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Milestone-Proposal:1972 - Rainer Weiss's Invention of the Gravitational Wave Antenna Used in the Large Interferometric Gravitational Observatory (LIGO)

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Docket #:2019-03

This proposal has been submitted for review.

To the proposer's knowledge, is this achievement subject to litigation? No

Is the achievement you are proposing more than 25 years old? Yes

Is the achievement you are proposing within IEEE's designated fields as defined by IEEE Bylaw I-104.11, namely: Engineering, Computer Sciences and Information Technology, Physical Sciences, Biological and Medical Sciences, Mathematics, Technical Communications, Education, Management, and Law and Policy. Yes

Did the achievement provide a meaningful benefit for humanity? Yes

Was it of at least regional importance? Yes

Has an IEEE Organizational Unit agreed to pay for the milestone plaque(s)? Yes

Has an IEEE Organizational Unit agreed to arrange the dedication ceremony? Yes

Has the IEEE Section in which the milestone is located agreed to take responsibility for the plaque after it is dedicated? Yes

Has the owner of the site agreed to have it designated as an IEEE Milestone? Yes

Year or range of years in which the achievement occurred:

1972 - 1997

Title of the proposed milestone:

Gravitational-Wave Antenna, 1972-1989

Plaque citation summarizing the achievement and its significance:

Hanford plaque: Gravitational-Wave Antenna, 1972-1989

Initially developed from 1972 to 1989, the Gravitational-Wave Antenna enabled detection of ripples in spacetime propagating at the speed of light, as predicted by Albert Einstein's 1916 Theory of General Relativity. Construction of Hanford's Laser Interferometer Gravitational-Wave Observatory (LIGO)

commenced in 1994. In 2015, LIGO antennas, located here and in Louisiana, first detected gravitational waves produced 1.3 billion years ago from two merging black holes.

Livingston plaque: Gravitational-Wave Antenna, 1972-1989

Initially developed from 1972 to 1989, the Gravitational-Wave Antenna enabled detection of ripples in spacetime propagating at the speed of light, as predicted by Albert Einstein's 1916 Theory of General Relativity. Construction of Livingston's Laser Interferometer Gravitational-Wave Observatory (LIGO) commenced in 1995. In 2015, LIGO antennas, located here and in Washington state, first detected gravitational waves produced 1.3 billion years ago from two merging black holes.

Virgo plaque: Gravitational-Wave Antenna, 1972-1989

Initially developed from 1972 to 1989, the Gravitational-Wave Antenna enabled detection of ripples in spacetime propagating at the speed of light, as predicted by Albert Einstein's 1916 Theory of General Relativity. Construction of the Virgo Gravitational-Wave Observatory commenced in 1997. In 2017, Virgo and two antennas located in the US launched the era of Multi-Messenger Astronomy with the coordinated detection of gravitational waves from a binary neutron star merger.

In what IEEE section(s) does it reside?

Region 5, Region 6, & Region 8

IEEE Organizational Unit(s) which have agreed to sponsor the Milestone:

IEEE Organizational Unit(s) paying for milestone plaque(s):

Unit: Region 5 Baton Rouge Section

Senior Officer Name: *Senior officer name masked to public*

Unit: Region 6 Richland Section

Senior Officer Name: *Senior officer name masked to public*

Unit: Region 8 Italy Section

Senior Officer Name: *Senior officer name masked to public*

IEEE Organizational Unit(s) arranging the dedication ceremony:

Unit: Region 5 Baton Rouge Section

Senior Officer Name: *Senior officer name masked to public*

Unit: Region 6 Richland Section

Senior Officer Name: *Senior officer name masked to public*

Unit: Region 8 Italy Section

Senior Officer Name: *Senior officer name masked to public*

IEEE section(s) monitoring the plaque(s):

IEEE Section: Region 5 Baton Rouge Section

IEEE Section Chair name: *Section chair name masked to public*

IEEE Section: Region 6 Richland Section

IEEE Section Chair name: *Section chair name masked to public*

IEEE Section: Region 8 Italy Section

IEEE Section Chair name: *Section chair name masked to public*

Milestone proposer(s):

Proposer name: *Proposer's name masked to public*

Proposer email: *Proposer's email masked to public*

Proposer name: *Proposer's name masked to public*

Proposer email: *Proposer's email masked to public*

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Please note: your email address and contact information will be masked on the website for privacy reasons. Only IEEE History Center Staff will be able to view the email address.

Street address(es) and GPS coordinates of the intended milestone plaque site(s):

Site 1: 19100 LIGO Lane, Livingston, LA 70754, GPS Coordinates: +30.56319, -90.77422; Site 2: 127124 N. Rt. 10, Richland, WA 99354, GPS Coordinates: +30.56289, -90.77424; Site 3: 56021 Santo Stefano a Macerata - Cascina (Pisa), Italy, GPS Coordinates: +43.631222 N, +10.504021 E

Describe briefly the intended site(s) of the milestone plaque(s). The intended site(s) must have a direct connection with the achievement (e.g. where developed, invented, tested, demonstrated, installed, or operated, etc.). A museum where a device or example of the technology is displayed, or the university where the inventor studied, are not, in themselves, sufficient connection for a milestone plaque.

Please give the address(es) of the plaque site(s) (GPS coordinates if you have them). Also please give the details of the mounting, i.e. on the outside of the building, in the ground floor entrance hall, on a plinth on the grounds, etc. If visitors to the plaque site will need to go through security, or make an appointment, please give the contact information visitors will need. Each site has an operational gravitational wave antenna as first described by Dr. Rainer Weiss in his 1972 paper, and are the locations where the first gravitational waves were detected. All three sites constitute a global network operated together to independently validate detections, and to triangulate the location of where on the sky the event originated.

Are the original buildings extant?

The buildings at the proposed plaque sites were erected as a part of a laboratory required to support the construction and operation of the gravitational wave antennas. Each of the sites have been designated as Historic Physics Sites by the American Physical Society (APS).

Details of the plaque mounting:

The mounting for the plaques is still to be determined but a permanent immovable mounting is envisioned in relative proximity to other plaques commemorating the site. For the EGO, the proposed location for the plaque is immediately after the entrance of the facility next to a plaque commemorating the inauguration of the site by the French and Italian ministers in 2003.

How is the site protected/secured, and in what ways is it accessible to the public?

Each observatory maintains visitor control. Each plaque will be mounted outside, and each are accessible for public viewing while on the observatory grounds.

Who is the present owner of the site(s)?

LIGO is funded by the U.S. National Science Foundation (NSF). The design and construction of LIGO was conducted by the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT). Construction of the facilities began in 1994, and the advanced LIGO installation was completed in 2014. Caltech has a cooperative agreement with the NSF to operate (jointly with MIT) the LIGO facilities for the NSF. At the LIGO Hanford Observatory, the NSF owns all buildings; the Department of Energy owns the land and allows Caltech and MIT to operate the facility through an MOU and Permit with the NSF. At LIGO Livingston Observatory, the NSF owns all buildings and the land is leased to the NSF by the Louisiana State University (LSU). The European Gravitational Observatory (EGO) is located near Pisa and hosts the Virgo interferometric antenna, where construction started in 1997. EGO is a consortium, established under Italian law, created in 2000 by the Virgo funding institutions (CNRS for France and INFN for Italy) to ensure the long term scientific exploitation of the Virgo interferometric antenna. EGO owns and manages the buildings, operations, maintenance and upgrades of the antenna. EGO is established under the Italian law. The first Virgo antenna was inaugurated in 2003. Later on (2007) NIKHEF joined the consortium as an observer. The Virgo collaboration, consisting of scientists and engineers from many European countries, assures the scientific exploitation of the antenna, proposes and realizes its sensitivity upgrades.

What is the historical significance of the work (its technological, scientific, or social importance)?

Following the progression of Human knowledge, four fundamental forces of nature have been identified. Early in our recorded history Earth, Wind, Water and Fire were considered by the Greek philosophers as the basis for explaining nature and the complexity of all matter. As our knowledge and scientific method evolved, we eventually identified the gravitational force, as described by Einstein's General Theory of Relativity, and the other three forces as quantum fields that are described by the Standard Model of particle physics. The other three forces are the strong nuclear force, the weak nuclear force and the electromagnetic force. LIGO represents the first time gravitational waves, the force-carrier of gravity as predicted by Einstein over 100 years ago, were directly observed.

The gravitational force was first described in mathematical terms by Isaac Newton in 1687 by inferring that all matter exerted an attractive force directly related to the mass of individual objects and the square of the distance between them. From 1687 to the early 20th Century, Newton's model reigned supreme. However, astronomical observations were made that defied explanation using Newton's laws of motion. These observations were related to objects whose velocities approached that of the speed of light, and to objects subjected to very high gravitational fields. The observations made by astronomers

over two centuries indicated that the orbit of Mercury deviated from that prescribed by Newton's laws of motion.

In 1915, Albert Einstein described in *The General Theory of Relativity* that gravity is the curvature of spacetime produced by the presence of mass-energy. Indeed, the anomalous precession of the perihelion of Mercury mentioned above was found to result from the intense gravitational field of the Sun. General Relativity further predicts that any rapid change in a gravitational field will travel through the Universe at the speed of light. These changes in the gravitational field are described as gravitational waves. From Dr. Weiss's original paper he stated, "In 1918, Einstein, using a weak-field approximation in his very successful geometrical theory of gravity (the general theory of relativity), indicated the form that gravitational waves would take in this theory and demonstrated that systems with time-variant mass quadrupole moments would lose energy by gravitational radiation. It was evident to Einstein that since gravitational radiation is extremely weak, the most likely measurable radiation would come from astronomical sources." Given the requirements of the measurement, in his paper Dr. Weiss went on to describe a proposed antenna design capable of detecting the gravitational waves predicted by Einstein. In 1979 the National Science Foundation (NSF) funded Caltech and MIT to develop and mature the proposed gravitational wave antenna as described by Dr. Weiss. Following ten years of research and prototype development, Congress approved funding for LIGO in 1991, and construction of the sites began in 1994 and 1995. In parallel in Europe, Adalberto Giazotto from Italy and Alain Brillet from France, pioneered new methods of seismic isolation ("superattenuators") and laser injection systems, later joined by Jean-Marie Mackowski on methods of production of extreme quality mirrors that formed the heart of the European proposal for the Virgo interferometer (1989), approved by CNRS and INFN in 1994 and whose construction started in 1997.

The first gravitational waves were simultaneously detected using the gravitational wave antenna at the two LIGO sites on September 14, 2015. The gravitational waves were produced by the merger of two black holes, in an event that occurred 1.3 billion years ago. The Virgo antenna obtained comparable sensitivities in August 2017 and, together with the two LIGO antennas in the US, was able to detect with unprecedented precision through triangulation, the site of two merging black holes, marking thus the beginning of precision gravitational wave astronomy. Three days later on the 17th of August the detection of a neutron star merger, again through the conjugated action of the three antennas (LIGO - Hanford, LIGO - Livingston and Virgo), permitted the follow-up of the event by nearly 70 electromagnetic observatories around the world, from the optical to radio wavelengths, thus marking a new beginning: this of "multi-messenger astronomy". The direct detection of gravitational waves by LIGO resulted in co-founders Rainer Weiss, Barry Barish, and Kip Thorne receiving the 2017 Nobel Prize in Physics.

What obstacles (technical, political, geographic) needed to be overcome?

Because gravity is the weakest of the four fundamental forces, gravitational forces are exceedingly small and, before the invention of the gravitational wave antennas used on LIGO and VIRGO, were impossible to measure directly. A strong astrophysical gravitational wave, caused by some of the most energetic events in the Universe, will produce a displacement at Earth of order 10-18 meters (1 atto-meter), which is about 1000 times smaller than the diameter of a proton. Waves of this strength are produced by very massive systems undergoing extremely large accelerations, such as two black holes merging into one at over half the speed of light. This measurement capability has been made possible in part through the

development and maturation of state-of-the-art technology in multiple electrical engineering disciplines including photonics, lasers, controls, computer systems, software, instrumentation, signal processing, etc. It took over 100 years of advanced multidisciplinary technology development to provide the capability of making sensitivity measurements capable of detecting gravity waves.

What features set this work apart from similar achievements?

There are no other similar achievements. The direct measurement of gravitational waves is a fundamental achievement.

Supporting texts and citations to establish the dates, location, and importance of the achievement: Minimum of five (5), but as many as needed to support the milestone, such as patents, contemporary newspaper articles, journal articles, or chapters in scholarly books. 'Scholarly' is defined as peer-reviewed, with references, and published. **You must supply the texts or excerpts themselves, not just the references.** At least one of the references must be from a scholarly book or journal article. All supporting materials must be in English, or accompanied by an English translation.

- 1) Reference for the original paper that described the detector: R. Weiss (1972), "Electromagnetically Coupled Broadband Gravitational Antenna" Quarterly Progress Report No. 105, Research Laboratory of Electronics, MIT, pg. 54 – 76. A PDF of that original paper is available here: <https://dcc-lho.ligo.org/public/0038/P720002/001/19720018652.pdf>
- 2) Construction Proposal: R. W. P. Drever, F. J. Raab, K. S. Thorne, R. Vogt, and R. Weiss, Laser Interferometer Gravitational-wave Observatory (LIGO) Technical Report, 1989, <https://dcc.ligo.org/public/0065/M890001/003/M890001-03%20edited.pdf>.
- 3) Prototype description: D. C. Coyne, 1996, "The Laser Interferometer Gravitational-Wave Observatory (LIGO) Project" 1996 IEEE Aerospace Applications Conference Proceedings, <https://dcc-lho.ligo.org/public/0037/G960051/000/G960051-00.pdf>
- 4) A. Giazotto, Phys. Reports 182, 365 (1989). A. Brillet, A. Giazotto et al., "VIRGO Proposal for the construction of a large interferometric detector of gravitational waves" (1989), https://www.ego-gw.it/public/about/VIRGO_Proposal_1989_VIR-0517B-15.pdf.
- 5) A. Brillet, A. Giazotto et al., "VIRGO Final Concept Design" (1992), https://www.ego-gw.it/public/about/VIRGO_Proposta_1987_VIR-0473B-15_clean.pdf (in Italian).
- 6) First gravitational wave detection: B. P. Abbott, et al., "Observations of Gravitational Waves from a Binary Black Hole Merger" Physical Review Letters, PRL 116, 061102 (2016), https://dcc-lho.ligo.org/public/0122/P150914/014/LIGO-P150914_Detection_of_GW150914.pdf
- 7) GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence LIGO Scientific and Virgo Collaborations (B.P. Abbott et al.) Phys.Rev.Lett. 119 (2017)
- 8) Detection of a binary star merger: B. P. Abbott, et al., "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" Physical Review Letters, PRL 119, 161101 (2017), <https://dcc-lho.ligo.org/public/0145/P170817/008/LIGO-P170817.pdf>
- 9) Parts of the Path to Today's Interferometric Gravitational-Wave Detectors, David Shoemaker, LIGO-G1401350-v4, Oct. 2014, Provides a good historical summary of the invention and development of the

gravitational wave antenna.

See <https://dcc.ligo.org/public/0116/G1401350/004/GW%20interferometry%20--%20history%20to%20aLIGO%20v4.pptx.pdf>

10) LIGO: The Dawn of Gravitational Wave Astronomy, Jameson Graef Rollins, LIGO-G1602295, PCaPAC 2016, Campinas, Brazil, Oct. 26, 2016 - Provides a good summary of what gravity waves are, the principles behind detecting them, an overview of the observatories, early measurements, and path forward. Contains several embedded Youtube videos.

See <https://dcc.ligo.org/public/0139/G1602295/001/main.pdf>

11) Interferometric Detection of Gravitational Waves, Adalberto Giazotto, Phsics Reports (Review Section of Physics Letters) 182, No. 6 (1989) 365 - 424, North-Holland, Amsterdam, https://www.ego-gw.it/public/about/Giazotto_Physics_Reports_1989.pdf

12) For a brief summary of the European Gravitational Observatory, see <https://www.ego-gw.it/public/about/welcome.aspx>.

Supporting materials (supported formats: GIF, JPEG, PNG, PDF, DOC): All supporting materials must be in English, or if not in English, accompanied by an English translation. **You must supply the texts or excerpts themselves, not just the references.** For documents that are copyright-encumbered, or which you do not have rights to post, email the documents themselves to ieee-history@ieee.org. Please see the [Milestone Program Guidelines](#) for more information.

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