MANTECH Publications

Journal of Research in Physics and Applied Sciences
Volume 9, Issue 1, January-June 2026
ISSN: 3139-1397 (Online)

Gravitational Waves: Detection Methods and Recent Discoveries — A Review of Interferometric Astronomy from LIGO-Virgo-KAGRA to the Next-Generation Era

Dr. Vivek Jain[1], Animesh Singh[2], Raveena Gupta[3]

ABSTRACT

Gravitational-wave astronomy has matured, within less than a decade, from a landmark first detection into a routinely productive observational discipline. This paper undertakes an analytical review of the detection methods underlying this transformation and the scientific discoveries they have enabled, from the first direct observation of gravitational waves in September 2015 through the completion of the fourth Advanced LIGO-Virgo-KAGRA observing run in November 2025. Drawing on secondary data compiled from the Gravitational-Wave Transient Catalogs published by the LIGO-Virgo-KAGRA Collaboration, public detector data releases, and peer-reviewed literature, the study examines the evolution of laser interferometric detection technology, cumulative detection trends across four observing runs, and landmark discoveries including the first binary neutron star merger observed with an electromagnetic counterpart and recent high-significance events from the current observing era. The analysis indicates that cumulative confirmed detections grew from 11 events at the end of the second observing run to over 250 candidate events by the conclusion of the fourth observing run, driven substantially by improvements in detector strain sensitivity and the expansion of the global detector network. The paper identifies a persistent research gap concerning the limited electromagnetic characterization of compact objects in the so-called mass gap between neutron stars and black holes, and the continued absence of a fully operational Southern Hemisphere or South Asian detector capable of closing existing gaps in all-sky localization coverage. Based on the findings, the study proposes an integrated conceptual framework linking compact binary inspiral, interferometric strain detection, multi-detector triangulation, and

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

astrophysical and cosmological insight, and discusses its implications for the planned next-generation detector era.

KEYWORDS: *Gravitational Waves, LIGO, Virgo, KAGRA, Interferometric Detection, Binary Black Hole Mergers, Multi-Messenger Astronomy, Gravitational-Wave Astronomy*

INTRODUCTION

Gravitational waves, ripples in spacetime curvature generated by accelerating massive objects, were predicted by Albert Einstein in 1916 as a consequence of the general theory of relativity [1]. For nearly six decades this prediction remained observationally unconfirmed, until Hulse and Taylor's 1974 discovery of the binary pulsar PSR B1913+16 provided compelling indirect evidence: precise timing of the pulsar's orbital decay matched the energy loss expected from gravitational-wave emission with remarkable accuracy [2], [3]. Direct detection, however, required measuring spacetime strain on the order of one part in 10^21, a technical challenge that motivated the decades-long development of kilometer-scale laser interferometers [4].

This challenge was met on September 14, 2015, when the twin Advanced LIGO detectors in Hanford, Washington, and Livingston, Louisiana, recorded a transient signal, subsequently designated GW150914, consistent with the merger of two stellar-mass black holes approximately 1.3 billion light-years away [4]. The detection, announced in February 2016 and later recognized with the 2017 Nobel Prize in Physics, opened an entirely new observational window onto the universe, one sensitive to phenomena, such as compact object mergers, that emit little or no electromagnetic radiation [4]. Since this landmark event, the global detector network, comprising the two LIGO detectors, the Virgo detector in Italy, and the KAGRA detector in Japan, has conducted four major observing runs, each incorporating detector sensitivity upgrades that have substantially expanded the volume of the observable universe [5], [9], [10].

The problem addressed in this paper is that, despite the rapid pace of discovery across four observing runs and multiple detector upgrades, comparatively few review-style analyses synthesize the technical evolution of interferometric detection methods alongside the resulting trajectory of astrophysical discovery within a single integrated framework, particularly

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

incorporating results from the most recently completed observing run. This paper responds to that gap by synthesizing secondary data from the LIGO-Virgo-KAGRA Collaboration's published transient catalogs, detector technical literature, and peer-reviewed discovery papers into an integrated analytical review, examining developments from 2015 through the conclusion of the fourth observing run in November 2025.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature across detection theory, interferometric methods, multi-messenger astronomy, and detector network expansion. Section 3 identifies the research gap, followed by the research objectives in Section 4. Section 5 describes the methodology, Section 6 presents the results and findings, and Section 7 discusses their significance. The paper concludes with the study's limitations, future research scope, and a numbered reference list.

LITERATURE REVIEW

A substantial body of literature spans the theoretical foundations, interferometric detection methods, multi-messenger discoveries, and detector network expansion underlying modern gravitational-wave astronomy. This section synthesizes that literature across four thematic areas.

Theoretical Foundations and Historical Precursors

Einstein's original derivation of gravitational radiation from the linearized field equations of general relativity predicted that accelerating mass distributions with a changing quadrupole moment would emit spacetime-strain waves propagating at the speed of light [1]. Direct observational confirmation remained elusive for decades, but Hulse and Taylor's discovery of the binary pulsar PSR B1913+16 provided decisive indirect evidence, and subsequent decades of precision timing by Taylor and Weisberg confirmed that the system's orbital period was decaying at a rate matching general relativity's gravitational-wave energy loss prediction to within observational uncertainty [2], [3].

Laser Interferometric Detection Methods

Direct gravitational-wave detection relies on kilometer-scale Michelson interferometers with Fabry-Perot arm cavities, in which a passing gravitational wave produces a differential strain between perpendicular arms measurable as a corresponding shift in interference pattern [4].

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

Achieving the requisite strain sensitivity, on the order of 10^-21, required successive technical advances, including power and signal recycling, seismic isolation systems, and quantum-noise reduction techniques such as squeezed-light injection, which the LIGO Scientific Collaboration demonstrated could measurably improve detector sensitivity beyond the standard quantum limit [5]. The first direct detection, GW150914, confirmed both the viability of this detection approach and the existence of stellar-mass binary black hole mergers as an observable astrophysical population [4].

Multi-Messenger Astronomy and Compact Binary Mergers

The August 2017 detection of GW170817, a binary neutron star merger, marked a milestone for multi-messenger astronomy: the gravitational-wave signal was accompanied by a short gamma-ray burst detected independently by the Fermi and INTEGRAL satellites, followed by an extensive electromagnetic follow-up campaign that identified an associated kilonova [6], [7]. This joint observation provided an independent measurement of the Hubble constant, direct evidence linking short gamma-ray bursts to neutron star mergers, and observational confirmation of heavy-element nucleosynthesis via the rapid neutron-capture process. Subsequent detections, including GW190521, a merger producing an intermediate-mass black hole populating the theoretically predicted pair-instability mass gap, have continued to reveal compact object populations not anticipated from electromagnetic astronomy alone [8].

Detector Network Expansion and Sky Localization

Sky localization precision for gravitational-wave sources improves substantially with the number of geographically separated detectors participating in triangulation, motivating the phased expansion of the global network from the two-detector LIGO configuration to include Advanced Virgo in Italy and KAGRA in Japan [9], [10]. Proposals for a fourth major detector, LIGO-India, sited in Maharashtra, have been advanced specifically to improve sky coverage and localization precision for the Southern Hemisphere and South Asian sky region, though the facility remains under construction as of the most recent observing run [11]. Successive Gravitational-Wave Transient Catalogs published by the collaboration document the cumulative growth of the confirmed detection population as network sensitivity and coverage have expanded [12], [13].

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

RESEARCH GAP

While the literature separately affirms the maturity of interferometric detection technology, the significance of multi-messenger discoveries, and the value of detector network expansion, three gaps remain evident. First, most existing reviews document individual landmark discoveries or specific detector technical upgrades in isolation, with limited synthesis connecting the trajectory of detector sensitivity improvement directly to the resulting growth in cumulative astrophysical discovery across all four observing runs. Second, the population of compact objects occupying the mass gap between the heaviest neutron stars and lightest black holes remains poorly characterized, since gravitational-wave detections of such objects generally lack electromagnetic counterparts that would otherwise help determine their nature. Third, the continued absence of a fully operational detector in the Southern Hemisphere or South Asian region, despite the LIGO-India proposal being formally endorsed, leaves a persistent gap in uniform all-sky localization coverage that has not been comprehensively assessed in recent integrated review literature. This paper addresses these gaps by constructing an integrated analysis of detection method evolution and cumulative discovery trends spanning 2015 to 2025, and by proposing a conceptual framework that links compact binary inspiral, interferometric detection, multi-detector triangulation, and astrophysical insight within a single observational pathway.

RESEARCH OBJECTIVES

- To review the evolution of laser interferometric gravitational-wave detection methods from initial to advanced detector configurations.
- To analyze cumulative gravitational-wave detection trends across the LIGO-Virgo-KAGRA observing runs O1 through O4.
- To examine key multi-messenger and mass-gap discoveries and their astrophysical significance.
- To assess the role of detector network expansion in improving gravitational-wave sky localization precision.
- To propose an integrated conceptual framework linking compact binary inspiral, interferometric detection, and astrophysical insight, and to discuss implications for the planned next-generation detector era.

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

METHODOLOGY

This study adopts a review-based and analytical secondary-data research design, appropriate for synthesizing dispersed technical and observational evidence into a coherent analytical framework. Rather than conducting primary interferometric measurement or waveform analysis, the study systematically compiles and analyzes publicly available detection catalogs, detector technical literature, and peer-reviewed discovery papers to identify consistent patterns linking detection methodology and astrophysical discovery.

Quantitative indicators were drawn from three principal categories of sources: the successive Gravitational-Wave Transient Catalogs (GWTC-1 through GWTC-5.0) published by the LIGO-Virgo-KAGRA Collaboration, public detector data releases available through the Gravitational Wave Open Science Center, and peer-reviewed literature retrieved through a systematic keyword search using terms including "gravitational wave detection," "LIGO," "binary black hole merger," and "multi-messenger astronomy" in the NASA Astrophysics Data System and arXiv databases, spanning publications from 1975 to 2025 to capture both foundational theoretical contributions and the most recent observational results.

Cumulative confirmed detection counts were compiled by observing run to construct Figure 2, drawing directly on figures published in successive Gravitational-Wave Transient Catalogs and collaboration announcements. Approximate binary neutron star inspiral range figures, a standard detector sensitivity metric, were compiled by observing run to construct Figure 3, drawing on published detector characterization literature and observing scenario documents. A comparative summary of observing runs and detector network configurations was constructed for Table 1, and findings from key discovery papers were synthesized into Table 2. The conceptual framework depicted in Figure 1 was developed inductively from the standard detection and analysis pipeline described across the reviewed literature, linking compact binary inspiral to interferometric strain detection, multi-detector triangulation and parameter estimation, and resulting astrophysical and cosmological insight.

Because this study is analytical and review-based rather than a primary interferometric data analysis, the reported detection counts and sensitivity figures are drawn directly from published collaboration catalogs and technical literature; the binary neutron star range values presented in Figure 3 should be treated as representative approximations, since actual detector sensitivity varies over the course of each observing run and across the detector network.

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

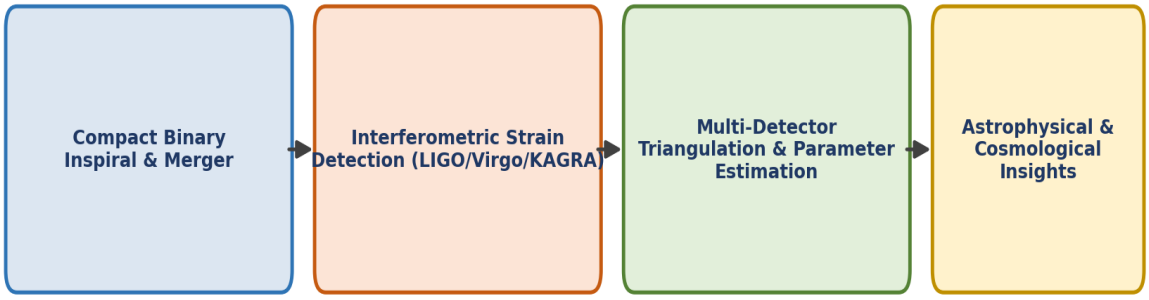


Figure 1: Conceptual Framework Linking Compact Binary Inspiral, Interferometric Detection, and Astrophysical Insight

RESULTS AND FINDINGS

Table 1 presents observing run periods, detector network configurations, and cumulative confirmed detection counts across the four completed LIGO-Virgo-KAGRA observing runs. The detector network expanded from a two-detector LIGO-only configuration during the first observing run to a coordinated three-detector network including Virgo and, from the fourth observing run onward, simultaneous KAGRA participation, with each successive run also incorporating substantial detector sensitivity upgrades [9], [10].

Table 1: LIGO-Virgo-KAGRA Observing Runs and Cumulative Confirmed Detections

Observing Run	Period	Detector Network	Cumulative Confirmed Detections
O1	Sep 2015 - Jan 2016	LIGO (2 detectors)	3
O2	Nov 2016 - Aug 2017	LIGO + Virgo (from Aug 2017)	11 (cumulative, O1+O2)
O3 (O3a + O3b)	Apr 2019 - Mar 2020	LIGO + Virgo	90 (cumulative)
O4 (through GWTC-4, O4a)	May 2023 - Jan 2024	LIGO + Virgo + KAGRA (partial)	218 (cumulative)
O4 (complete, candidates)	May 2023 - Nov 2025	LIGO + Virgo + KAGRA	~250 (candidates, analysis ongoing)

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

Figure 2 illustrates the growth in cumulative confirmed gravitational-wave detections across observing runs. The combined first and second observing runs yielded 11 confirmed detections, published in the GWTC-1 catalog [12]. The third observing run brought the cumulative total to 90 confirmed events. Comprehensive analysis of the first segment of the fourth observing run alone added 128 further significant events, bringing the cumulative confirmed total to 218, while the collaboration reported observing approximately 250 candidate signals in real time by the run's conclusion in November 2025, with detailed analysis of the later segments still ongoing at the time of writing. This trajectory reflects an approximately exponential growth in detection rate, driven jointly by improving detector sensitivity and the maturation of near-real-time detection pipelines.

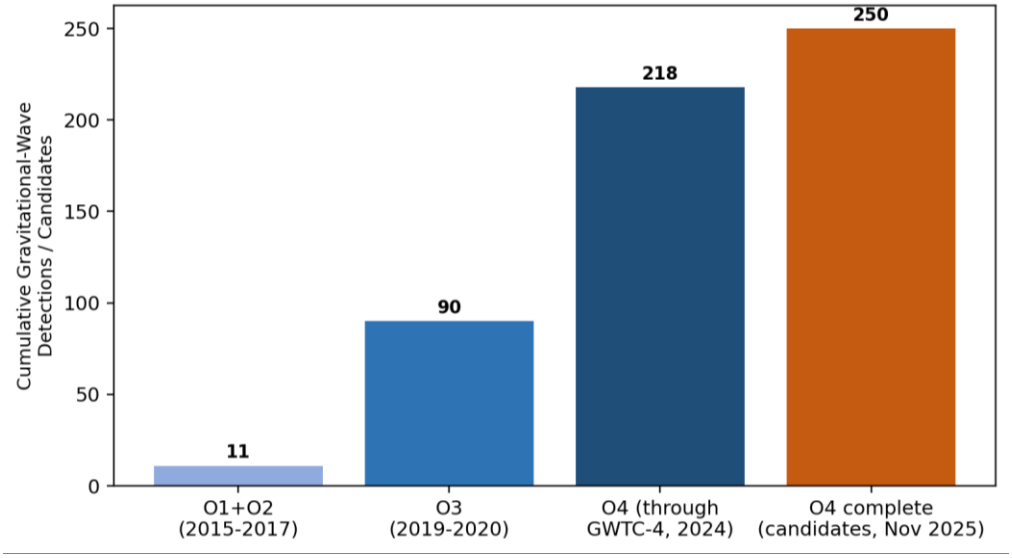


Figure 2: Growth in Cumulative Gravitational Wave Detections across Observing Runs

Figure 3 presents the approximate binary neutron star inspiral range, a standard proxy for detector sensitivity representing the distance at which a typical binary neutron star merger could be confidently detected, across the four observing runs. This range more than doubled from approximately 75 megaparsecs during the first observing run to approximately 165 megaparsecs during the fourth observing run, corresponding to more than a sevenfold increase in surveyed spacetime volume given the cubic relationship between detection range and volume [5], [9].

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

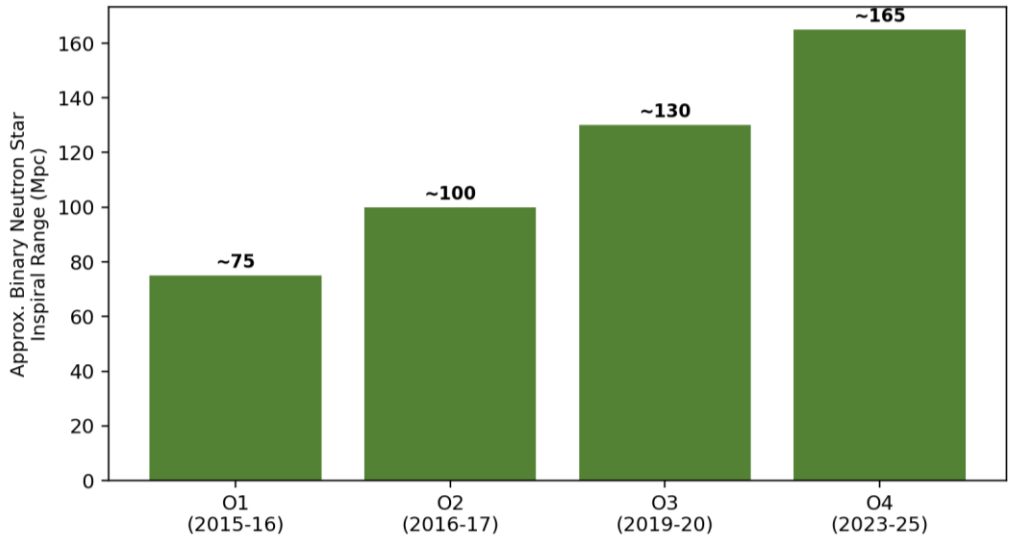


Figure 3: Approximate Improvement in LIGO Detector Sensitivity (Binary Neutron Star Range) Across Observing Runs

Table 2 synthesizes key findings from five landmark discovery papers examined in this review, spanning the first direct detection, the first multi-messenger neutron star merger observation, and subsequent discoveries of previously unobserved compact object populations. Collectively, these studies illustrate how each successive observing run has not only added to the cumulative detection count but has also revealed previously unanticipated categories of astrophysical sources.

Table 2: Summary of Landmark Gravitational-Wave Discoveries

Event / Study	Discovery	Method	Key Finding
GW150914; Abbott et al. (2016) [4]	First direct detection	Interferometric detection	Confirmed direct observation of gravitational waves from a binary black hole merger.
GW170817; Abbott et al. (2017) [6], [7]	First multi-messenger BNS merger	Joint GW and electromagnetic observation	Linked binary neutron star mergers to short gamma-ray bursts and kilonova nucleosynthesis.

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

GW190521; Abbott et al. (2020) [8]	Intermediate-mass black hole formation	Interferometric detection	Revealed a merger product populating the theoretically predicted pair-instability mass gap.
GWTC-1; LVC (2019) [12]	First transient catalog	Catalog compilation	Consolidated 11 confident detections from the first two observing runs.
GWTC-5.0 (2026 release) [13]	Record sensitivity and localization	Catalog compilation	Reported the highest signal-to-noise event and most precise sky localization observed to date.

DISCUSSION

The findings synthesized in this review carry several implications. First, the roughly exponential growth in cumulative detections documented in Figure 2 demonstrates that gravitational-wave astronomy has transitioned from a discovery-validation phase, centered on individual landmark events, to a population-scale observational science in which statistical analysis of the compact object merger population is now feasible, including constraints on black hole mass and spin distributions [8], [13]. Second, the more than sevenfold increase in surveyed spacetime volume between the first and fourth observing runs indicates that continued detector sensitivity improvement remains one of the most direct levers for accelerating discovery, complementing rather than substituting for detector network expansion [5], [9], [10].

Engineering and Scientific Significance

From a scientific standpoint, the results highlight the continued importance of the mass gap population, compact objects with masses between the heaviest known neutron stars and lightest known black holes, as a target for combined gravitational-wave and electromagnetic follow-up observation. Because most such detections to date lack an identified electromagnetic counterpart, their fundamental nature, whether unusually massive neutron stars or unusually low-mass black holes, remains an open question with direct implications for nuclear equation-of-state physics and compact object formation theory [8].

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

Practical Applications

From a practical standpoint, the findings suggest several applications. For the gravitational-wave research community, the demonstrated value of multi-detector triangulation in achieving high-precision sky localization, as illustrated by recent record-setting localization results, supports continued investment in expanding and upgrading the global detector network, including timely completion of the LIGO-India facility [11]. For electromagnetic follow-up observers, the growing detection rate underscores the practical necessity of automated, rapid-response alert infrastructure capable of keeping pace with an increasingly prolific gravitational-wave discovery stream. For funding agencies and the broader physics community, the trajectory documented in this review supports continued investment in next-generation detector concepts capable of extending sensitivity to earlier cosmic epochs and lower-mass source populations [14], [15].

LIMITATIONS

This study is subject to several limitations. First, it relies on secondary, aggregated indicators drawn from published catalogs and technical literature rather than primary interferometric data analysis, which limits the granularity of the analysis and precludes independent verification of individual event significance. Second, the binary neutron star range values presented in Figure 3 are approximate and vary within each observing run as detector commissioning progresses, so the reported figures should be interpreted as representative rather than precise. Third, at the time of writing, detailed analysis of the later segments of the fourth observing run remained ongoing, meaning that the final cumulative detection count for this run may be revised upward as analysis is completed. Finally, as a review-based and analytical study, the paper does not perform independent gravitational-wave data analysis or waveform modeling, and relies instead on results as reported by the LIGO-Virgo-KAGRA Collaboration and associated peer-reviewed literature.

FUTURE SCOPE

Future research should extend this analysis as the remaining segments of the fourth observing run are fully analyzed and as the fifth observing run, anticipated with further sensitivity upgrades, begins. Continued electromagnetic follow-up campaigns targeting mass-gap compact object mergers would help resolve outstanding questions about their fundamental nature. Comparative studies tracking the progress of the planned LIGO-India facility toward operational status would help assess its eventual contribution to sky localization precision for

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

the Southern Hemisphere and South Asian sky region. Given ongoing design and construction planning for third-generation ground-based detectors such as the Einstein Telescope and Cosmic Explorer, and for the space-based Laser Interferometer Space Antenna, future studies should examine how these next-generation facilities are expected to extend gravitational-wave astronomy to new source populations, including supermassive black hole mergers and signals from the early universe.

CONCLUSION

This paper has examined the evolution of gravitational-wave detection methods and the discoveries they have enabled through an analytical review of secondary data and existing literature spanning 2015 to 2025. The findings confirm a sustained, roughly exponential growth in cumulative confirmed detections across four observing runs, driven jointly by detector sensitivity improvements and global network expansion, alongside the emergence of previously unanticipated compact object populations.

The study's proposed conceptual framework, linking compact binary inspiral, interferometric strain detection, multi-detector triangulation, and astrophysical and cosmological insight, offers a structured basis for future research and for planning the next generation of gravitational-wave observatories. As the field moves toward third-generation ground-based detectors and space-based observatories capable of probing entirely new source populations and cosmic epochs, understanding the trajectory documented in this review will remain essential for astrophysics and fundamental physics research planning.

REFERENCES

1. Einstein, A. (1916). Näherungsweise Integration der Feldgleichungen der Gravitation. Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften, 688-696.
2. Hulse, R. A., & Taylor, J. H. (1975). Discovery of a pulsar in a binary system. Astrophysical Journal, 195, L51-L53.
3. Taylor, J. H., & Weisberg, J. M. (1982). A new test of general relativity: Gravitational radiation and the binary pulsar PSR 1913+16. Astrophysical Journal, 253, 908-920.
4. Abbott, B. P., et al. (LIGO Scientific Collaboration and Virgo Collaboration). (2016). Observation of gravitational waves from a binary black hole merger. Physical Review Letters, 116(6), 061102.

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

5. Aasi, J., et al. (LIGO Scientific Collaboration). (2013). Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light. Nature Photonics, 7(8), 613-619.
6. Abbott, B. P., et al. (LIGO Scientific Collaboration and Virgo Collaboration). (2017). GW170817: Observation of gravitational waves from a binary neutron star inspiral. Physical Review Letters, 119(16), 161101.
7. Abbott, B. P., et al. (LIGO Scientific Collaboration and Virgo Collaboration). (2017). Multi-messenger observations of a binary neutron star merger. The Astrophysical Journal Letters, 848(2), L12.
8. Abbott, R., et al. (LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration). (2020). GW190521: A binary black hole merger with a total mass of 150 solar masses. Physical Review Letters, 125(10), 101102.
9. Akutsu, T., et al. (KAGRA Collaboration). (2021). Overview of KAGRA: Detector design and construction history. Progress of Theoretical and Experimental Physics, 2021(5), 05A101.
10. Acernese, F., et al. (Virgo Collaboration). (2015). Advanced Virgo: A second-generation interferometric gravitational wave detector. Classical and Quantum Gravity, 32(2), 024001.
11. Unnikrishnan, C. S. (2013). IndIGO and LIGO-India: Scope and plans for gravitational wave research and precision metrology in India. International Journal of Modern Physics D, 22(1), 1341010.
12. LIGO Scientific Collaboration and Virgo Collaboration. (2019). GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs. Physical Review X, 9(3), 031040.
13. Abbott, R., et al. (LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration). (2023). GWTC-3: Compact binary coalescences observed by LIGO and Virgo during the second part of the third observing run. Physical Review X, 13(4), 041039.
14. Punturo, M., et al. (2010). The Einstein Telescope: A third-generation gravitational wave observatory. Classical and Quantum Gravity, 27(19), 194002.
15. Amaro-Seoane, P., et al. (LISA Consortium). (2017). Laser Interferometer Space Antenna. arXiv preprint arXiv:1702.00786.

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved

***Author for Correspondence**

Animesh Singh

E-mail: animesh44@yahoo.co.in

[1]Lecturer, Department of Physics, Himachal Pradesh University, H.P.

[2]Lecturer, Department of Physics, Himachal Pradesh University, H.P.

[3]Research Scholar, Department of Physics, Himachal Pradesh University, H.P.

Received Date: January 12, 2026

Accepted Date: February 25, 2026

Published Date: March 10, 2026

Citation: Dr. Vivek Jain, Animesh Singh, Raveena Gupta. Gravitational Waves: Detection Methods and Recent Discoveries — A Review of Interferometric Astronomy from LIGO-Virgo-KAGRA to the Next-Generation Era. Journal of Research in Physics and Applied Sciences. 2026; 9(1): 9-22p.

Page 9-22 © MANTECH PUBLICATIONS 2026. All Rights Reserved