White Paper on International Collaboration in Ground-based Gravitational Wave Detection

The LIGO Scientific Collaboration, The GEO Collaboration, The Virgo Collaboration, The LCGT Collaboration, The ACIGA Collaboration

Abstract. International partnerships have been a key feature of the development of ground-based gravitational wave detection technology. All of the high-sensitivity interferometric detectors work together to function as an integrated global network. Thus, we have laid the groundwork for optimally extracting scientific information from the signals that we expect to detect in the Advanced Detector era, starting around 2015. Looking farther into the future, we foresee further growth of the global network of detectors, as well as strengthening of ties to the international community of electromagnetic and particle astronomers.

1. Introduction

The development of ground-based gravitational wave detectors has made excellent progress. Although signals have not yet been detected in data analyzed to date, discoveries are confidently expected once the next generation of interferometers (Advanced LIGO and Advanced Virgo) come on line at their design sensitivity (expected by around 2015.) [1] When this occurs, an important new branch of observational relativistic astrophysics will have been born. [2] [3]

For good scientific reasons, intense international cooperation and collaboration have always been a hallmark of this field. In this White Paper, we first describe those scientific reasons, then summarize the history of international collaboration in ground-based gravitational wave detection. In the remainder of this White Paper, we outline the likely development of the field, emphasizing how international collaboration will continue to play a central role.

2. Why ground-based gravitational wave detection is an inherently international enterprise

2.1. Signal detection

The network of high-sensitivity ground-based gravitational wave detectors seeks signals that can be divided into four categories:

- quasi-sinusoidal "chirping" signals from the coalescences of binaries of compact objects (neutron stars and/or black holes), which have well-determined waveforms,
- brief transient signals from supernovae, "silent" core collapses, or other processes without well-determined waveforms,
- a stochastic background of gravitational waves, perhaps from quantum processes in the early universe or perhaps from the superposition of many discrete signals, and
- nearly-sinusoidal signals from pulsars that don't have pure axial symmetry.

For all except the last category, data from several detectors with large spatial separation are required, simply to make a detection.

The reasons aren't hard to see, although they do depend somewhat on the signal category. The first two signal categories are transient signals. Weak signals compete for visibility in our detector outputs not only with the Gaussian noise associated with fundamental instrument physics (quantum measurement noise in the interferometer output and Brownian motion of the mechanical parts of the interferometer), but also with non-Gaussian "glitches" of poorly understood origin. Transient signals can be distinguished from glitches by requiring that matching signals be seen in multiple widely-separated detectors (so that no plausible non-gravitational-wave coupling can be responsible), at the same time (within the interval expected by travel of the signal at the speed of light across the detector network.)

For a stochastic background, there is no time-coincidence requirement to apply; the signal is present all the time. For that reason, there is no hope of recognizing such a signal in the output of a single detector, as the signal cannot be distinguished from noise in the detector's output. With multiple detectors, though, one can recognize the presence of a stochastic background by cross-correlating the detector outputs. True noise will not be correlated, but a stochastic signal is correlated between the detectors.

Only for a signal from a pulsar is a single detector's output, which could be supplemented with radio measurements of the pulsar's rotation, likely to suffice for discovering a signal. The steady pulsar signal is almost sinusoidal, but has distinctive modulation from the rotation and revolution of the Earth. This is likely to allow a true signal to be distinguished from sinusoidal noise processes in the detector.

Thus, in this early stage of the field where signal detection is the first thing to accomplish, multiple detectors are required. This is a strong impetus for international collaboration. The U.S. National Science Foundation provided funds for the LIGO project to construct two separate observatory sites within the U.S. – LIGO Hanford Observatory in the state of Washington, and LIGO Livingston Observatory in Louisiana. This means that in principle LIGO alone has enough resources to detect with confidence transient or stochastic signals. Other large detectors were constructed by collaborations between countries: the French-Italian Virgo interferometer in Pisa, and the British-German GEO interferometer near Hannover. Japan also built the TAMA interferometer near Tokyo, and is considering construction of a large interferometer called LCGT under Kamioka mountain. In addition, an Australian consortium has built a high-power testbed near Gingin in Western Australia; their goal is to extend this facility into a large detector in the future.

2.2. Doing the best gravitational-wave science after first detections are made

If simply making a detection of gravitational waves were the only scientific goal of the field, the U.S. LIGO project could have considered autonomous operation (even if the other projects around the world could not.) That, however, would be to neglect the long-term scientific promise of the field, which is to develop gravitational waves as a new observational channel for astronomy.

Complete study of a gravitational wave signal goes beyond merely registering its presence and arrival time, and includes:

- determination of the direction on the sky from which the signal comes, and
- reconstruction of the time domain waveform in the two orthogonal polarizations.

Building sky maps is a classic astronomical technique for investigating the nature of new phenomena. Waveform analysis, on the other hand, exploits one of the unique features of gravitational wave astronomy. The waveform traces the history of the coherent motions of mass that generated the signal (specifically, it gives the history of the second time derivative of the source's mass quadrupole moment.) Thus, the waveform encodes very clear information about the dynamics of the source.

Reconstruction of the waveform and determining the direction to the source require that a signal be detected at three or more widely-separated instruments spread across the globe. Large separations give a real advantage here; use of time-delay triangulation to determine source position makes this clear. The difference in orientations of interferometers on different continents also gives an advantage in sky coverage, with some interferometers filling in the dips in the (broad but not perfectly isotropic) antenna patterns of other detectors. Data analysis methods that use fully coherent combinations of the data from multiple detectors are now being used to extract all of this information.

The present network of kilometer scale interferometers (the two LIGO sites plus Virgo and GEO 600 interferometer) just barely meets the minimum requirements for a global network; it would clearly be advantageous to have other high-sensitivity detectors at other locations around the globe.

The requirements for study of a stochastic background are somewhat different. Pairs of interferometers should ideally be relatively close to one another (so that signals from most directions are coherent at the two detectors), while still far enough apart so that there is a negligible level of correlated non-gravitational-wave noise. But a pair of detectors just suffices to indicate a detection of a signal, with no independent check. So, ideally one would want pairs of relatively close detectors on different continents to make a confident measurement.

Detection of gravitational wave signals should become frequent in the Advanced LIGO/Advanced Virgo era (the second half of the next decade.) Building sky maps and catalogs, and making detailed study of the waveforms of individual events, will be the bread-and-butter tools of gravitational wave astronomy. For almost every aspect of these activities, a global network of high-sensitivity detectors is required. *Thus, there is a strong scientific impetus for world-wide collaboration.*

3. History of international collaboration in gravitational wave detection

In the era before the present generation of gravitational wave interferometers went on line, there was already a large degree of technical cooperation between people associated with different projects. This helped prepare the foundation for the more formal collaborations that developed later.

One important milestone in the history of the field was the creation of the LIGO Scientific Collaboration (LSC) in 1997. This formally opened up research on LIGO to the participation of scientists outside LIGO's home institutions, Caltech and MIT. Notably, among the founding institutions were members of the GEO Collaboration. Now consisting of over 650 scientists at roughly 60 institutions, the LSC carries out the scientific program of LIGO.

Also in 1997, the Gravitational Wave International Committee (GWIC) was formed "to facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide." [4] The membership of GWIC consists of leaders of all of the world's active gravitational wave detection projects, both ground-based and space-based. Recently, radio astronomers specializing in pulsar analysis have also joined. Formally, GWIC is constituted as a sub-panel of IUPAP's Working Group 4, Particle and Nuclear Astrophysics and Gravitation International Committee (PaNAGIC). GWIC also has members who represent the International Society on General Relativity and Gravitation and other members who represent the astrophysics and relativity theory communities. It has functioned as an extremely valuable channel of communication that has facilitated the specific project-to-project linkages described below.

One early step toward formal collaboration was an agreement between LIGO and the GEO Collaboration in 2001 to allow full reciprocal data exchange, and to open up all collaboration meetings to members of both projects. This arrangement was strengthened in 2004 to a more complete connection between the projects. Now, all members of the GEO collaboration are, by virtue of that fact, also members of the LIGO Scientific Collaboration. Data collected by LIGO and by GEO are treated as one unified data set, analyzed jointly by all members of the LSC. Management of the detectors is done separately by LIGO and GEO, but with close consultation to coordinate run times and commissioning activities.

Today, about 170 of the ~ 650 members of the LSC are members of GEO. They come from 11 institutions in Germany, the U.K., and Spain. In addition, the LSC contains about 90 members from other countries: Australia, Hungary, India, Italy, Japan, and Russia. All members participate equivalently in technical work and all earn authorship on observational papers by the same criteria.

Other models have been used for other international collaborations. The LSC has published joint analysis papers with the Japanese TAMA Collaboration and with the Italian resonant-mass gravitational wave detector AURIGA. In each case, the LSC negotiated a Memorandum of Understanding that laid out a collaboration of finite duration for the specific purpose of analyzing particular data sets.

In early 2007, a very close relationship was negotiated between the LIGO Scientific Collaboration (including GEO) and the Virgo Collaboration. While in no sense a merger, the agreement established a mode of working together that will result in joint analysis and publication of all data collected since May 2007. It also established mechanisms to ensure coordination of schedules for data collection and instrument development.

The agreement between the LSC and Virgo is still young, but it is already functioning well. Collaboration meetings are now held jointly between the projects, and data analysis groups have merged. The first joint analyses have been produced, and joint papers are just starting to be published. Other coordinating bodies have been functioning well.

3.1. Lessons learned

Looking back on this process, we can see that we have achieved the goal of constructing a global network of the most sensitive detectors, which will enable us to do the best possible science with our gravitational wave observations. We did not use a "one size fits all" approach, but instead negotiated arrangements best suited to the various groups involved. We believe that we are well situated to move the field forward as it makes the widely-anticipated transition to an active field of astronomy sometime in the next decade.

4. Likely next steps

4.1. Within gravitational wave detection

In the near future, we expect some natural growth in the LSC, some of which is likely to come from international members. The addition of a group in Hungary, for example, came just in the past couple of years.

If other large interferometer projects are approved, we anticipate forging the appropriate relationships with them to bring them into the global network. We hope that the Japanese government will approve the LCGT proposal. There are also hopes to build a large interferometer in Australia, and discussions are taking place about possibilities for a detector in India. We maintain strong contacts with these projects; the proponents of the Australian project are members of the LSC, for example, and are partners in Advanced LIGO.

Such developments are explicitly foreseen in the LIGO-Virgo Memorandum of Understanding, which states that

> We enter into this agreement in order to lay the groundwork for decades of world-wide collaboration. We intend to carry out the search for gravitational waves in a spirit of teamwork, not competition. Furthermore, we remain open to participation of new partners, whenever additional data can add to the scientific value of the search for gravitational waves. All partners in the collaborative search should have a fair share in the scientific governance of the collaborative work. [5]

There is also a concerted effort to plan a new "third generation" of gravitational wave interferometers. Leading the way is the Einstein Telescope design study project supported by the European Commission. The participants come from Italy, Germany, France, the U.K., and Holland. In the U.S., a group is investigating the suitability of the Deep Underground Science and Engineering Laboratory (DUSEL) as a location for an underground detector. [6] These efforts are being coordinated through a Roadmap exercise carried out by the Gravitational Wave International Committee. (See below.)

4.2. Connections with astronomers

There is another line of development that will be of especial interest to the authors and readers of the Decadal Survey. In the past year, there has been a dramatic growth in the intensity of contacts between the gravitational wave community and a widening circle of (electromagnetic) astronomers and workers in particle astrophysics. Those contacts have not quite reached the stage of signed Memoranda of Understanding, so it would be inappropriate to describe details. What can be said is this: There has been a mutual recognition that gravitational wave detectors have already reached the sensitivity where detections are possible (although not yet likely), and that chances of a discovery will be enhanced by coordinating observations from multiple "messengers." Equally importantly, when we look ahead to the Advanced Detector era when gravitational wave detection is expected to be frequent, scientific progress will be most rapid if multi-messenger observations can be brought together. Pilot projects just about to begin will explore how to promptly share information about a transient detection in one channel with observers using complementary instruments. Success in these pilot projects may lead to a future regime of issuing prompt public gravitational wave alerts, perhaps similar to the GCN network. Interesting results may come from either direction of information exchange; the gravitational wave detector network could pass pointing information to electromagnetic telescopes, and observations of electromagnetic transients can trigger a focused search in the recorded gravitational wave data. The combination of all messengers will help us to build a comprehensive picture of violent phenomena in the universe. A more complete account of possible interactions is given in the White Paper of Bloom et al. [7]

As with the collaborations within the gravitational wave community, the present stages build on earlier collaborative work. The LSC has already benefited from data exchange with radio astronomers who contributed pulsar timing observations; we have published two papers that included astronomers from Jodrell Bank Observatory as co-authors. The LSC also published a paper on searches for soft gamma repeaters that included four (U.S.) gamma ray astronomers as co-authors, and another on GRB070201 with one gamma ray astronomer as a co-author.

5. The more distant future

5.1. Open data

Looking forward, one can see some trends now starting that will develop fully over time. One of these is the transition that will occur in gravitational wave detection from the present regime where data are available only to those directly involved in the observation and analysis (and impossible to interpret reliably by someone not familiar with the instruments), to an arrangement where gravitational wave data become generally available. The details of the transition to an open data model are now under discussion with the National Science Foundation and the European funding agencies. While not necessarily "international" in its motivation, this transition will certainly enable new forms of international scientific work. In addition, because of the international character of our collaborations already in place, the new rules will of necessity have to be negotiated in an international context.

5.2. Long term science directions

Under the auspices of GWIC, a committee has been formed to prepare a global roadmap for the field of gravitational wave physics and astronomy. The committee will consider both ground-based and space-based projects, and will look over a 30-year horizon. The committee has sought broad input from within the gravitational wave community; it will present its report by summer 2009. [8]

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