"BLIND INJECTION" STRESS-TESTS LIGO AND VIRGO'S SEARCH FOR GRAVITATIONAL WAVES

The LIGO Scientific Collaboration and the Virgo Collaboration completed an end-to-end system test of their detection capabilities at their recent joint collaboration meeting in Arcadia, CA. Analysis of data from LIGO and Virgo's most recent observation run revealed evidence of the elusive signal from a neutron star spiraling into a black hole. The collaboration knew that the "detection" could be a "blind injection" -- a fake signal added to the data without telling the analysts, to test the detector and analysis. Nonetheless, the collaboration proceeded under the assumption that the signal was real, and wrote and approved a scientific paper reporting the ground-breaking discovery. A few moments later, according to plan, it was revealed that the signal was indeed a blind injection.

While the scientists were disappointed that the discovery was not real, the success of the analysis was a compelling demonstration of the collaboration's readiness to detect gravitational waves. LIGO and Virgo scientists are looking forward to observations with the advanced detectors which are expected to contain many real signals from the distant reaches of the universe.

GRAVITATIONAL WAVES:

There's a lot at stake here. Gravitational waves, a firm prediction of Einstein's General Theory of Relativity, have never been directly detected, although there is convincing indirect evidence for their existence from precise timing of the orbits of binary pulsars in the Galaxy. The direct detection of these waves through the tiny distortions of space-time that they produce when they arrive at Earth from distant astrophysical sources would be a major scientific milestone, and would open up the new field of gravitational-wave astronomy.

GRAVITATIONAL-WAVE DETECTORS:

Substantial effort has gone into the design and construction of kilometer-scale Michelson interferometers to detect gravitational waves. There is now a global network of such detectors: the two LIGO detectors, one in Hanford, Washington and one in Livingston, Louisiana (built by Caltech and MIT for the US National Science Foundation); the Virgo detector in Pisa, Italy (built by teams from France and Italy); the GEO 600 detector in Hanover, Germany (built by teams from the United Kingdom and Germany); and the TAMA and CLIO detectors in Japan.

L-R: The LIGO Livingston Observatory, LIGO Hanford Observatory, and Virgo

These are "first-generation" detectors, designed to demonstrate the technologies that can sense motions at the level of one-ten-thousandth of the diameter of a proton (or 10^{-19} meter), which may only be barely sensitive enough to detect the waves.

The next generation of detectors coming online in the next 3-5 years -- the Advanced LIGO detectors, Advanced Virgo, LCGT in Japan, and the proposed LIGO Australia --- will be ten times more sensitive. Based on our current understanding of the abundance of gravitational wave sources, these detectors will certainly find the waves and study their properties and the sources in detail. They will allow us to explore the universe in a completely new way, complementary to electromagnetic observations.

BLIND INJECTIONS:

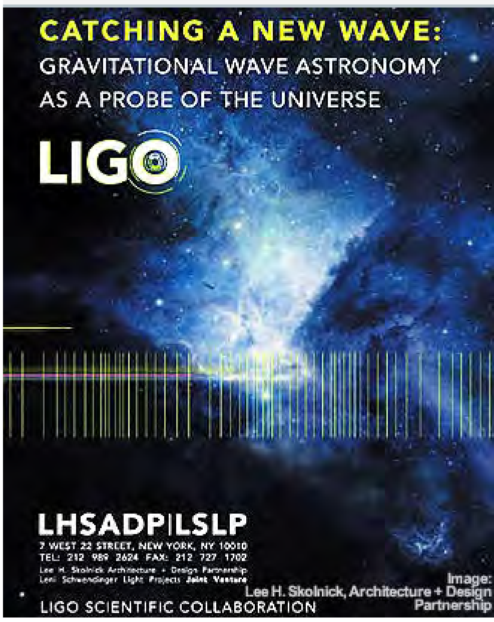
The LIGO Scientific Collaboration and the Virgo Collaboration conducted their latest joint observation run (using the LIGO Hanford, LIGO Livingston, Virgo and GEO 600 detectors) from July, 2009 through October 2010, and are jointly searching through the resulting data for gravitational wave signals standing above the detector noise levels. To make sure they get it right, they train and test their search procedures with many simulated signals that are injected into the detectors, or directly into the data streams. The data analysts agreed in advance to a "blind" test: a few carefully-selected members of the collaborations would secretly inject some (zero, one, or maybe more) signals into the data without telling anyone. The secret goes into a "Blind Injection Envelope", to be opened when the searches are complete. Such a "mock data challenge" has the potential to stress-test the full procedure and uncover problems that could not be found in other ways.

The outcomes from previous blind injection exercises were reported in 2010, in this publication and this publication.

THE SIGNAL:

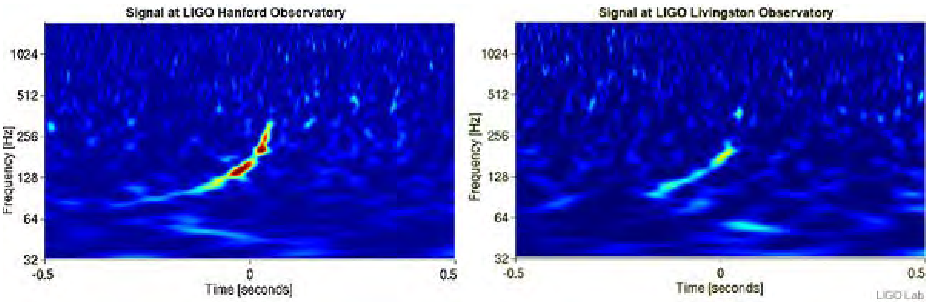
A rather strong signal was observed on September 16, 2010, within a minute or so of its apparent arrival at the detectors. The scientists on duty at the detector sites immediately recognized the tell-tale chirp signal expected from the merger of two black holes and/or neutron stars, and sprang into action. They knew that it could be a blind injection, but they also knew to act like it was the real thing.

CATCH THE WAVE!



Catching a New Wave - design study for the LSC World Science Festival LSC display.

The event was beautifully consistent with the expected signal from such a merger. The figures below show the strength of the signal (redder colors indicate more signal power) in time (horizontal axis) and frequency (vertical axis). The signal sweeps upwards in frequency ("chirp") as the stars spiral into one another, approaching merger. The first plot is what was seen in the LIGO Hanford detector, and the second is what was seen at the same time in the LIGO Livingston detector. Despite apparent differences, the two signals are completely consistent with one another. The dark and light blue regions are typical of fluctuating noise in the detectors.



The loudness of the signal was consistent with it coming from a galaxy at a distance between 60 and 180 million light-years from ours.

The detector network is capable of locating the source in the sky only crudely; it seemed to be coming from the constellation Canis Major (the "Big Dog") in the southern hemisphere (the event was dubbed "the Big Dog" shortly thereafter). They sent alerts to partners operating robotic optical telescopes in the southern hemisphere (ROTSE, TAROT, Skymapper, Zadko) and the Swift X-ray space telescope, all of which took images of the sky on that and/or subsequent days in the hope of capturing an optical or X-ray "afterglow".

IS IT REAL?

In the subsequent days and weeks, numerous teams of scientists tried to get definitive answers to many questions. The event was seen strongly in the two LIGO detectors, less strongly in the Virgo detector, and nothing was seen in the less sensitive GEO detector. Could the event be explained as an accidental coincidence of noise fluctuations? The initial estimate was that the chance of the event being due to noise in the detectors was "much less than 1%", but much more work was required to say how much; after careful analysis, the teams agreed that such a noise coincidence might happen once in 7,000 years.

Could the detectors have exhibited some never-before-seen instrumental effect just then, maybe one that could somehow be correlated between sites that are separated by thousands of kilometers? Despite many investigations and much thought, no plausible scenario for this could be found (except for a blind injection).

After studying all of the evidence, the hundreds of scientists in the collaborations convinced themselves and each other that this was not an instrumental artifact.

IS THERE AN AFTERGLOW?

Was there any sign of an optical or X-ray "transient" in the telescope images? A binary black hole merger would not be expected to emit any kind of light; but if one of the objects was a neutron star rather than a black hole, it would emit a burst of gamma rays that could be seen from across the universe, and an afterglow of X-rays and optical light. Teams worked with their partner astronomers to analyze the images, which only covered a small part of the sky that the signal could have come from. They looked for transients, and eliminated imposters such as variable stars, near-earth asteroids, distant supernovae, etc. Preliminary results revealed no candidate optical or X-ray transient event on the sky that could be associated with this signal.

WHAT KIND OF MERGER?

Mergers of black holes and/or neutron stars are very rare, but they can come in many shapes and sizes. What were the masses of the two stars? If one was significantly less than 3 solar masses, it could be a neutron star, not a black hole, and this is an important distinction to astrophysicists. Whether black holes or neutron stars, they might be expected to be spinning; can this be determined from the signal? And where, precisely is the system located on the sky, and at what distance?

All told, there are fifteen parameters that can be extracted from the signals at the LIGO and Virgo detectors, and several different teams of scientists were able to measure them. The result, however, depended on the waveform models used, and the most realistic models were also the most complex.

DOCUMENTING THE "EVIDENCE":

The scientists gathered all this information together in a paper entitled "Evidence for the Direct Detection of Gravitational Waves from a Black Hole Binary Coalescence". (Coalescence refers to the inspiral of the two stars, their merger into a single perturbed black hole, and the "ringdown" into a final quiet black hole, all through the emission of gravitational waves). A second paper described the parameter estimation procedures and results. A third summarized the search for binary coalescence and the overall results (only one event was observed above the background noise).

Material was prepared for the open release of data relevant to this event, and a whole suite of resources for education and public outreach was assembled. The event was renamed "GW100916", for the year, month and date that it was recorded.

OPENING THE ENVELOPE:

An independent "Detection Committee" reviewed and double-checked all of this work, and reported their findings to the two collaborations. Everyone voted on whether the work, and all the documentation, was sufficient to announce the first detection; the result was a unanimous "yes". The Blind Injection Envelope was opened on March 14, 2011 at a joint meeting of the LIGO Scientific Collaboration and the Virgo Collaboration in Arcadia, CA. There were 300 people in the room and another 100 connecting through a video teleconference. The envelope was opened -- and there was the event: it was a blind injection, not the first direct detection of gravitational waves.

DID THEY GET IT RIGHT?

The event parameters were revealed: it was indeed a binary merger injected at the time when the "big dog" event was observed. The waveform recovered by the search was a good match to the one which was injected. However, there were some surprises: the injected signal was composed of a neutron star and a black hole, not two black holes; and it wasn't from anywhere near Canis Major. What happened?

Within hours, the answer became clear: there was a problem in the blind injection software. The team that injected the simulated gravitational wave signal into the detector had used some old software containing two "bugs": an old waveform model that had more recently been replaced by an improved one (this explained why the signal looked like two black holes), and a sign error in the injection to one detector that made it look like the signal was coming from a different part of the sky. When these errors were taken into account, the analysis easily recovered the "right" parameters. But most importantly, those bugs did not prevent the scientists from finding the injected event in the first place.

LESSONS LEARNED:

Aside from that one problem, everything else in the process seemed to go right. Procedures are now being established to ensure that problems like these will not happen again, which is one of the primary purposes of these mock data challenges.

The blind injection challenge was an extremely successful exercise for the LIGO and Virgo scientists, demonstrating their ability to detect gravitational waves from coalescing binaries and providing a concrete example of how the momentous first detection might play out.

Of course, the first real detection may well look nothing like this exercise: it could be a burst signal from a core-collapse supernova; a continuous sine wave from a spinning neutron star in our Galaxy; a hiss of noise from the earliest moment of the Big Bang; or something that they have not yet anticipated. It could be in the data already collected, since the searches for all anticipated signals are not yet complete. Or we might have to wait a few more years for the data from the next generation of detectors.

Overall, it was an exhilarating and extremely valuable exercise, even if it was disappointing in the end. The LIGO and Virgo teams are now much more prepared for the first real detections.

View data associated with this blind injection (representative of what the LIGO Scientific Collaboration might release for the first real detection(s)).

MORE INFORMATION: LIGO ... VIRGO ... GEO 600 ... LCGT

BLOGS: LIGO NEWS ... LIVING LIGO ... COSMIC VARIANCE ... DISCOVERY NEWS

THE LIGO OBSERVATORY

The Laser Interferometer Gravitational-Wave Observatory (LIGO) consists of two widely separated installations within the United States — one in Hanford Washington and the other in Livingston, Louisiana — operated in unison as a single observatory. LIGO is operated by the LIGO Laboratory, a consortim of the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT). Funded by the National Science Foundation, LIGO is an international resource for both physics and astrophysics.

THE EUROPEAN GRAVITATIONAL OBSERVATORY

The European Gravitational Observatory is located in the countryside near Pisa in the Commune of Cascina. In order to ensure the long term scientific exploitation of the VIRGO interferometric antenna for gravitational waves detection as well as to foster European collaboration in this upcoming field, the VIRGO funding institutions (CNRS for France and INFN for Italy) have created a consortium called EGO (European Gravitational Observatory). VIRGO is a 3-km long interferometer built in the framework of a French-Italian collaboration. This collaboration involves 17 laboratories with more than 190 scientists in France, Italy and also in the Netherlands and Poland as well. EGO is established under the Italian law. Its governing body is the Council composed of members nominated by the funding institutions. The Council appoints a Director who is the legal representative and chief executive of EGO.