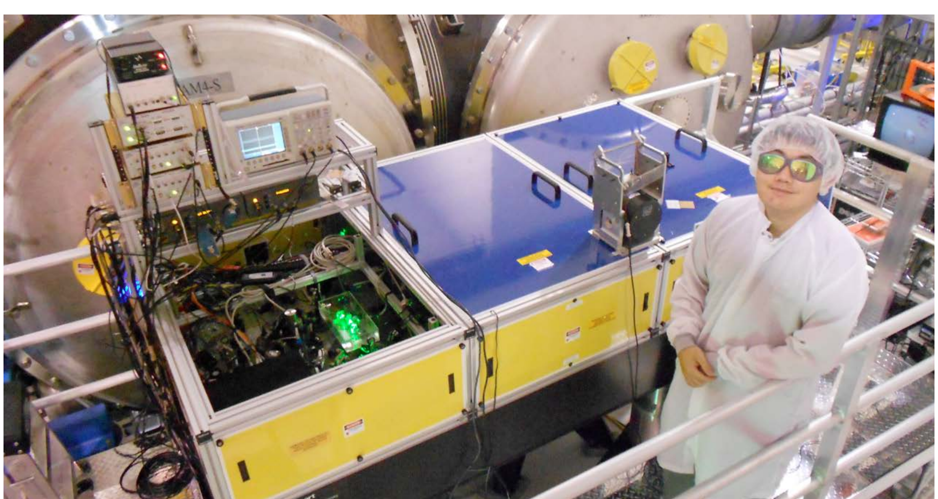


Figure 2: Sheon Chua prepares to use the shaker sitting on top of the squeezer enclosure directly to his right, to move the entire squeezer table and so measure the coupling of squeezer table motion to the interferometer noise.

never imagined that making the sensitivity worse could be so exciting! After a few nights of working we were able to see a tiny improvement in the sensitivity. At first the improvement was so small that we had to look at the band limited RMS noise at shot noise limited frequencies to convince ourselves that we had any improvement at all. We used the rest of the time available in that window to do some measurements of backscatter from the squeezer (which did not depend critically on the losses), iron out some wrinkles in our lock of the squeezer to the interferometer, and work more on the mode matching. By the end of that window we could measure just barely more than 1 dB of squeezing.

Thankfully, the Livingston output mode cleaner was shipped to Hanford, and in late October a group of experts, including Nic Smith-Lefebvre, Keita Kawabe and Mike Landry, converged to help us swap out the mode cleaners, giving us a chance to measure a more respectable level of squeezing. With a second window in late November and early December we hoped to demonstrate that squeezing can really improve the interferometer's sensitivity. Every evening after installation activities ended for the day, we would begin work. Keita Kawabe projected a plot of the best sensitivity measured during S6 in the control room, challenging us to beat it. There were several times that everything seemed perfectly set up, and we thought this would be the night. Over Thanksgiving we had the whole weekend to ourselves, but a large storm in the Pacific Ocean caused microseism so high that the interferometer wouldn't stay locked. There were a few nights when we were doing quite well until, right around 11 pm, we would see the higher frequency seismic noise skyrocket for about an half hour, then fall and rise repeatedly until about 3 am. This turned out to be heavy trucks transporting contaminated soil from one part of the Hanford nuclear reservation to another, passing a few hundred meters from the X end station. Unfortunately the best times for interferometry, when there is not much traffic and the wind is low, are also the best times to transport contaminated material without exposing the public. We learned to take naps when the trucks started, and set alarms for 3:30 am to get a few more hours in before installation work started at 8 am. Finally, there were several nights when everything seemed to work, we saw that we could improve the sensitivity beyond the best measured during S6 without introducing noise to the spectrum anywhere, and we could see 2 dB of squeezing.

Figure 3: Lisa Barsotti and Sheila Dwyer relax with the squeezer safely installed in its home near the anti-symmetric port. The enclosure around the squeezer prevented dust from getting on the squeezer during the experiment when it could not be inside of a cleanroom because of space constraints.

After demonstrating that we could improve the sensitivity, we wanted to understand the level of squeezing angle fluctuations in the interferometer. The interaction of our squeezer with the interferometer was increasing the level of fluctuations. We finally understood that this was due to lock point errors in our control scheme at low frequencies, but didn't have any idea what was causing that. One night Lisa Barsotti adjusted the interferometer alignment slightly while squeezing was injected. A few minutes later we noticed that our squeezing had degraded, and Sheon Chua changed the lock point of the squeezing angle control loop to recover the squeezing. We were all sleepy, and it took several moments for anyone to realize that we had just found the cause of our lock point error! We saw that we could reduce the squeezing angle fluctuations by fine tuning the interferometer alignment, which gave us the possibility of measuring more squeezing, if we could improve our mode matching. By this time it was our last night of squeezing, and very late. When the morning came, and the installation team was ready to start taking the H1 laser down, I was ready to accept that what we had done was actually good enough: we had understood backscatter, our loss budget, and our squeezing angle fluctuations, we had measured better high frequency sensitivity than during S6. Better mode matching would have to be left until next time. We walked around the instrument floor, transitioning the area to laser safe conditions so that the installation team could start their work, and saying a fond good-bye to H1. Results from the H1 squeezer experiment appeared in Nature Photonics on the 21st of July 2013 [1].

[1] J. Aasi et al. `Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light', Nature Photonics 7, 613–619 (2013)

Know your squeezing

by David McClelland (see article pages 6-11)

A squeezed introduction to squeezed states

A famous concept from Quantum Mechanics is the Heisenberg Uncertainty Principle (HUP): for two non-commuting observables, it is not possible to accurately measure both observables at the same time. From Quantum Optics formalism, a light beam's phase (f, or the arrival time of photons) and amplitude (A, or the number of photons) obey such an Uncertainty relation, that is:

$$(DA)(Df) \geq 1$$

This uncertainty can be visualised using the 'Ball on Stick' diagram, the combination of a classical phasor and quantum ball of noise. The coherent state is the state produced by an ideal laser, and is well represented by a real world laser. Even with no coherent light beam present, there must be quantum noise (or else the HUP is violated). Even nothing is noisy. This null state is named the vacuum state, a special case of the coherent state (the coherent beam "stick" is zero), and is present where there is no other occupying quantum light state.

However, the inequality is multiplicative. This means that an uncertainty component can be below the lower limit, or squeezed, if the other uncertainty component is above the limit or antisqueezed, provided that the Uncertainty relation is maintained. An example noise power trace is shown in A2.

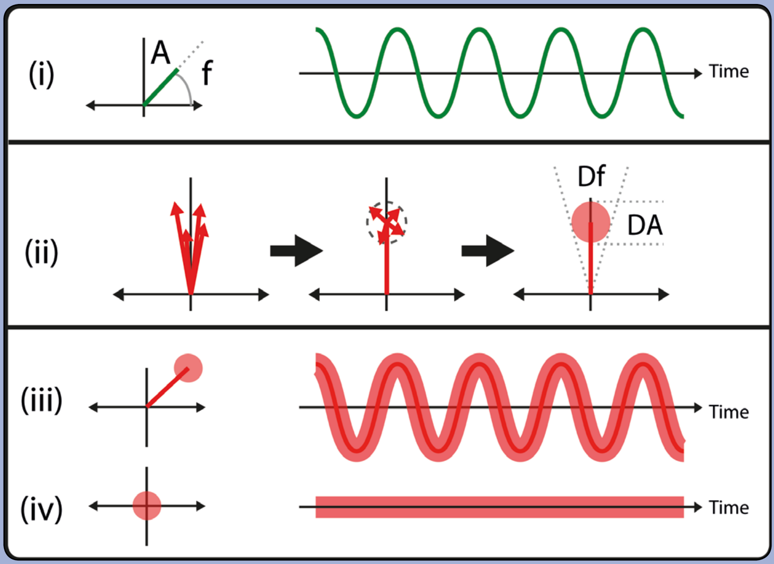
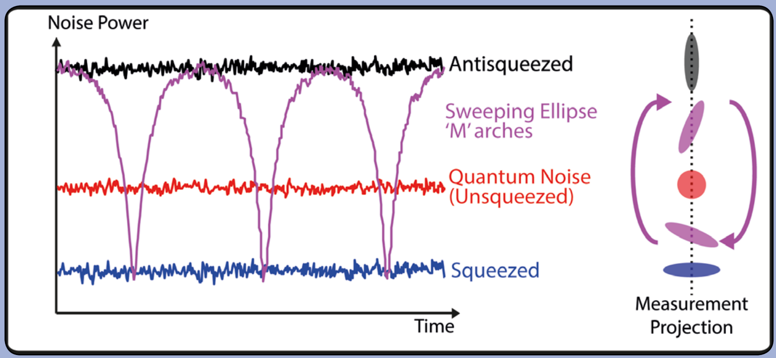
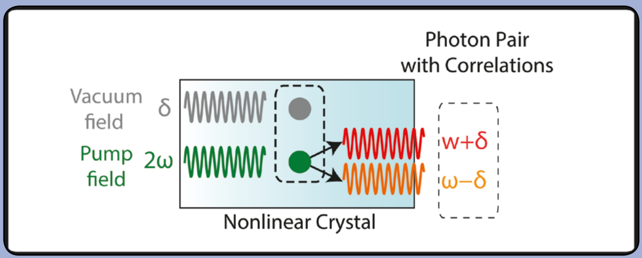


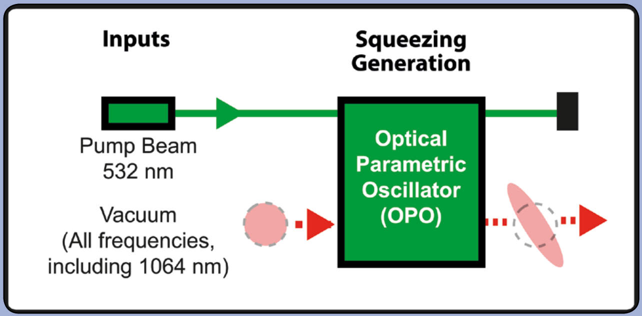
Figure A1: (i) Classical Phasor diagram, with precise amplitude and phase. (ii) Uncertainty in amplitude and phase (many phasors), combined to represented by a classical phasor and quantum ball of noise, the 'Ball on Stick' Diagram. (iii) Pictures of a Coherent state and (iv) Vacuum state.



A2: Noise Power measured at a single detection frequency versus time. Different colouring to distinguish between measurement projections of the same squeezed state.



B1: A cartoon view of squeezed vacuum state generation.



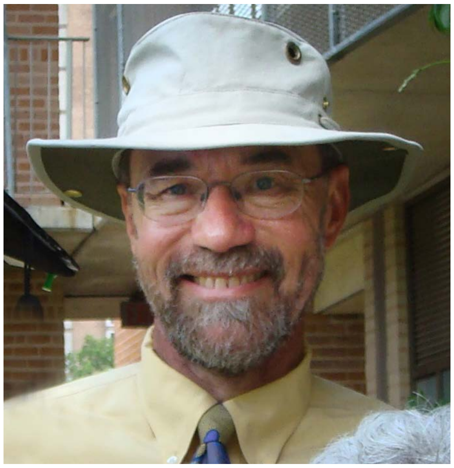
B2: Simplified schematic of squeezed state generation at 1064 nm

Generating squeezed states

A cartoon view of the nonlinear optical process used to produce squeezed states is shown in B1. The nonlinear process is driven by the Pump beam, and is seeded with vacuum state. The process causes a very small number of pump photons to down-convert to photon pairs with correlated noise properties. These photons with correlations give squeezing.

To generate squeezed states, a simplified schematic is shown in B2. The squeezed state is generated using an Optical Parametric Oscillator (OPO), whose nonlinear process is driven by the Pump beam. The incoming vacuum field at 1064nm can now be converted to a squeezed field (with a very small number of photon pairs).

Realizing Squeezing: An interview with Carlton Caves



Carlton Caves

Carlton Caves is a Distinguished Professor at the University of New Mexico and Director of the Center for Quantum Information and Control. His 1981 paper in Physical Review D titled "Quantum-mechanical noise in an interferometer" set the stage for the use of squeezed states of light to reduce quantum noise in gravitational wave detectors, an idea now coming to fruition.

Mike Landry: How did you come up with this description of shot noise in an interferometer? What were you thinking?! And how did you first recognize that you had to study the fields entering the anti-symmetric input port?

Carlton Caves: I started thinking about these questions because of a "lively, but unpublished controversy" regarding the origin of the anti-correlated radiation-pressure fluctuations in an interferometer. These anti-correlated radiation-pressure fluctuations are the back action that drives fluctuations in the differential position of the end mirrors and thus, together with the shot noise, gives rise to the standard quantum limit for determining the differential position.

From today's perspective, it is hard to see how there could be any controversy at all, but the thinking at the time was this: The only active thing around is the laser that powers the interferometer. Its fluctuations must give rise to the differential radiation-pressure fluctuations. But how could that be since the laser's fluctuations divide equally at the input beamsplitter and thus lead to common-mode fluctuations in the two arms? This is a good example of asking a question the wrong way so as to make it a puzzle.

The question is asked from a wave perspective, and the answer is obvious if one switches to a particle perspective: Each laser photon divides equally at the beamsplitter, but since a photon can't be split, the division produces anti-correlated photon-number fluctuations in the two arms regardless of the laser's photon statistics. This explanation is entirely correct, but I wasn't satisfied because it didn't address the wave perspective. So I worked that out, too, and found that an equivalent explanation of the anti-correlated radiation-pressure fluctuations is that they are due to interference of the laser light with vacuum fluctuations entering the interferometer's antisymmetric port.

The paper describing this was published in PRL with an admirably brash abstract (I was a Techer after all): "*The interferometers now being developed to detect gravitational waves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do." [1]*

This PRL is a good example of why physicists are really obliged to give every explanation they can think of. The particle perspective, though intuitive and right, is sterile. The less intuitive wave perspective is the royal road to realizing that squeezing can be used to reduce shot noise at the output of an interferometer. The mystery is why this wasn't completely obvious the moment vacuum fluctuations in the antisymmetric port were invoked to enforce quantum limits. The answer for me was that I hadn't realized that only one quadrature of the vacuum fluctuations – the quadrature that is in phase with the laser light in the two arms – is implicated in the radiation-pressure fluctuations. Once this is realized, it is more or less obvious that the conjugate quadrature of the vacuum fluctuations – the quadrature that is out of phase with the laser light – must be responsible for the shot noise. Squeezing the noise in that quadrature will thus reduce the interferometer's shot noise.

I got to this realization because Kip Thorne, Ron Drever, Vern Sandberg, Mark Zimmermann and I were involved at that time in our work on back-action-evading, quantum nondemolition (QND) measurements of the quadrature components of a mechanical oscillator. Ron badgered me repeatedly, "Carl, there must be some way to use these QND ideas in an interferometer." I would assure him that, no, those ideas applied to a mechanical oscillator, whereas the end mirrors in an interferometer were essentially free masses. Anyone who has ever worked with Ron knows that this wouldn't faze him in the least – his pestering continued unabated – and I eventually realized that the quadratures to think about were those of the light field, not the mechanical system. That's what led to my 1981 paper , which ends with the sentence (Star Trek had taught me that sometimes you have to split an infinitive):

"Experimenters might then be forced to learn how to very gently squeeze the vacuum before it can contaminate the light in their interferometers." [2]

And so they have.

M: How long did it take until the community accepted your findings? Were there any reservations?

C: This is an interesting question. In the quantum-optics literature, there were treatments of light after a beamsplitter that were clearly wrong because they had one input mode splitting into two output modes. It's hard now to see how anyone could think this – you didn't preserve commutators and thus weren't consistent with unitarity. Using two input modes was manifestly the right thing to do, and it made clear that what happens in an interferometer depends on the quantum state of the light in both input modes. So the acceptance in the quantum-optics community was very quick. Even though none of the quantum opticians had ever heard of me – I came from a relativity background – I never heard anybody question the correctness of the idea of using squeezed light.

M: In the mid-80's, within a few years of your proposal to use squeezed states, proof of principle experiments were done (for example, Slusher et al. *[3]* , Xiao et al. *[4]*). Important as they were, those experiments showed very modest levels of squeezing (in the ~1 dB range). Were those early demonstrations disheartening or did they give hope that there would be sufficient progress to make squeezed light useful in interferometers?

C: Those were heroic efforts, but indeed the improvements beyond shot noise were pathetically small. They did make it seem unlikely that interferometric gravitational-wave detectors – or any other real-world interferometer for that matter – would ever use squeezing. Not only was the squeezing small, it was also at the wrong frequencies for gravitational-wave detection, so it looked like an incredibly daunting task to make squeezing useful. Luckily, there were experimenters, some explicitly encouraged by participating in the LIGO Collaboration, who went at it for the requisite 25 years to get the job done. Perhaps their attitude was the sensible one that the whole job of building LIGO-style interferometers looks so hard that they might get the squeezing ready before any gravity waves were detected. And so they have.

M: What do you think of recent developments in the GEO600 and LIGO interferometers, in which squeezed vacuum states have been shown to reduce noise in the detectors?

C: What do I think? Well, that invites me to ramble a bit.

Technical: These are spectacular achievements, the result of work by scientists at several institutions around the world to make the advances so that we now have 10-dB squeezing at kHz frequencies and below and by the GEO 600 and LIGO scientists and engineers to incorporate the squeezing sources into the existing real-world detectors. The whole thing works like a charm, as far as I can tell from the publications. That's a compliment to the teams who have made it work like a charm, not a minimization of the magic required to get the charm working.

Scientific: What an achievement it will be when Advanced LIGO starts popping off with detections. A lot of people are counting on that. And it will be icing on the cake if squeezing is part of that success story, making it the only nonclassical-light effect ever put to use in real metrology.

Personal: Ideas are important, and they don't come along very often. Most of us spend most of our time working on things that in the end don't go very far. For my own part, I work on things not to produce concepts or ideas that are practical, but because I want to understand something that I don't understand. That's why I worked on quantum limits in gravitational-wave detectors. It is both sobering and personally satisfying that an idea produced this way has motivated hundreds of people working over 30 years to reduce the idea to practice.

M: We always struggle to explain to non-experts how squeezed light can be used to reduce quantum noise in an interferometer. Have you found a way to do that in simple words?

C: There are certainly ways to explain it that make it seem very improbable. A few photons into the normally unused antisymmetric input port are going to reduce the noise associated with the 10 to the umpty-ump photons from the laser that powers the interferometer? Fat chance. When stated this way, even I think the whole thing seems pretty improbable.

The point is that the fluctuations entering the antisymmetric port are promoted into importance by interference with the laser light. So I think the best explanation is roughly the one I came up with 30 years ago, perhaps made simpler by the passage of time.

You think in terms of classical electromagnetic waves and of the shot noise as due to quantum fluctuations on top of classical fields. Then the explanation goes like this. An interferometer is a device for converting the differential phase shift between the two arms into a detectable change in photon counts at the interferometer's output. To conserve energy, a small fluctuation entering the antisymmetric port that increases the power in one arm must decrease the power in the other arm; that is, the anti-correlated power fluctuations in the two arms are due to the quadrature entering the antisymmetric port that is in phase with the laser light. The same holds true for the conjugate quadrature entering the antisymmetric port. It produces anti-correlated phase fluctuations in the two arms, and that has to be what produces the fundamental limits on detecting a differential phase shift.

M: You're now focused on the physics of information. Can you tell us in the gravitational wave community what you mean by that, and about what else you are working on now?

C: Most of the physics of information is now what is called quantum information science, a field where we explore how to make quantum systems do jobs we want done instead of what comes naturally. You could say that LIGO, when pushed to quantum limits, is a terrific example of engineering macroscopic quantum systems to do what we want, in this case to provide information about tiny differential phase shifts induced by passing gravitational waves. Indeed, much of the investigation of quantum limits on detecting classical parameters – the differential phase shift is an example of such a parameter – has been subsumed by quantum information science and is now called quantum metrology.

Here's an example of some very recent work on quantum metrology in my research group at the University of New Mexico. My student Matthias Lang and I have considered an interferometer powered by laser light into the primary input port, modeled as coherent-state light, and light in an arbitrary quantum state into the secondary input port. With a mean photon-number constraint on the light into the secondary port, we have shown that the sensitivity to differential phase shifts is rigorously limited by something called the Quantum Cramer-Rao Bound and that the optimal state to put into the secondary port is squeezed vacuum. It's odd that this real-world practical question of the ultimate quantum limit on phase sensitivity has never been rigorously addressed, but it's good to know that squeezed vacuum is the answer.

Interview by Michael Landry

[1] C. M. Caves, PRL 45, 75 (1980)

[2] C. M. Caves, PRD 23, 1693 (1981)

[3] Slusher, R.E. et al., Phys. Rev. Lett. **55,** 2409-2412 (1985)

[4] Xiao, M. et al., Phys. Rev. Lett. **59**, 278-281 (1987)

A Squeezed Light Source

An interview with Roman Schnabel and Henning Vahlbruch

Roman Schnabel *Henning Vahlbruch*

Roman Schnabel is Professor at the Leibniz Universität Hannover. During his free he likes to ski or play squash.

Henning Vahlbruch is a post-doc working on squeezed-light generation and squeezing implementation at GEO 600, AEI Hannover. In his free time he may refer to himself as a "guitar nerd".

Tobin Fricke: How did you get involved in squeezed light?

Roman Schnabel: I was just finishing my PhD thesis in laser spectroscopy on plasmas and thinking about what to do next. I was sure I wanted to change my field. This was in late 1998. At the same time there were two teleportation experiments reported, by Jeff Kimble using squeezed beams, and by Anton Zeilinger who was counting photons. I had no idea what was going on in those experiments, but was fascinated and thought "teleportation is what I definitely want to understand."

Hans Bachor told me in 1999 that he would do a teleportation experiment in Australia and I thought "I really would like to join this group!" I won an Alexander von Humboldt fellowship with Hans being my host and went to Australia together with my family – my wife and my eight-months-old daughter – in September 2000.

T: How was your time in Australia?

RS: Great! The group led by Hans and Ping Koy Lam gave me a great introduction to quantum optics. We made quite a few publications and in the end even the teleportation experiment worked. When I went to Australia, in fact, I had no idea where squeezed light could be useful – well, apart from teleportation. Rather late I realized that for gravitational wave detection there is an application. Hans Bachor and David McClelland introduced me to Caves' paper, just a few weeks before I left.

When I came back to Hannover after one and a half years, I was unemployed for three months. In this period I wrote a grant proposal with the goal to set up a squeezed-light source that in principle (after a lot of R&D!) would be able to improve gravitational wave detectors. Based on this (not yet granted) proposal Karsten Danzmann gave me the chance to build up a group at the AEI.

When you start a new group you obviously have a problem: you need to find people being brave enough to jump into unknown waters. I was quite lucky to find 3 people at the same time. Simon Chelkowski started as a PhD student. Alexander Franzen and Henning started as diploma students. One year later, Boris Hage joined the group. The group quickly grew more and more. Basically my full group worked on squeezed light generation.

T: Did you have in mind from the beginning injecting squeezed light into GEO?

RS: That was the far goal, definitely, from the very beginning. It seemed very far away. We dreamed of getting 10 dB of squeezing down to 10 Hertz – in 10 years of R&D. Honestly, none of us believed in 2003 that this would be possible. Our first publication, in fact, was the demonstration of up to 3 dB of squeezing at sideband frequencies down to 80 kHz. The progress we made was step by step. In 2006 new nonlinear crystals with higher homogeneity and low-loss coatings enabled us to measure 6 dB at MHz frequencies. In 2007 the group led by Akira Furusawa in Tokyo had published a new record value of 9 dB. Just half a year later we reached a similarly high noise reduction.

T: Did you feel like you were catching up?

Henning Vahlbruch: Indeed, and we wanted to see the 10 dB first. Together with Moritz Mehmet I worked hard to get this result. We reduced optical losses as much as possible and also paid attention to phase noise. Eventually, we indeed saw the quantum noise dropping down to 10 dB below shot noise. After manual adjustments we repeatedly observed 10 dB for several hundreds of milliseconds before it usually then slightly degraded to about 9 dB.

T: For hundreds of milliseconds... at what frequency?

HV: At a few Megahertz. The time period was clearly limited by the unity gain of the "human servo". In parallel we had also developed a control system that we expected to enable us the observation of strong squeezing also at audio-band sideband frequencies.

T: When did you decide to build the GEO squeezer?

RS: This happened at the Amaldi conference in Sydney in 2007. At Sydney harbor, we were outside – just the people from GEO, maybe six of us, and I made this claim that we now have all the technology together – we need to combine it in order to build a squeezer for GEO!

We all realized the high potential, but it was not like everybody immediately said "Yes, now we do it", because nobody could really estimate how difficult it would be to integrate a squeezer to a complex interferometer system like GEO600. In the end, we made a decision: we were going to do this experiment. From that day on it was a clear goal to build a source that was not only another demonstrator (in the sense that something's still missing), but the plan was to build a device that can be used in observational runs.

T: The squeezer was built at the AEI and then transported to the GEO600 site?

HV: Yes, it was built by myself and Alexander Khalaidovski, in our clean room facility. Everything went rather smoothly. Transport to the GEO600 site was a one-day action. The squeezer was in a rigid case with 6 handles. The weight was 130 kg, so for 6 people basically an easy job. But then a tricky situation happened when we brought it into the cleaner part of GEO 600 where it had to go through a hole in the floor. We had two options, and we definitely took the wrong one.

T: What happened?

HV: The professional option was to use a crane to lift the lid of the hole in the floor. We thought it would be much faster to just do it by hand. When the squeezer was already in the lower floor, we had to bring back the lid into place quickly. The lid was square. So it could in principle fall down crashing into the squeezer. It was a very heavy lid! You certainly do not want to have your fingers "squeezed" between two metal edges. The people holding the lid removed their hands one by one. Don't be the last! Alexander was the last. For a couple of seconds, it looked like the lid would directly crash into the squeezer. But we got very lucky and the lid fell directly into place and stuck. This was very, very close to a full disaster!

T: How long was it before you observed squeezing at GEO600?

HV: We brought it out in April 2010. First we started with a lot of excess noise in GEO before we were able to detect squeezing. The first squeezing we observed at the end of June.

T: When was the celebration?

HV: The biggest celebration was, I think, when we got the acceptance from Nature Physics.

RS: Over the years – at least the two of us – we didn't have any doubt that the squeezer would work. So it was not like a relief "yeah it works!" But then, to see a high-quality manuscript come out of the research, to place it in a highly visible journal – great.

T: You said that the goal in 2003 was 10 dB at 10 hertz in 10 years....

RS: When you take the slogan it was just about the squeezed-light source itself. This was the GEO-squeezer, and this was basically finished in the end of 2009 – just 6 years!

T: Having achieved all this, what's next?

HV: To me it has been important to have the squeezer running for one year instead of just for minutes. This has been another major step. The interface between a kilometer-scale interferometer and a squeezed-light source is currently the interesting thing: mode-matching, phase-matching, influence of higher order modes, phase noise, auto-alignment systems. This will be work for the next couple of years. We have the chance at GEO600 to learn what's important to in order to get 6 or possibly even 10 dBs detected squeezing in a gravitational wave detector, learn what breaks after how many years, and gain experience with long term stability.

Interview by Tobin Fricke

LIGO 2013

GEO600 Astrowatch Mode

Hartmut Grote

Hartmut Grote leads the GEO600 team and researches whether the interferometer has its own will.

Since September 2011, when a joint Virgo-GEO600 science run was finished, GEO600 has been engaged in an Astrowatch program. While the LIGO and Virgo detectors pursue their respective advanced detector upgrade programs, GEO600 is the most sensitive, and the only interferometric, gravitational wave detector in operation. GEO is also undergoing an upgrade program (GEO-HF), however, unlike the other detectors, only rarely do the upgrades prevent us from taking science quality data outside of normal work hours.

Although we are insensitive to the frequent weak events that a multi-detector network usually searches for, we still have a small chance to observe rare loud events that may occur during this single detector era. To guide our search for gravitational waves, we rely on coincident detection with electromagnetic or astro-particle signals that indicate a source from which we would also expect gravitational waves. An example candidate from which GEO could observe gravitational waves is the red supergiant Betelgeuse. This star is quite close on the galactic scale (~600 light years from the earth), and is expected to explode in a type II supernova, perhaps within the next 100,000 years! If this star were to go supernova while GEO was observing, then this would be an ideal event for GEO to observe gravitational waves.

GEO is very stable and can operate with a high duty cycle, which is limited primarily by upgrade and commissioning work. Over the last two years, we have taken data in Astrowatch mode for about two thirds of the time. Running in Astrowatch mode requires extra care when making changes to the detector. At the end of each day the detector must be put into a stable state where it can be left unattended. Over weekends and holidays we ensure that at least one operator, post-doc, or graduate student is monitoring the state of the detector. This requires a bit of infrastructure, which allows us to monitor the detector status from home (or anywhere with internet access), or to be alerted by an automatic text message if something goes wrong. This works fine for about 80% of weekends, but sometimes someone has to go to the site to solve a problem. This means the person on duty cannot party as much as everyone else, but going shopping or having a walk is fine! A lot of effort has been put into making the re-locking procedure automatic. Even so, we lose around 1% of observation time due to situations where the detector loses lock, and is not able to automatically relock.

A lot of this work is performed by our operators, who not only make sure the detector is locked, but also look after the vac-

Left: Two of the GEO Operators and Engineers: Mark Brinkmann (left) and Michael Weinert (right), in front of the GEO operations corner. The large screen shows live images of laser beams in the locked GEO600 detector.

uum system, air-conditioning, computers needed for control and data-taking, and much more.

Since 2010 GEO has been running with injected squeezed vacuum, which is a novel technique to reduce noise at the higher side of the frequency band. We at GEO are testing the long-term stability of squeezing, its compatibility with the main detector, and trying to improve the amount of noise reduction it provides. So far the squeezing works well, and is applied to GEO for 90% of the time. But of course it's yet another subsystem of the detector that needs to be taken care of.

Over the coming years GEO will continue in this Astrowatch mode of operation while performing upgrades to improve the sensitivity. This will continue while the advanced LIGO and Virgo detectors come online, at which point they will be running with lower duty cycles during periods of intense commissioning. Therefore it will be important that GEO continues to operate with a high duty cycle during this period.

A Day in the Life of Astrowatch

I was reading the newspaper on a sunny Saturday afternoon when I got a message on my cell phone from a colleague: "Interesting GRB, please check your email." The very bright GRB 130427A had happened a few hours before, and the excitement was spilling from the gamma-ray burst community to the LIGO management. That weekend GEO was in a good mood. It locked on Friday evening and stayed that way until Monday morning when commissioning work started. I looked at the data and found some glitches in the few minutes around the gamma-ray burst time, but all of them were due to known issues with the squeezer error point and Michelson alignment. So we were in a good position to make a statement about gravitational waves. However, around that time the results from the 8 meter Gemini telescope on Hawaii came in: despite its brightness the burst of gamma rays came from 2 Gpc away, far beyond what we can hope to see with our detectors. An interesting afternoon in any case, and a proof that we would be ready if Betelgeuse decides to explode!

Michał Wąs

GEO and squeezer team happy after the transport of the squeezer to the GEO site in April 2010.

Squeezed light at GEO600

Resisting change is an important concept that goes a long way when running a gravitational-wave detector in data-taking mode. However, in 2007 we started to develop a first real plan of how to incorporate squeezing in GEO as part of the GEO-HF upgrade program. In frequent meetings from 2008 to 2010 we brought the AEI squeezing group and the GEO team together to discuss the implementation and technical solutions needed to make squeezing at GEO work. Besides trying audio-band squeezing in a suspended, signal-recycled km-scale interferometer for the first time, we also wanted to show that squeezing can be used as a permanent and reliable subsystem of a gravitational-wave detector. The first exciting 0.5 dB of GEO squeezing were then observed on 29 June 2010, a bit over two months after we had brought the squeezer to the site. A noise reduction of 3.5 dB was the record result by October 2010, as published in the Nature Physics paper (Nature Physics 7, 962–965, 2011).

It is easy to assume that something that worked once will work continuously, but it takes quite some work to get there. Besides lowering the shot noise of GEO by 3 dB, we now continue to demonstrate that squeezing can be applied over the long-term and does not increase the glitch rate of the main interferometer. The injection of squeezed light has thus qualified as a regular subsystem of a gravitational wave detector, a result we have reported recently (Phys. Rev. Lett. 110, 181101, 2013). As of today, 530 GEO lab-book entries document the work around the implementation of squeezing, its improvements, and the problems solved. With the GEO interferometer being in operation over the last several years, we had and have the chance to study the interface between a squeezed light source and a gravitational wave detector in detail. We could test a number of new control signals, control strategies, and automatic alignment, and we have made the squeezing automation seamlessly integrate with the automated locking of GEO. We recently understood that the GEO squeezing source has slightly degraded over the years of continuous operation. With several years of experience we believe that observing even better squeezing levels at GEO is a goal within reach. We continue!

H. Grote

Advanced LIGO Pre-Stabilized Laser Installation

The Advanced LIGO Pre-Stabilized Laser (PSL) consists of a 200W laser system, a pre-mode cleaner, a frequency stabilization servo and a power stabilization servo. This system was developed and manufactured in Hannover, Germany by the Laser Zentrum Hannover (LZH) and the Albert Einstein Institute (AEI). Three identical copies of the system were delivered to the Livingston and Hanford sites. Two are now operational, the third rests in storage at Hanford and a fourth Reference System remains operational at the AEI.

Final approval of the PSL design occurred in February 2010. By then the third iteration of the high power laser known as the engineering prototype including the prototype electronics for the stabilization loops had been installed at the AEI. LIGO's PSL requirements were quite challenging – a single-mode, single-frequency, continuous-wave laser beam at 1064nm with a stable output power of more than 150W. At the time these requirements were set, the power noise limit at the interferometer input of 2×10^{-9} $\mathrm{Hz}^{-1/2}$ at 10 Hz had never been demonstrated.

We faced significant additional challenges beyond the building of a very stable laser system. In Hannover the first full PSL required one year of continuous effort for assembly and installation. This duration was unacceptably large for the installations at

Christina Bogan

Christina Bogan is a postdoc at the AEI Hannover. She is currently working on phase noise measurements for the LISA mission.

the sites. We were required to switch from metric components on the laser table to their imperial counterparts, a very complicated circumstance given that all components inside the closed boxes remained metric and that imperial versions simply didn't exist for some items. A high level of care was necessary during the installations; only once or twice somebody tried to turn a metric screw into an imperial thread or vice versa. In order to coordinate the travel schedules of the PSL team, we needed to thoroughly understand each step of assembly and installation. The group also needed a detailed understanding of work that was outside of our own scope, such as the construction of the laser area enclosures (LAE's) at the sites. In the end we needed to make a detailed schedule and stick to it, something that scientists usually don't like to do.

The laser system is very complex and contains many parts. Therefore, we decided to assemble and align each high power laser at the LZH in a dedicated clean room environment prior to its shipment. This initial assembly included not only the optical and mechanical parts but the entire array of electronics and cooling water connec-

Christina and Patrick at work on the Frequency Stabilization Servo in Livingston. The PSL enclosure and clean rooms are newly constructed. The laser table and reference cavity (yellow cylinder), are reused from initial LIGO.

tors, needed for the stand-alone operation of the high power laser. In the summer of 2010 we performed the first test of the installation of a high power laser box. The engineering prototype was replaced at the AEI by the final reference system. We assumed that this process would be easier than the installation at the sites since we possessed the ability to quickly fix or procure needed parts and we faced no schedule pressure (yet).

At first glance, the water cooling system might seem less challenging than the other complex optical and electronic components. Plumbing is an old and well under-

stood technology and one expects it to be simple. Nevertheless, one week before the engineering prototype was replaced, we discovered a small fountain erupting from the high power laser box. The cause? A broken water hose inside the laser. On examination, other hoses appeared on the verge of rupturing. Consequently all hoses inside all laser boxes were replaced with a less flexible but more robust type of material.

Trouble also arose in the water supply to the laser. When we installed the reference system at the AEI, we could not achieve the same water flow as had been measured at the LZH. In both cases 100m water lines were utilized, even though the distance to the chiller at AEI was much shorter. The 100m lines mimicked the situation at the LIGO sites. At the LZH, the water lines consisted of hoses but at the AEI we mounted dedicated water pipes. The routing of the the AEI plumbing involved many 90 degree turns, which, we observed, limited the water flow. To boost the flow, we opened the installed pipes and inserted sections of hose. We advised our LIGO colleagues at the sites to use larger diameter pipes. In future instances, I would strongly encourage developers to hire a professional plumber or a physicist with extensive experience in plumbing.

Apart from plumbing issues, the reference system installation unfolded smoothly. The optical path of the stabilization loops only needed minor modifications such as an optimised mode-matching when swapping the high power laser box. Adequate time allowed us to route the cables and place the racks in a manner that closely approximated the site layouts. We developed installation procedures for detector sites. The LZH crew felt optimistic that more space would exist at the sites for pulling the 100m fibers than at the AEI. But as you will see, some dreams come true and some do not.

Completion of the reference system sounded the starting pistol for the first installation at Livingston. In Hannover we would need to assemble and align the LLO laser oscillator at the LZH. The process included a full characterization of the laser at LZH to ensure that all parameters lay within specifications (at least prior to shipment). At the AEI the team undertook the fabrication of all electronics and mechanics and the ordering of any additional components. We

Top: Peter, Oliver and Mike lifting the 300 kg High Power Oscillator onto the laser table at L1. This was the first thing brought inside the new build room and the first item on the cleaned PSL table. At that time the room was not yet operated as clean room.

Bottom: Lutz and Oliver during the alignment of the high power laser.

also decided to perform a full characterization of the reference system in order to have a baseline for the measurements we would perform in Livingston.

A detailed installation procedure was needed to answer a number of potential questions. "Are two days sufficient for three people to pull the fibers? Could we use three days and only two people? Can we install the water manifold in parallel with the fibers, or must we do this before, or after?" In numerous discussions we tried to identify numbers of personnel and lengths of service time. In the end we settled on five months for the Livingston installation with at least three team members on site throughout. The complete group for the first installation consisted of twelve people who rotated and Jan Põld, who remained at LLO from start to finish.

LLO needed to close down the L1 interferometer and disassemble the Initial LIGO PSL table. The laser area enclosure (LAE) design went out for bids. Once LIGO decided on the PSL table height ("Do we want a periscope or should we increase the table height so that we don't need one?"), construction began. The Advanced LIGO schedule called for the completion of the LAE prior to the arrival of the PSL team.

In the meantime we packed the entire system into several boxes by putting each component into small plastic boxes, which were wrapped in cleanroom-compatible foil. These small boxes were put into larger wooden boxes, which were lined from the inside with aluminum foil containing small bags with desiccant. These boxes were then nested inside larger wooden crates. A shipping container full of the crates headed for New Orleans. We followed the route of the ship carefully via tracking information viewable online. Everyone felt relieved when the cargo arrived intact after more than four weeks at sea.

Arriving at Livingston in March 2011, we found the laser system waiting for unpacking and installation. The LAE, however, wasn't ready. So . . . we changed our schedule (the first of many times). Rolling up our sleeves, we installed insulating foam, mounted flat screen monitors, caulked seams and assembled cupboards. As circumstances allowed, we also began the PSL installation procedure: Install and run the chiller, connect the laser diodes, route the cables, place the electronic racks, and pull the fibers. The fibers required additional preparation. Because the cable trays for the fibers were quite high, we needed training in order to be allowed to operate the scissor lift and a fall protection safety class. After passing both tests we were finally allowed to pull the fibers. The hope for extra space to pull the fibers was not realized; the installation was as complex as at the AEI. One of the team had to stand at a height of approximately three meters between two walls and thread the fiber bundles through small holes in both walls, which were approximately 0.6m apart. The fibers could not be cut to the exact length and the excess had to be pulled back to the laser diode room and coiled in one of the high cable trays.

At the sites we not only needed to obtain permission for potentially hazardous work, but permission to work at all. Everyone had to attend a work permit meeting each morning at 8:15 a.m. for discussions of the day's work activities. I often wondered how this would work at our institute in Germany, where most of us work on flexible time schedules. In the afternoons, the control room operator's shift ended at 4:00 PM and we were not allowed to work inside the LAE afterwards.

We received a warm welcome at the site, even though we completely filled the visitors office during our stay, which became known as "the German office" for a while. After five months of continuous work, we finished the installation, including all of the measurements necessary to ensure the acceptance of the PSL by the Advanced LIGO project. Additionally, we provided a PSL tour and a training session for personnel who would operate the system at the sites. In February 2012 the PSL in Livingston was accepted by the LIGO Lab.

Advanced LIGO requires three interferometers; two more PSL's needed to be assembled and installed. The second system was to be placed at Hanford over a span of three months instead of five. The time shrinkage necessitated more advance preparation. All of the mirrors, lenses and bases were pre-assembled and labeled. Looking ahead, we sent the components (but not the laser) for the third PSL in the same shipping container. Plans at that time called for the third interferometer to be located at Hanford.

The container and its contents arrived at LHO in good condition after seven weeks in transit. On October 3, 2011, the installation of the H2 PSL began. This time the enclosure was ready and we started the installation procedure immediately. Again we received a warm welcome and an office trailer to call our own. Having installed the first system successfully, we grew in sophistication. We brought our own coffee machine and some German coffee, which quickened the installation pace. We finished a week ahead of schedule. Along the way we managed to test the LAE's acoustic shielding: an alarm from a scheduled fire drill couldn't be heard inside the PSL cleanroom, even though it was quite loud nearby. The observatory staff had anticipated this and so a phone call that we received inside the cleanroom informed us of the drill, and we exited the building. We were encouraged by the enclosure's performance.

The H2 installation had been completed before LIGO decided to suspend installation work on H2 over the detector's possible relocation to India. After this decision, LIGO asked the PSL team to move the H2 installation to the H1 LAE and to store the third interferometer's PSL at Hanford. When we returned to LHO in April 2012, we disassembled the H2 PSL part by part, carried the parts across the laser and vacuum equipment area (LVEA) to the H1 enclosure and installed them there. At 300kg, the high power laser required a crane for its flight across the LVEA. Two people had left the team prior to the H1 installation. Even so we estimated just eight weeks for the job, with the opportunity to come back if necessary. And just like the two installations before, this one went smoothly and was completed on time.

After four installations, three of four PSLs are installed, one Reference System at the AEI and two Observatory Systems at the Livingston and Hanford sites. The Livingston PSL was already accepted and the Hanford system is very close to that state. The fourth and remaining Advanced LIGO PSL is properly stored at Hanford waiting for its installation in the third interferometer.

PSL team at the installation of H2, from left to right: Lutz Winkelmann, Benno Willke, Jan Põld, Peter King, Mathias Janssen, Bastian Schulz, Michaela Pickenpack, Meik Frede, Raphael Klutzig, Oliver Puncken, Michael Rodruck (not pictured: Rick Savage, Patrick Oppermann, Peter Wessels, Mike Fyffe, Marcin Damjanic, Patrick Kwee, Christina Bogan)

Can you solve our unique LIGO sudoku puzzle?

LIGOku grid

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

Standard Sudoku rules apply!

Each row, column and 3 x 3 box should contain exactly one of the nine symbols commonly used in gravita-tional 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 ...

Awards

P. Ajith received a Ramanujan Fellowship from the Department of Science and Technology, India.

Lisa Barsotti was awarded the IUPAP General Relativity and Gravitation Young Scientist Prize, "for her numerous contributions to the development of gravitational wave detectors, especially for leading the demonstration of the utility of squeezed light in improving gravitational wave detector performance." http://www.isgrg.org/IUPAPprize.php

Charlotte Bond, currently a PhD student at the University of Birmingham working on instrumentation for advanced GW detectors, has been awarded a Mary Bradburn Scholarship by the British Federation of Women Graduates (BFWG). These competitive scholarships reward academic excellence and are open to women from all areas of academia.

Sarah Caudill, now a postdoc at University of Wisconsin-Milwaukee, was awarded the 2012 LSU Distinguished Dissertation Award for Science, Technology and Mathematics.

Lynn Cominsky received the "Women Honoring Women" award for her "continuing work for the education of women and girls in the field of Science" from the Sonoma County Commission on the Status of Women during Women's History month, March 2013. The "Women Honoring Women" award is given to outstanding women of the Sonoma county (California) community who have made great efforts for the enhancement and well-being of women and girls.

The LSC Student Poster Prizes in March, 2013 went to **Robert Coyne** of George Washington University in the Analysis/Theory division, and **David Kelley and James Lough**, both from Syracuse University, in the Instrumental/Experimental division

Andreas Freise was awarded the "Excellence in Doctoral Supervision Award" for the College of Engineering and Physical Sciences of the University of Birmingham.

Paul Fulda won the 2012 GWIC Thesis Prize. He completed his Ph.D. at the University of Birmingham and is continuing to work in the LSC, now at the University of Florida.

Kiwamu Izumi (who completed his thesis at the University of Tokyo and is now at the LIGO Hanford Observatory) and **Vivien Raymond** (who completed his thesis at Northwestern University and is now at the LIGO Laboratory, Caltech) won the Stefano Braccini Thesis Prize 2012.

Denis Martynov from Caltech and **Daniel Hoak** from the University of Massachusetts, Amherst are the recipients of the LIGO student fellowship for 2013–2014. Denis will spend a year at the Livingston site working on the cancellation of seismic and scattered light noise. Daniel will spend a year at the Hanford site working on detector characterization and subsystem tuning in support of interferometer commissioning.

Chiara Mingarelli from the University of Birmingham was awarded a Universitas 21 Scholarship to study new tests of General Relativity with Prof. Ingrid Stairs of the University of British Columbia.

Holger Pletsch has been awarded the 2013 Heinz Maier-Leibnitz Prize from the German National Science Foundation, a recognition for his work on new methods to detect continuous gravitational waves, and their applications to finding new gamma ray pulsars.

Sebastian Steinlechner received a Feodor Lynen Stipend by the Alexander von Humboldt Society, for a postdoc stay at the IGR in Glasgow, hosted by Jim Hough and Stefan Hild.

Newly-elected fellows of the International Society of Gravitation and General Relativity

Bala Iyer for his work in applying the post-Minkowskian and post-Newtonian approximations to the problem of compact binary systems, and for his leadership of the gravitational-wave community of India.

Peter Saulson for his contributions to understanding sources of noise in laser interferometric gravitational-wave detectors, and for his leadership in the detector collaborations.

Bernard Schutz for his work on instabilities in rotating relativistic stars, on measuring cosmological parameters using gravitational-wave observations; for his leadership in developing gravitational-wave observatories on the ground and in space; and for his innovations in physics publishing.

Tarun Souradeep for his contributions to the forefront of contemporary cosmology and his leadership in developing gravitational wave astronomy in India.

PhD graduations

Daniel Clarke received his Ph.D. in Mechanical Engineering from Stanford University in March 2013, with a dissertation titled "Control of Differential Motion Between Adjacent Advanced LIGO Seismic Isolation Platforms." He is now working for a small medical devices startup in Silicon Valley.

Rory Smith defended his thesis, "Gravitational-wave astronomy with coalescing compact binaries: detection and parameter estimation with advanced detectors" in April. He is now a post-doctoral fellow at Caltech, working on gravitational-wave parameter estimation and modelling gravitational-wave signals from compact binaries.

Katrin Dahl defended her PhD dissertation on July 1st at the Albert Einstein Institute and has begun a position as a development engineer at Diehl BGT Defence. Her dissertation is titled "From design to operation: a suspension platform interferometer for the AEI 10 m prototype."

Tobias Eberle defended his PhD dissertation titled "Realization of Finite-Size Quantum Key Distribution based on Einstein-Podolsky-Rosen Entangled Light" on July 5th at the Albert Einstein Institute.

Sebastian Steinlechner defended his PhD dissertation on July 16th at the Albert Einstein Institute and will begin a post-doc at the University of Glasgow. His dissertation is titled "Quantum Metrology with Squeezed and Entangled Light for the Detection of Gravitational Waves."

Christian Gräf defended his PhD dissertation on July 18th at the Albert Einstein Institute and has begun a post-doc at the University of Glasgow. His dissertation is titled "Optical Design and Numerical Modeling of the AEI 10m Prototype sub-SQL Interferometer."

Laura Nutall completed her PhD at Cardiff this summer and started a postdoc at University of Wisconsin-Milwaukee focusing on the intermediate Palomar Transient Factory.

Henning Kaufer defended his PhD dissertation titled "Opto-mechanics in a Michelson-Sagnac interferometer" on August 30th at the Albert Einstein Institute.

Career updates

P. Ajith, formerly a postdoc at Caltech, has accepted a faculty position at the International Centre for Theoretical Sciences in Bangalore. He will continue to be a part of the LSC through IndIGO.

Frank Brückner, previously a postdoc at the University of Birmingham, is now an R&D project manager at Carl Zeiss Meditec in Jena, Germany. He will be working on the development of innovative laser systems for eye surgery.

Ludovico Carbone, previously at the University of Birmingham, has recently joined ASML, a Dutch company producing photolithography systems for the semiconductor industry, in a role of Senior Physics Development Engineer. Ludovico will develop Imaging and Alignment Sensors for lithography scanners of the next generations.

Will M. Farr has been appointed a Birmingham Fellow and will be joining the faculty at University of Birmingham on September 1st, moving from Northwestern University, where he has been a CIERA Postdoctoral Fellow.

Peter Kalmus writes: "After many interesting years with LIGO I've decided to switch fields. I've accepted a position in the climate physics group at JPL. Initially I'll be trying to understand how clouds work, and how they might change as the planet continues to warm. I wish you all the best. I look forward to the detection paper, but even more to the "unknown unknowns" that you shed gravitational radiation on!"

Jonah Kanner recently started a new job as staff at the LIGO Lab, Caltech. He'll be working mostly on the new LIGO Open Science Center.

Drew Keppel, previously a Senior Scientist at AEI, is now a Senior Algorithms Architect developing human interface algorithms with Synaptics. Joined by his wife Lisa, daughter Moriah, and dog Maxwell's Equation, he has relocated to sunny Phoenix, AZ.

Joey Shapiro Key will be starting a new position as the Director of Education and Outreach for the Center for Gravitational Wave Astronomy at the University of Texas at Brownsville. Joey was previously the Education Specialist for the Montana Space Grant Consortium and before that a graduate student with Neil Cornish at Montana State University.

Jeff Kissel, previously a postdoc at MIT, is now a Controls Engineer at LIGO Hanford Observatory.

Duncan Macleod writes: "I'm going to LSU to work on scientific computing for the LIGO Data Grid used by the LSC. Specifically I'm working on the online state vector system, and computing tools for detector characterisation."

Sean McWilliams is now an Assistant Professor at West Virginia University, focusing on theoretical gravitational wave astrophysics and the potential for future detectors.

Gabriele Vajente, previously working in the Virgo collaboration as a post-doc at INFN Pisa, is moving to Caltech to join the LSC. Gabriele will work on commissioning and R&D for Advanced LIGO.

Michał Wąs, currently a post-doc at GEO600, will be moving back to Virgo and starting a staff researcher position at the LAPP in Annecy, France. He plans to work on Advanced Virgo commissioning and gamma-ray burst related astrophysics.

We Hear That ...

Elections

Gabriela González was re-elected as LSC spokesperson in March.

Jocelyn Read was elected as member-at-large of the APS Topical Group in Gravitation Executive Committee.

David Tanner was appointed chair of the LSC Election and Membership Committee, replacing Sheila Rowan who stepped down after several years of service. The Committee also welcomed Ed Daw, Soma Mukherjee, Vern Sandberg, and John Whelan (replacing Susan Scott) as new members. Heartfelt thanks go to Susan for serving in the committee for the last three years, Erik Katsavounidis and Sathya for continuing to serve, and especially to David for accepting to lead this important committee and to Sheila for leading it in the past years.

Other news items

Andreas Freise writes: After more than 13 years of work and 25 releases version 1.0 of the interferometer simulation tool Finesse has been released (http://www.gwoptics.org/finesse)! It is freely available for many platforms, is fully open source and comes with simple examples and an extensive manual. This version 1.0 completes the initial open source release of Finesse after a period of extensive testing and optimising the modelling of higher-order modes for beam shape changes and mirror surface distortions. The future of the Finesse development lies in the implementation of radiation pressure effects and quantum noise calculations.

Will M. Farr writes to announce publication of ***Functional Differential Geometry*** by Gerald J Sussman and Jack Wisdom with Will Farr (MIT Press, Cambridge, MA, 2013), which presents a new approach to learning the fundamentals of differential geometry necessary for the study of general relativity or quantum field theory. The book emphasizes the development of the covariant derivative and avoids of the use of traditional index notation for tensors in favor of a semantically richer language of vector fields and differential forms. The authors integrate computer programming into their explanations. By programming a computer to interpret a formula, the student soon learns whether or not a formula is correct. Students are led to improve their program, and as a result improve their understanding.

Rumor has it that the film ***Interstellar***, a movie "based on the theories of Kip Thorne" and maybe even featuring a cameo by LIGO, may have begun filming in Alberta, Canada. Check out the unofficial fan site at http://www.interstellar-movie.com/.

The LSC Academic Advisory Committee now has a publicly viewable page for job advertisements, thanks largely to the work of Brandon Stephens, Scott Koranda, and Veronica Kondrasov. The page can be found at https://wiki.ligo.org/LAAC/JobPostings.

The University of Glasgow and the University of the West of Scotland gravitational wave groups have been jointly working with cell biologists in controlling stem cell behavior which was reported on BBC News at http://www.bbc.co.uk/news/uk-scotland-glasgow-west-22035696.

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?

Recent papers

The article "Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light" was published in Nature Photonics in July 2013. This article is published in Nature Photonics 7, 613–619 (2013). In the first demonstration of injecting squeezed states into the US-based LIGO interferometers, the LIGO scientists achieved a 28% reduction in shot noise. This 28% reduction, which translates directly to sensitivity improvement in frequencies above 150 Hz, would allow an increased volume of space to be searched for gravitational-wave signals. The experience gained in deploying such squeezing techniques on LIGO can be directly applied to a future upgrade of Advanced LIGO in order to increase the sensitivity of those instruments. For an insider's perspective on this work, don't miss Sheila Dwyer's article in this issue.

As we draw even closer to the first observing runs of Advanced LIGO, the thoughts of collaboration scientists increasingly turn towards the question of how best to extract the wide range of astrophysical science output that will be possible with these new instruments. Two LSC and Virgo authored papers that have been released since the last issue of LIGO magazine are both focused on the science that we can do with gravitational-wave interferometers.

The first of the two papers, entitled "Prospects for localization of gravitational wave transients by the Advanced LIGO and Advanced Virgo observatories" is available at http://arxiv.org/abs/1304.0670. This paper presents an observation scenario for Advanced LIGO and Advanced Virgo with first observing runs starting in 2015. A network of at least five interferometers is expected to be operating in 2022. The paper emphasizes that during the first Advanced LIGO observing run in 2015, which is expected to last roughly 3 months, the interferometers are not expected to operate at design sensitivity. The US-based LIGO instruments are expected to reach full design sensitivity in 2019. Advanced Virgo is anticipated to reach design sensitivity circa 2021 and the proposed India-based LIGO instrument is not expected to be operating at design sensitivity until 2022.

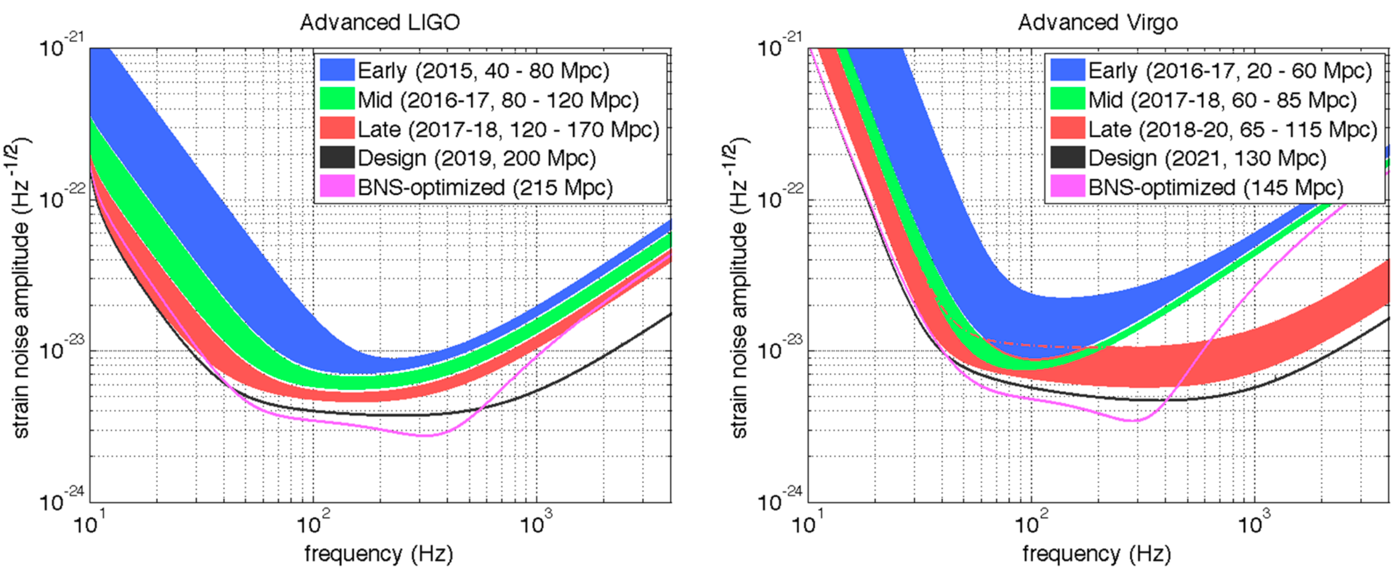
Even though none of the instruments will be operating at design sensitivity before 2019, we can still do a lot of useful science, and hopefully make the first gravitational-wave detections. As construction and commissioning progresses, the document will be updated to better reflect the reality of the evolution of detector sensitivities and operation.

The second paper is entitled "Parameter estimation for compact binary coalescence signals with the first generation gravitational-wave network" and is available at http://arxiv.org/abs/1304.1775. This paper describes and presents results of parameter estimation algorithms which ran on hardware and software injections during LIGO's sixth, and Virgo's second and third, science runs. Hardware injections are signals that directly actuate the mirrors at the end of the long interferometer arms to simulate the passage of a gravitational wave. Software injections are simulated signals that are added to the strain data before analysis takes place. The analyses presented in this paper rely on a Bayesian framework to calculate confidence intervals for each of the parameters. The difficulty arises from the fact that as many as fifteen independent parameters must be determined requiring a vast amount of computing resources to sample all possible values.

To mitigate this, sampling algorithms based on Markov Chain Monte Carlo and Nested Sampling techniques are used.

The examples shown in this work cover the range of expected observation classes in Advanced LIGO for compact binary coalescences. A combination of the two masses, called the chirp mass, is recovered with very good accuracy, typically less than 2%. However, accurate determination of the component masses requires a reliable determination of both the chirp mass and another combination of the masses, the symmetric mass ratio. In the cases shown, this second parameter is often not well determined because of strong degeneracies between it and the angular momenta of the binary's components. Additionally, the precision with which the distance can be measured is limited by the correlation between the inclination of the source to the line of sight. However, when the signal is observed in three detectors its origin is often restricted to a single patch on the sky.

Compiled by Ian Harry



Advanced LIGO and Advanced Virgo projected strain sensitivities as a function of frequency. The average distance to which binary neutron star signals could be seen is given in Mpc. Images taken from Figure 1 of http://arxiv.org/abs/1304.0670.

Sarah Zuraw

Sarah Zuraw is a rising Senior in physics and mathematics at the University of Massachusetts, Amherst. In her free time she enjoys playing music and social dancing, Lindy Hop of course being the most fun!

Amaldi 2013 Impressions from Poland

Watching the Polish countryside roll by from my train car window I was amazed by how wonderfully... flat, it was. The exact opposite of how I was feeling. I was ecstatic! I was on my way to my very first conference in Warsaw, Poland. The GR 20/Amaldi 10 conference was held in the third week of July and drew hundreds of scientists from all over the world. My goal, as I entered the halls of the Warsaw University Auditorium Maximum was to learn as much as I could and to meet other scientists. For me the conference was an amazing success.

I am currently a student at the University of Massachusetts, Amherst and have been doing LIGO related research for almost 3 years under Professor Laura Cadonati. My work for the most part has been on data analysis as part of the Burst Search group. That all changed this summer when I had the opportunity, through the University of Florida IREU program, to travel to Germany for a summer. In Germany I joined a team of experimentalists at the Albert Einstein Institute working on the 10-meter Prototype. Much of my group was attending the conference, so thanks to the kindness of the institute I got to go along for the ride.

The conference covered such a wide variety of topics, it was enough to make your head spin. There were theorists, simulation experts and experimentalists who had all come together to discuss the topic of gravitational waves. Talks ranged from loop quantum gravity to the status of advanced detectors being built in the soggy caves of Kamioka-cho, Japan. One of the most memorable collection of talks had to be the session entitled "Q&A: All the things you wanted to know about gravitational waves but were too embarrassed to ask." As a student I thought this was right up my alley, but as I walked into the room I saw it filled with other scientists. I sat on the floor, as did many others. The talks were lively and engaging. There was even a good dose of humor, as the result of the final talk would decide a wager over a bottle of fine vodka. Fitting considering the venue.

The city deserves an article all of its own. Warsaw has to be one of the most beautiful cities I have ever visited. The old part of town was so bright and vibrant. The history of Warsaw, and indeed of Poland itself, is one of struggle and defiance. In World War II Warsaw was completely leveled, no building was left standing. You wouldn't know that from how it looks today.

There is much to be said for the future of Poland and the future of gravitational wave research. Just as Poland is entering an era of new economic strength and growth the field of gravitational wave research is on the threshold of important scientific discoveries. The upgrade of the major ground based interferometric detectors is nearing completion and these new observatories will soon be searching the skies, initiating a whole new field of gravitational wave astronomy.

Crossword Clues

The numbers in the parentheses after the clues denote how many letters are in the solution, and whether the solution consists of two or more parts. For example if the clue is "Its capital is Washington D.C. (1,1,1)" the answer would be USA. Or if the clue is "He wrote the theory of relativity (1,8)" the answer would be A. EINSTEIN.

ACROSS

1) We're all in this together (1,1,1)
4) The next one, with no go? (1,1,1)
7) A logic state (4)
11) Location of a large scale IFO (abbr.) (3)
12) If you do this you probably zoom as well (3)
13) A succession of waves or a single large wave (5)
14) Domain of the NSF (3)
15) Front end storage media (1,1,1)
16) They make holes that we won't detect (5)
17) What most of the detector once was (3)
18) Plural of Eidos (4)
20) Fly to here to get to an observatory (3)
22) He's well known in the field (3)
23) Advanced LIGO task (abbr.) (3)
26) Professional org. established in 1899. (1,1,1)
28) License plate version of what we seek? Tell the spokesperson we need more than one! (1,5)
31) The one in the middle (1,1,1,1,1)
34) Statistically his name frequently causes disagreements (5)
35) This magazine could be like this (6)
37) Home of college football's death valley (1,1,1)
38) A kind of programming (1,1,1)
39) University down under (1,1,1)
41) Most U.S. students know their score (1,1,1)
44) Makers of the roadmap (1,1,1,1)
45) Schrödinger may have had one (3)
47) Site of a future GW detector? (5)
51) Desired responses from funding agencies (3)
53) Indigo member (1,1,1)
54) What we started as (1,1,1,1,1)
55) Used to compare two power levels (3)
56) Force? Felt during periods of high acceleration (3)
57) In German or Latin the root of these is related to 9 down (4)
58) Domain of most of 1 Across (3)
59) What to do with a question (3)

LIGO Crossword #1: Three Letter Acronyms

DOWN

1) Contains many members of 1 Across (1,1,1,1)

2) Shuts down the Louisiana site once a year (5)

3) Early dwellings explained some fundamental noise (5)

4) A division in this would be good for the field (1,1,1)

5) Another of Albert's theoretical discoveries forms the basis for one of our fundamental technologies (6)

6) Site of a future GW detector (5)

7) What LHO had (3)

8) Used to commute in Paris (1,1,1)

9) A notable birth took place here on March 14 1879 (3)

10) The detectors all look like this (3)

13) Where the prize might be given (abbr.) (3)

19) What KAGRA had to do (3)

21) Useful crystalline materials (4)

23) League of Columbia (3)

24) Maiden name (3)

25) Sound of a leak? (3)

27) SLC and TCS are part of this advanced LIGO subsystem (1,1,1)

29) A deliverable-oriented decomposition of a project into smaller components (1,1,1)

30) If global warming continues we may all want to join this organization (1,1,1,1)

31) European counterpart of 1 across (1,1,1)

32) Site shorthand (1,1,1)

33) A place for many of our papers (1,1,1)

36) A degree of freedom (3)

37) With "out" we hoped to have done this in S6? (6)

40) Daughter of Tantalus (5)

42) Southern Hemisphere group (1,1,1,1,1)

43) Data is still stored on these (5)

44) European detector (3)

46) Star ____ (4)

47) ___ sprechen Deutsch at site of 44 down (3)

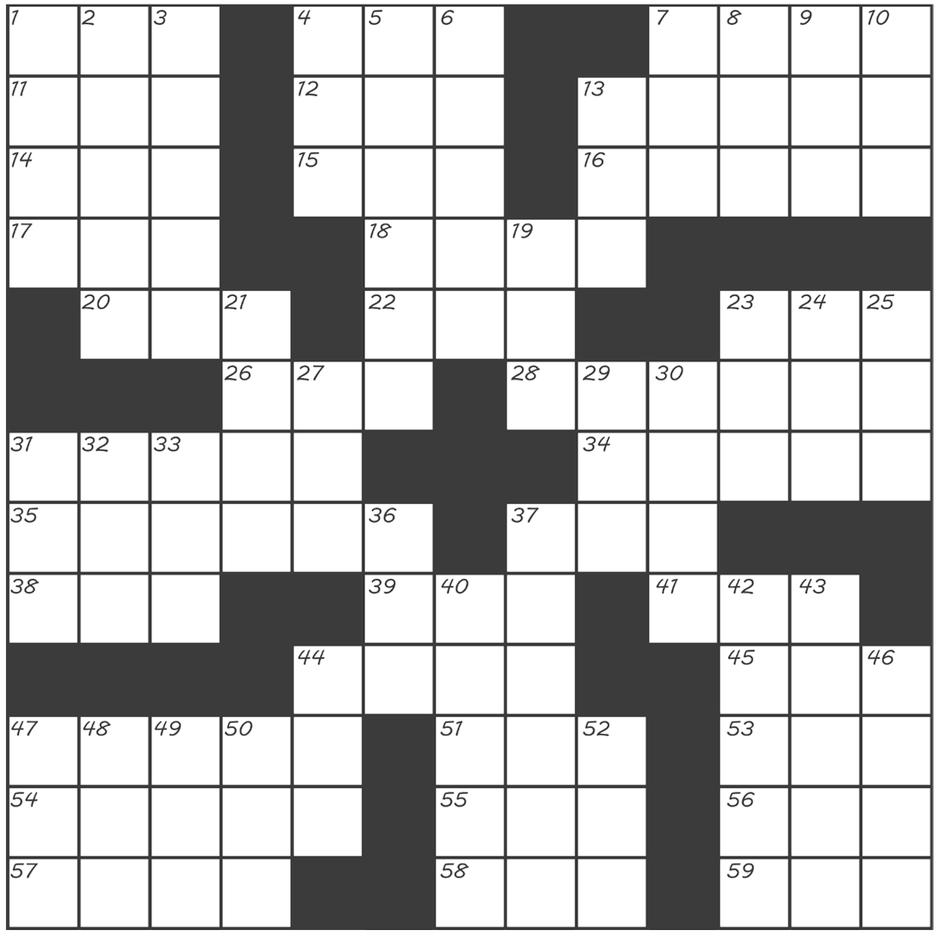
48) Widely used for synchronization purposes (1,1,1)

49) What we can't do with our telescopes (3)

50) System of units (1,1,1)

52) Member of 1 across that is closest to a LIGO detector (1,1,1)

By Brian O'Reilly



The LIGO Magazine

LIGO is funded by the National Science Foundation and operated by the California Institute of Technology and Massachusetts Institute of Technology. This material is based upon work supported, in part, by the National Science Foundation. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

We gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory, the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. We also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the International Science Linkages program of the Commonwealth of Australia, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Economía y Competitividad, the Conselleria d'Economía Hisenda i Innovació of the Govern de les Illes Balears, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the National Aeronautics and Space Administration, OTKA of Hungary, the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the National Science and Engineering Research Council Canada, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

Online ISSN: 2169-4443
World Wide Web URL: http://www.ligo.org/magazine
Publisher: LIGO Scientific Collaboration, Pasadena, CA, USA
LIGO DCC: LIGO-P1300098
Contact: magazine@ligo.org

How does it work? Squeezed light

Classical light can be described as a wave with amplitude and phase. However, quantum mechanics tells us that measurements of the light's amplitude and phase are governed by the Heisenberg uncertainty principle, which places a minimum on the product of two types of uncertainty, in this case, amplitude noise and phase noise. The light that comes out of a stabilized laser often has the minimum uncertainty allowed, equally distributed between amplitude noise and phase noise. If we turn the laser off, the uncertainty principle still applies, meaning that even in completely dark empty space there is still a minimum amount of noise, called vacuum fluctuations. There is no analog to these tiny fluctuations in our classical understanding of light. Nonetheless, they cause the very real quantum noise that will limit the sensitivity of advanced detectors at almost all gravitational wave frequencies.

Squeezing is what we call the process to create light that has less of one type of noise than the light from a laser. Squeezed light can also have the minimum total noise allowed by the uncertainty principle, but redistributed, or "squeezed." For example, squeezed light could have less amplitude noise than normal laser light but in that case the uncertainty principle would require it to have more phase noise. The vacuum fluctuations can also be squeezed, meaning that there can be states of light that have less of one type of noise than no light at all! This is counter to our classical intuition about light and noise, which is why squeezing can seem mysterious and it is not so easy to explain it in simple words.

The good news is, even if this sounds mysterious, it is rather simple to do in practice. We use a special optical cavity and place it in the path of the vacuum fluctuations that cause the quantum noise in an interferometer. The cavity squeezes the vacuum fluctuations before they enter the interferometer and thus we can improve the sensitivity. This may be easier and less risky to implement than other ways of reducing quantum noise, such as using higher laser power.

Sheila Dwyer

A light-painting made inside the main experimental hall of the GEO600 gravitational wave detector. In the foreground is GEO's 'strange-light source,' a table-top system which uses green light to generate squeezed infrared light. The squeezed light is injected into the anti-symmetric (output) port of the interferometer, reducing shot noise and improving the strain sensitivity above about 1 kHz. Vacuum tanks containing the test masses can be seen in the background. Photograph by Kate Dooley, Emil Schreiber, and Michał Wąs.