

IndIGO and LIGO-India: Scope and Plans for Gravitational Wave Research and Precision Metrology in India

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Abstract

Initiatives by the IndIGO (Indian Initiative in Gravitational Wave Observations) Consortium during the past three years have materialized into concrete plans and project opportunities for instrumentation and research based on advanced interferometer detectors. With the LIGO-India opportunity, this initiative has taken a promising path towards significant participation in gravitational wave (GW) astronomy and research, and in developing and nurturing precision fabrication and measurement technologies in India. The proposed LIGO-India detector will foster integrated development of frontier GW research in India and will provide opportunity for substantial contributions to global GW research and astronomy. Widespread interest and enthusiasm about these developments in premier research and educational institutions in India leads to the expectation that there will be a grand surge of activity in precision metrology, instrumentation, data handling and computation etc. in the context of LIGO-India. I discuss the scope of such research in the backdrop of the current status of the IndIGO action plan and the LIGO-India project.

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1 Preamble

The IndIGO Consortium for mobilizing and facilitating participation of Indian scientists and engineers in gravitational wave (GW) observations was set up in 2009 after a series of informal discussions during conferences and workshops related to gravitation because both the need and fresh opportunities for such participation was realized by the handful of people working in this area for over two decades. It was felt that with the plans for advanced GW detectors in the US and Europe, as well as with the possibility of new projects in Australia and Japan, there was new opportunity opening up, missed earlier due to limited resources during the era of initial GW interferometer detectors like LIGO and Virgo. This turned out to be true when the idea was strongly encouraged and supported by the global GW research community. For over two decades, there have been important and influential contributions to research in the theoretical aspects of the generation and detection of gravitational waves from India (S. V. Dhurandhar at IUCCA, Pune on data analysis strategies, methods and templates, and Bala Iyer at RRI, Bangalore on GW generation processes, source modeling and waveforms). However, when the small community of researchers in gravitation experiments and gravitational waves discussed the possibility in the 1990s, the human and financial resources that could be mustered in India were not perhaps anywhere near the needs of the project and in any case no experimental activity in the field was taken up at that time. Meanwhile, the community of researchers in those theoretical aspects were steadily growing in India due to sustained research at IUCAA and RRI as well as due to the possibility of signatures of primordial gravitational waves in CMBR data attracting researchers in cosmology (like Tarun Souradeep at IUCAA, Pune) to the task of detection of gravitational waves. The possibility of an advanced large scale detector in India, after suitable smaller steps of research and implementation, was discussed enthusiastically again recently in the context of Advanced LIGO [1] and Virgo [2], the upgraded GEO-HF [3] and the space-based LISA [4], prompted and encouraged by several researchers (Bernard Schutz, Rana Adhikari and David Blair). The formation of the IndIGO consortium was followed up with a road-map for the Indian GW observational program that was charted out during a meeting I organized with Munawar Karim on experimental gravitation (ISEG2009) in Kochi in January 2009 [5]. This document was prepared in association with ACIGA, the Australian consortium, represented in the meeting by D. Blair. It was natural to try

to participate in the ACIGA plans for a new advanced detector (AIGO) in Perth, Australia [6] and it was envisaged that a limited yet active participation in hardware and human resources for an advanced interferometer detector was feasible and practical as a first serious step. Also, it was decided that a prototype detector in India was an essential element of this effort, for training and research. The overwhelming feeling during these steps was that the opportunity was ‘now, or never’.

To assess the feasibility of this participation quantitatively, the IndIGO consortium members sought a grant for ‘Establishing Australia-India collaboration in GW Astronomy’ in 2009, mainly to facilitate meetings between AIGO and IndIGO, and this was immediately funded by the Australia-India Strategic Research Fund (AISRF) managed by the Department of Science & Technology (DST) in India. Research in gravitational waves was already recognized as a thrust area in the vision document of the DST. This was very important because it enabled timely participation of the IndIGO representatives in meetings in Shanghai (October 2009) and later in Perth and Gingin in Australia (February 2010) where the idea of LIGO-Australia was presented. LIGO-USA assessed the important scientific advantages of moving one of the 4-km arm-length Advanced LIGO (aLIGO) detectors from Hanford to a remote location outside the continent, and made the offer of contributing important hardware of the interferometer to the Australian detector project. Australian scientists had the responsibility for the infrastructure, assembly, commissioning and operation of the detector. IndIGO envisaged a 15% participation in hardware deliverables and human resources and prepared a project proposal to the DST seeking support. With LIGO-Australia [7] as the primary project for our participation, it was decided to attempt to construct a relatively small, yet advanced, prototype interferometer at the Tata Institute of Fundamental Research (TIFR), Mumbai where the availability of space is difficult, but facilities and support for fabrication and testing etc. are excellent. The proposal for the 3-m scale power recycled Michelson-Fabry-Perot interferometer with a conservative budget of about \$500,000 went through extensive reviews, being a new endeavour, and was successful in getting funded within a year, in 2011. Several aspects of Indian collaboration for LIGO-Australia was discussed in the India-Australia meeting under the AISRF grant, during February 2011 in Delhi. Based on a joint proposal with IUCAA, Pune and Caltech, USA as the node institutions, IndIGO obtained a grant for an Indo-US centre for gravitational wave physics and astronomy from the Indo-US Science & technology Forum

(IUSSTF) in July 2011, to facilitate mutual visits and joint work. Another significant development was that the IndIGO consortium became a member of the Gravitational Wave International Committee (GWIC), in July 2011. However, there were serious difficulties for substantial funding in Australia for realizing the large scale LIGO-Australia detector within a reasonable schedule, set as about mid-2011.

The flavour of the plans for GW research in India changed drastically after mid-2011 with the dawn of the possibility of a LIGO-India detector, to be constructed and operated in India with the hardware for the interferometer from LIGO-USA and the infrastructure to house it provided by India. The arrangement for LIGO-India is similar to what was envisaged for the LIGO-Australia detector, with the additional, and very important, task of selecting a suitable site in India for locating the detector. This ‘amazing opportunity’, as I call it, was facilitated due to both the mutual trust and confidence developed during several interactions between the US and Indian scientists in GW research as well as the support for the idea from key researchers in the field of gravity, like A. Ashtekar, K. Thorne, and B. Schutz. An important milestone in this fast-paced developments was the IndIGO consortium becoming a member of the LIGO Scientific Collaboration (LSC) in September 2011. The plan for LIGO-India was well in accordance with the goals of development of the field, especially for international collaboration and network operation, outlined in the road-map of the GWIC [8]. In October 2011, a panel of the National Science Foundation (NSF), USA reviewed the case LIGO-India and found its science case compelling enough to go forward, albeit with cautious evaluation criteria. Ever since, the LIGO-USA team has been working relentlessly to ensure with proper evaluation that the LIGO-India detector is feasible, by setting and examining several target criteria. The scientists, science managers and the funding agencies in India were already sensitized to the importance of the national participation in GW research and astronomy, from the several meetings and discussions in the context of IndIGO and LIGO-Australia project, and this enabled IndIGO to prepare a detailed project proposal [9], which was submitted to the potential funding agencies - the Department of Science and Technology and Department of Atomic Energy, Government of India. This was discussed in a meeting in November 2011 and LIGO-India proposal received enthusiastic support and encouragement along with several other astronomy mega-projects. This paved way for the Planning commission of India discussing the project as a potential ‘12th plan’ mega-science project, to be initiated during the 12th 5-year plan of the

government of India, during 2012-2017. When the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, and the two key technologically highly endowed institutes under the DAE – The Institute for Plasma Research (IPR), Gandhinagar and the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore – agreed to take key responsibilities for the projects, things fell into sharp focus. Speedy and cautious response and support from the NSF, USA in the form of visits of key persons and reviews of the proposal by special committees resulted in quickly giving concrete form to the LIGO-India project. Four senior level visits from the LIGO-Laboratory to the LIGO-India lead-institutions for technical assessment and discussions were followed by three in depth reviews by a NSF panel. All this culminated in a review by the National Science Board, USA, in August 2012 and the following resolution: ‘Resolved, that the National Science Board authorize the Deputy Director at her discretion to approve the proposed Advanced LIGO Project change in scope, enabling plans for the relocation of an advanced detector to India’. The Department of Atomic Energy is putting together the papers for a note to the Cabinet seeking ”in-principle” approval of the project, and permissions to sign the relevant MOUs and release of seed funding for the project. It is significant that LIGO-India is listed prominently in the communication from the US state department on U.S.- India Bilateral Cooperation on Science and Technology [10].

2 The LIGO-India project: Science case

The idea of LIGO-India (as well as the earlier LIGO-Australia) arose due to compelling science reasons when it was realized that a network of three advanced detectors, preferably of the same nature of design and sensitivity, forming a large triangle across the globe has significantly more advantages than the operation of the same three detectors in just two geographical sites, as was envisaged in the LIGO plan. In addition such a change of plan has the advantage of bringing in a new country and scientific community into the global GW research and astronomy effort. Of course, there is a change in the noise cancellation capability at one of the sites where the two detectors were supposed to operate simultaneously in the same vacuum enclosure (Hanford in this case). However, that was seen as a small price to pay for the great advantages LIGO-India would offer in terms of source localization, duty cycle, sensitivity and sky coverage [11, 12, 13]. A study by B. Schutz, in which

a general framework based on three new figures of merit was developed for studying the effectiveness of networks of interferometric gravitational wave detectors, showed that enlarging the existing LIGO–Virgo network with the planned detectors in India (LIGO-India) and Japan (LCGT) brought major benefits, including much larger detection rates and more uniform antenna pattern and sky coverage [14]. I summarize here the main scientific advantages that are discussed in these papers.

2.1 Source localization

The obvious advantage of locating a third aLIGO detector far away from the other two in the USA is the ability to locate a source in the sky with three identical detectors, with an accuracy of about a degree or so. In the pre-LIGO-India plans this was expected to be accomplished by timing measurements involving the aLIGO detectors in two locations and the Virgo detector at Cascina near Pisa. This of course is possible. However, there is significant improvement in the source localization ability when the LIGO-India detector is added to the network. The advantage is quantitatively similar with the third aLIGO detector in either Australia or India due to the bounded positioning possibilities on the spherical earth, with marginal advantage (10%) in the slightly larger baselines to Australia from the US sites (there is significant difference to the baseline to Virgo, however, of about 40%). Figs. 1 and 2, from ref. [13], indicate the locations of the detectors and the improvement in localization. (H - Hanford, USA, L - Livingston, USA, V - Virgo, Pisa, Italy and I - LIGO-India, assumed to be located near Bangalore for these estimates. The sensitivity of localization error to the exact position in India is mild). Since binary neutron star mergers are the most promising events for detection when the advanced detectors start their operation, the analysis in this paper is based on a population of binary neutron stars distributed over the sky at a luminosity distance of 200 Mpc, corresponding to the average distance reach of the advanced detectors.

With a baseline of about 14000 km, the theoretical resolution for localization is about 10 sq. degree. Of course the details depend on the projection of this baseline on the sky, and hence varies with direction. With the four-detector network involving LIGO-India, HLVI, there is dramatic improvement, by an order of magnitude in the worst case of just the HHLV network. For 50% of the sources the average localization error improves from 30 sq. deg to 8 sq. deg. Apart from localizing the source on the two-dimensional sky, it

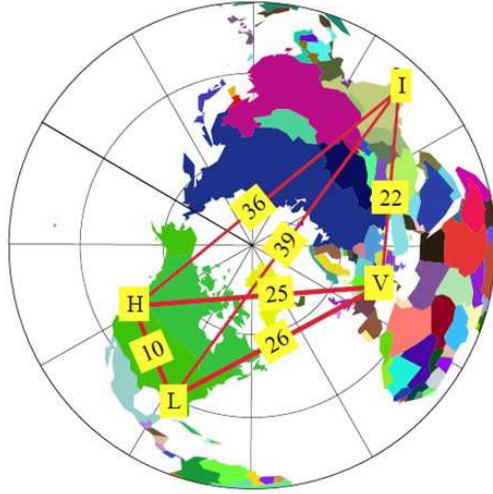


Figure 1: Schematic detector locations with maximum delays in milliseconds. H: Hanford, L: Livingston, V: Virgo and I: LIGO-India. (Figure credit: Ref. [13]).

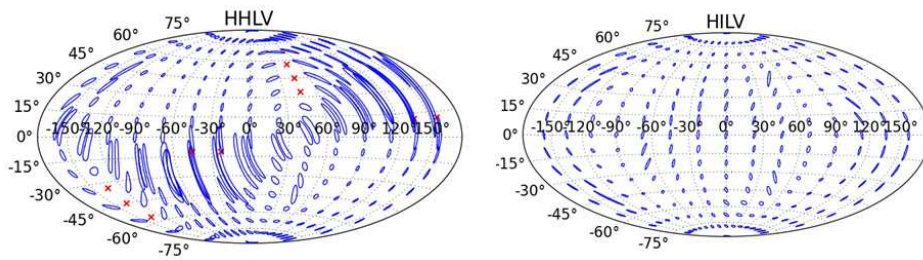


Figure 2: The remarkable improvement in the source localization error is evident in the comparison of the figures for HHLV and HILV. (Figure adapted from Ref. [12, 13]).

is also possible to measure the distance to the source because binary neutron stars are standard candles, and it is estimated that four or three-detector networks involving LIGO-India can measure distances to better than 30%, the improvement resulting from the large baseline as well as the ability to sense the orbital orientation of the binary relative to the line of sight. These measurements will be important for the independent determination of the Hubble parameter.

2.2 Sensitivity

There will be a 10-fold improvement in the sensitivity of individual Advanced LIGO and Virgo detectors, compared to the earlier versions. In network operations, the overall sensitivity is determined by noise rejection capabilities achieved in coincidence detection. Therefore, the original HHL configuration had extra sensitivity coming from the fact that there are two Hanford detectors in the same UHV enclosure. Together with the Livingston detector, the sensitivity for detection along the normal to the US continent was almost twice or even 3 times of that in other direction rotated 90 degrees away (see left panel of Fig. 3). The sensitivity is smoothed out more uniformly in all directions in the HLVI configuration [11]. Even though there is marginal reduction in the best sensitivity (about 15%), the worst sensitivity in some directions is only about half of that of the best sensitivity and significant region of the sky is visible with much better sensitivity (20%-30%) than possible with the HHLV configuration.

2.3 Sky coverage

Due to the fact that the new detector is significantly out of plane compared to the HLV configuration, the blind bands in the HHLV configuration are eliminated considerably in the HLVI configuration. Compared to a sky coverage of about 47% in the case HHLV, the HLVI network has 79% sky coverage. With the addition of the KAGRA detector in Japan (HLVIJ) this reaches 100%, compared to 74% of HHLVJ. The details are listed and discussed in ref. [13].

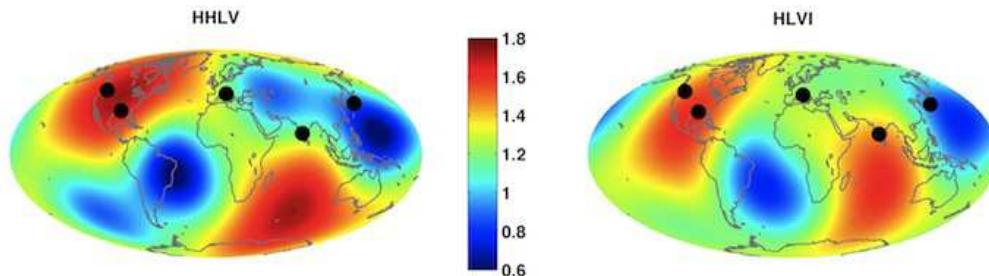


Figure 3: Comparison of sensitivity for detection in the original HHLV configuration and the proposed HLVI configuration. While it is true that the sensitivity diminishes around the normal vector of the HL detector locations (and 180 degree across), there is significant improvement in other regions (reduction of blue patches). (Plot credit: P. Ajith, IndIGO).

2.4 Duty cycle

Each advanced detector is expected to have a duty cycle below 80%, due to the need for regular maintenance. Regular operation with good precision in localization requires a minimum of three detectors and therefore the duty cycle for a 3-detector operation is limited to about 52% in the HHLV configuration where the down time of one H detector has significant overlap with the down time for the other because they share the same UHV envelop, similar infrastructure etc. However, with HLVI, there are four 3-detector configurations available with total effective duty cycle of 41%, equal to the four-detector duty cycle itself, adding up to 82%. This is a significant improvement for the ‘on’ time for the network telescope, and this fact alone is worth relocating one detector to India, from the point of view of astronomy (Fig. 4). Of course, source localization is still considered as the most important single factor in the many scientific advantages of LIGO-India because it is a crucial factor in source identification with simultaneous observations with other types of telescopes operating in the electromagnetic spectrum.

3 The LIGO-India project: Plan of execution

The LIGO-India project [9] is a joint endeavour between the consortium of research laboratories and universities funded by the Government of India and

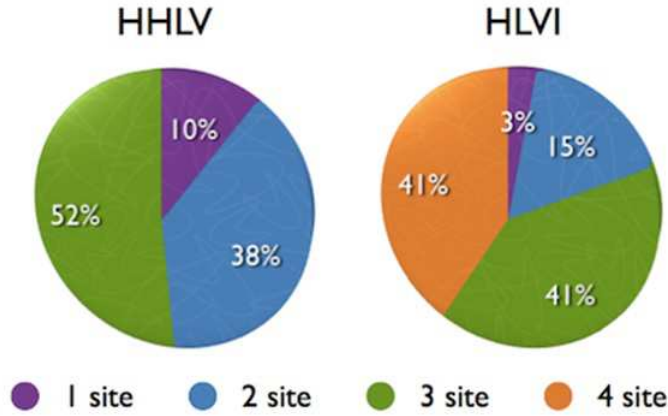


Figure 4: Improvement in the duty cycle with the 3-detector operation. (Figure credit: Ref. [13]).

the LIGO Laboratory of the USA, funded by the National Science Foundation, USA. The LIGO Laboratory will provide the complete design and all the key detector components of the Advanced LIGO (aLIGO) detector. These include the vibration isolation platforms and systems, the pre-stabilized laser with amplifier, complete optics and suspension systems for mode cleaners and the interferometer, sensors, control systems and electronics, software, design and assembly drawings and documents etc. India would provide the infrastructure and human resources to install the detector at a suitable site in India and would be responsible for commissioning and operating it. The infrastructure involves the appropriate site, suitably prepared, UHV enclosures and the 2x4km beam tubes, laboratories and clean rooms etc. The aim is to realize a third aLIGO detector, as close as possible in design and operating characteristics to the other two aLIGO detectors in the USA, in time to enable GW astronomical observations in a multi-detector network. The proposed observatory would be operated jointly by IndIGO and the LIGO Laboratory and would form a single network along with the LIGO detectors in USA and Virgo in Italy, the advanced detectors under assembly and commissioning, and possibly the KAGRA detector in Japan, which is in its beginning stage of construction. It will bring together scientists and engineers from different fields like optics, lasers, gravitational physics, astronomy and astrophysics, cosmology, computational science, mathematics and various branches of engineering. In order to fully realize the potential

of multi-messenger astronomy, the LIGO-India project will join forces with several Indian astronomy projects. Potential collaborators include the space-based ‘Astrosat’ multi-wavelength astronomy project [15], the high altitude gamma-ray observatory (HAGAR)[16], the India-based Neutrino Observatory (INO) [17], the Giant Meter-wave Radio Telescope (GMRT) [18] and other optical/radio telescopes.

The total estimated budget over 15 years is about \$250 million on the Indian side and the value of the interferometer hardware from LIGO-USA, including the research input, is estimated at about \$120 million. The arrangement drastically cuts down the time required, perhaps by 8-10 years, to fabricate the key components and modules to specifications, assemble and operate a new advanced detector at a third location with large baseline, and this is of course the greatest advantage from the point of view of Indian scientists. By using exactly the same hardware and software as the aLIGO detectors, the confidence in the quality and understanding of the data collected in the 3 similar detectors is ensured to large extent. The two aLIGO detectors are now operational in their first observational run (O1) with about 1/3 of their projected sensitivity. The assembly and testing of the LIGO-India detector is expected to start in 2019, and by then the two aLIGO detectors and the Virgo detector will be fully operational in the network and it is likely that the KAGRA detector will be ready as well. This staggered schedule, inevitable due to the large infrastructure to be prepared, especially the UHV enclosures and beam tubes, also helps in eventual speed up during 2018-22. Some of these details are discussed in the LIGO-India ‘detailed project report’ (DPR) public document, ref. [9]. The reasonable expectation from this tight schedule requiring systematic and sustained work is that India will operate an advanced gravitational wave detector with strain sensitivity similar to the aLIGO and advanced Virgo detectors by 2022.

4 The LIGO-India project: National participation

A long term megascience project like the LIGO-India can be taken up and completed only with an inclusive national participation involving research institutes with different expertise and experience. In addition, strong industry participation is necessary while creating the infrastructure, especially the

UHV enclosures and the clean room environments. Fortunately, IndIGO has been able to identify and mobilize several key research institutes in India to take up the challenge and contribute in various ways to the project. Most importantly, three major institutes volunteered to play the lead role, with crucial contributions of deliverables in their areas of expertise. These are the Institute for Plasma Research (IPR), Gandhinagar (near Ahmedabad), Raja Ramanna Centre for Advanced Technology (RRCAT), Indore and the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune. The IndIGO consortium that started out with several theoretical and data analysis scientists and two or three experimental physicists has now grown to a large membership of over 120, with half its strength coming from experimenters and engineers. The possibility of the mega-science detector project ‘at home’ with a global presence and collaboration is unprecedented and it is certain that a larger community will form as we progress through the detector construction towards operation.

4.1 University participation

In India, fundamental science projects that involve large scale infrastructure and collaboration of a large number of people have been pioneered and managed by some of the national laboratories, notably the Tata Institute of Fundamental Research, Mumbai. Indian universities, by and large, have kept away from large scale national projects due to constraints of funding and other administrative difficulties, even though small groups have been participating as partners in accelerator based particle physics research for some time now. The Indian Institutes of Technology (IIT) faculty have been very active in several projects of small and large scales with a technology flavour, but have been minor partners in large scale astronomy or physics projects. The Inter-University Centres were set up to increase the participation of university scientists in fundamental research through centralized facilities. The LIGO-India project has generated tremendous enthusiasm among both communities and the timing coincides with the new national initiative for high quality undergraduate education through several newly set up institutes (IISER) in several states of India. We expect that the LIGO-India project will bring together researchers and students from universities, IITs and IISERs in an unprecedented scale and level of integration.

4.2 Industry participation

From infrastructure development in the initial stages to the commissioning of the detector, strong industry participation is required for the success of LIGO-India project. The large scale sophisticated infrastructure required to house the GW detector, involving technologies for UHV, steel processing, robotic welding, clean rooms, hydraulics, computing clusters, power handling etc. can be realized only with the participation of the relevant industries. Particularly important is the creation of ultra-clean laboratory environment and ultra-clean ultra-high vacuum. Therefore, ensuring participation of some of these industries, especially those related to UHV technology, in some of the discussion meetings leading to the LIGO-India project has been a priority. Even though some of the fabrication aspects that are LIGO-specific are new for the industrial partners that we have started to identify, there is a sense of new national adventure in these circles that will help them to take up the challenges. This is possible only by adhering well to the schedule and budget expenditure plan. The lead institutes and the IndIGO consortium council are keenly following up the specific needs of the LIGO-India project in this context with the funding agencies and policy makers.

We will be interacting strongly also with the electronics and computer industrial sources and a mutually beneficial long term partnership is envisaged. When the detector is operational a large amount of computing in the cloud environment is expected and it is natural that the project will contribute to the development in distributed computing in India.

The detector components, contributed by LIGO-USA define several goals for technology achievements within the country for optical components, sensor technologies, feed-back control systems, mechanical fabrication etc. Our interaction with the industry in the context of ideas and hardware for next generation detectors will help to realize some of these goals with benefits of global exposure and market for relevant specialized industries.

4.3 Outreach and higher education

There are very few internationally competitive physics and astronomy instruments operating within India. The lack of accessible and visible facilities for research that involves high technology and high finesse instrumentation directly affects the interest and motivation for choosing experimental physics and engineering physics as a career, especially in areas that requires a long

term commitment and field work. The LIGO-India project will dramatically change this situation and a large number of tested remedial steps will be built into the operation of the detector for continued engagement with undergraduate and post-graduate students in physics, astronomy and engineering. This will include introductory and advanced schools, hands-on laboratories at site as well as in associate centres at universities, IISERs and IITs, summer training programs at associated laboratories in India and abroad for selected motivated students, special LIGO-India fellowships for specialized training etc. The LIGO-India detector will be one of the very few research facilities in India of this scale, international relevance and technological innovation to which the general public and students can have access through an interface centre located not far from to the actual detector. It has the additional fascination as an instrument for astronomy of the neutron stars and black holes in distant galaxies. Creation and operation of a public outreach centre where key technologies and physical principle that make the detector will be on display, some of which for hands-on access, is an integral part of the project, as has been the practise in LIGO-USA, AIGO etc. as well. This will also serve, through direct interaction and through web-based services, as a centre for continuing education on these topics. Subsidiary centres of a similar nature will also be set up in the associate centres of the IndIGO consortium for wider reach, especially to school students. We will also tie up with national planetariums in different cities in India for programs on gravitational wave astronomy and teacher training in related areas. The home computer based 'Einstein@home' program for data analysis for continuous wave sources that is currently running as part of the gravitational wave detection global activity will add to the public outreach program. It is not inconceivable that with the enthusiasm among students in India to get involved in such projects this program will touch a 1 million user mark and 1000 Tflops peak.

4.4 Synergy of funding sources

A national megaproject of this scale and spread of participation needs synergic funding and support from multiple national agencies. Indeed, the project proposal was considered by the two prominent national agencies that support fundamental research in physics and astronomy in India - the Department of Science and Technology (DST) and the Department of Atomic Energy (DAE). Projects requiring large financial support need to generate a consensus among scientists, science planners and public funding agencies.

The IndIGO consortium prepared and submitted the LIGO-India proposal in time before the National Planning Commission finalized its allocations for the fresh 5-year plan for revenue spending in India (2012-17), after making several presentations in several forums, stressing the imminent detection of gravitational wave and the potential and importance of ensuing GW astronomy. In a joint meeting of representatives of the entire astronomy community in India, which discussed several large scale astronomy projects, LIGO-India received enthusiastic support, and the two agencies (DST and DAE) agreed to include the LIGO-India proposal in the list of Mega-Projects being considered by the planning commission of India.

5 Prototype detector at TIFR, Mumbai

It was realised from the outset that an advanced prototype interferometer detector that incorporates all essential features of the large scale detector is an important element in the road-map for GW research and astronomy in India. Therefore a detailed proposal for 3-m scale power-recycled interferometer detector was prepared in 2010 and submitted to the TIFR, Mumbai where associated expertise and facilities for taking up such a project existed. After extensive discussion and evaluation this project at an estimated cost of \$500,000 was approved. However, the need to construct an entirely new laboratory building and the delay in fund flow as well as in the approvals for LIGO-India have introduced some schedule uncertainty. It is expected that there will be an operational interferometer with a displacement sensitivity of about $10^{-17}m/\sqrt{Hz}$ by 2018, in the newly constructed laboratory. I now summarize the main design features and goals of this prototype detector (Fig. 5).

The prototype detector is expected to serve as the research and training platform with all the features of the aLIGO-like detectors, scaled down to displacement sensitivity around $10^{-17}m/\sqrt{Hz}$ above 100 Hz. It will be the Indian research platform for features like signal recycling, DC read-out, and most importantly the use of squeezed light and noise reduction for precision metrology. It is envisaged that some parallel development on squeezed light based measurement technologies will be developed and this will be implemented in the prototype interferometer after 2018. It will also serve as a superb instrument for novel studies on short range gravity and QED force, especially a measurement of the Casimir force in the range 10 -100 microns

Subsystem	Design features
Interferometer	Power-recycled Michelson-Fabry-Perot, 3 m long FP arms, Finesse FP:300, Finesse PR:35
UHV System	10 m ³ volume, 10 ⁻⁸ mbar 1.8 m x 0.75 m (H x dia.) UHV chambers, 20 cm dia. beam tubes
Pumps	600 l/s Ion pumps and 3000 l/s NEG pumps
Laser	1 W NPRO pre-stabilized, 200 mW into the interferometer
Optics	15 cm dia. mirrors and beam splitter in Aluminium holders, 3 kg approx.
Suspensions	Steel & Tungsten ribbons and fibers
Mode cleaners	Triangular cavity (< 3m)
Vibration Isolation	Passive. 3 vertical stages (1 Hz) : attenuation > 10 ⁹ @100 Hz 4 horizontal stages (1 Hz) : attenuation > 10 ¹¹ @100 Hz (with one stage of pre-isolation)
Feedback controls	Optical sensors and magnetic force control. LabView and NI cards on PXI platform in the first phase.
Projected displacement sensitivity	<10 ⁻¹⁷ m / $\sqrt{\text{Hz}}$ @ 100 Hz

Figure 5: Feature summary of the small prototype detector.

where no previous measurements exist [19]. The main idea here is that even though the response of the suspended end mirror to a modulated force at frequency ω contains the attenuation factor $(\omega_0/\omega)^2$, the already fine displacement sensitivity $10^{-17}m$ can be enhanced with integration to below $10^{-19}m$ over several hours. This makes the Casimir force measurable with good precision for separations larger than 10 microns. Possible coincidence operation with next generation cryo-mechanical detectors by optimizing the sensitivity at 2kHz+ by signal recycling and use of squeezed light (at strain sensitivity approaching $10^{-20}m/\sqrt{Hz}$) is also envisaged.

6 Satellite projects and Precision metrology

A natural outcome of a project like LIGO-India is its catalyzing ability. With a large number of advanced technologies that have been stretched to their present limits in use in LIGO-India, the project is at once a model system for the use of similar technical strategies in other areas of precision metrology of both fundamental and practical nature, and a motivating platform for the

next generation technologies. Only when the limits are visible, one is spurred into conceiving the next generation of technologies. In our laboratory, satellite projects to develop matter-wave interferometers based on both ultra-cold atoms and liquid helium will be taken up with a view to contribute to next generation gravitational experiments, potentially including GW detection. Cold atom interferometers are just an additional step or two from a wealth of technologies that we already developed at TIFR, working with ultra-cold Rb and K atoms as well as Rb Bose-Einstein condensate. The fact that the gravitational coupling energy and therefore the gravitationally induced phase for an atom with a mass of 100 GeV is about 10^{11} times the gravitational energy of a 1 eV photon is the major advantage of a matter-wave interferometer exploring gravity. However, the size of matter-wave interferometers are tiny compared to optical interferometers and the possible configurations are limited. Yet, it is speculated that these might allow breakthroughs in several types of gravitational experiments, including the detection of gravitational waves [20]. Matter wave interferometers are also important in addressing foundational questions on the quantum dynamics of particles in gravitational fields [21].

It is expected that a significant number of researchers in IISERs and IITs will take up small scale projects associated with LIGO-India aimed at technologies to be incorporated in the next generation detectors. Novel sensor modules and electronics, UHV compatible devices, compact and sensitive tilt meters, displacement and angle sensors, accelerometers and gyroscopes, computing strategies, integrated optics etc. are some examples. Due to the stringent requirements on the spatial placements of LIGO optical components, high precision survey has been an important aspect of the LIGO installation, and the methods used in defining the coordinates for LIGO-India precision installation are expected to contribute to geophysical measurements and survey strategies. The LIGO-India detector itself, equipped with its elaborate active vibration isolation system, is a sensitive instrument to monitor geophysical phenomena in the acoustic frequency range.

7 LIGO-India and the Indian space science program

It is clear that the greatest potential for gravitational wave astronomy resides in the wavebands in the range 10^{-5} Hz - 1 Hz. Only a space-based detector with sufficient large arm length in that relatively noise-free environment can sense these signals. Even though the original LISA project is currently not realized, new thinking on this possibility will remain active due to its importance, and the inevitability from the point of view of the physicist and astronomer. Other possibilities are also being discussed, like the ASTROD-GW (China) [22], eLISA (ESA) [23] or DECIGO (Japan) [24]. In addition there are a few space-based gravitation experiments of high significance, like the GG [25], which can benefit from the involvement of an active space-based fundamental physics program in India. We expect that LIGO-India will motivate new initiatives within the highly successful Indian Space Research Organization itself towards new astronomy and fundamental physics.

8 LIGO-India: Schedule and Progress

Though many of the steps in bringing the proposal to the final stages of approvals have been taken, the final approval and funding allocation for the project from the cabinet committee of the government of India is still awaited, as of October 2015. Given this situation, there are constraints on going ahead with the initial tasks on site identification and selection, identifying potential partner institutions and industries, visits to LIGO-USA etc. However, the lead institutes have been active on the project and have now identified expert teams within, for several technical tasks of LIGO-India. Working visits from IndIGO members as well as training of researchers, engineers and post-doctoral fellows at the LIGO observatories at Hanford and Livingston in the several technical aspects of the aLIGO detectors is an intergral part of the early schedule. The EGO consortium in Europe, managing the Virgo detector, also has extended help in the matter of training and technology exposure. The IndIGO consortium members have been working on the initial tasks with support from the lead institutes. Most significantly, several potential sites in several states of India have been visited and preliminary measurements on seismicity and environmental noise factors have been con-

ducted. The policy is not to compromise on the strict constraints laid out for a suitable site in terms of its long term isolation from seismic and man-made noise, while keeping in mind the accessibility for construction and operation on schedule.

The ground noise models at the LIGO Hanford and Livingston sites are indicated, for reference, along with the requirement on residual noise after the pre-isolation stage, in figure 6. The active pre-isolation system for LIGO is already designed and fabricated to bring down the ground vibration noise at the two LIGO sites to the required level, with isolation factor of about 1000 in the frequency range 1-30 Hz.

India has several low seismicity areas, usually indicated as zone II in seismic activity maps in India. From short term seismic surveys conducted over two weeks each, it is now known that isolated areas in these zones are seismically quiet enough to install an advanced gravitational wave detector. Many potential sites that are more than 150 km from the ocean in such areas, spread around India in the Deccan plateau in Karnataka and Andhra Pradesh, and in Madhya Pradesh, Rajasthan and Chathisgarh, for example, have been visited for preliminary evaluations. Long term weather data from the meteorology department or from the repository at the nearest airport, as well as about 2 weeks of seismic noise data have been obtained. Typical ground noise measured in such sites during quietness is shown in the figure 7, obtained from IndIGO measurements spanning about 2 weeks with a 3-axis wideband Gurlap seismometer (more recent extended measurements confirm this trend). Since the typical ground noise at the sites we briefly explored in this frequency range seems comparable to that in the LIGO sites, the same isolators are expected to ensure their intended isolation levels in LIGO-India.

As for development of other infrastructure, the review of technical drawings on the interferometer stations and the UHV infrastructure has progressed well enabling readiness for quick start after the cabinet approval. Capability for handling the pre-stabilized laser as well as for the fabrication and welding of the silica fiber suspensions of optics is now developed and the sense of technical readiness is strong.

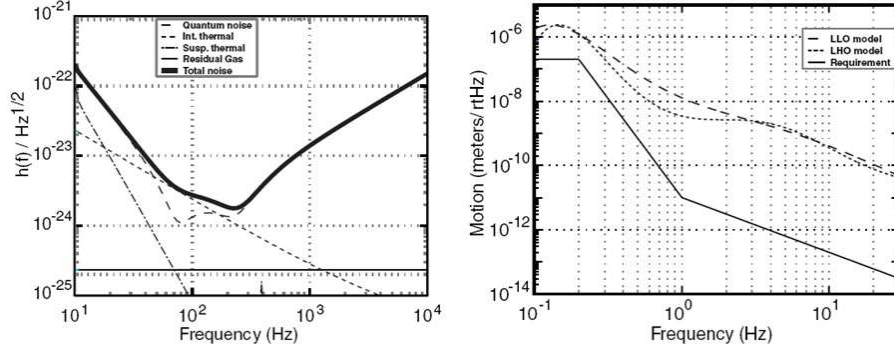


Figure 6: Left: Sketch of aLIGO projected strain sensitivity. Right: Approximate displacement noise spectral densities at the two LIGO sites Hanford and Livingston, along with the requirement (solid curve) on displacement noise where the seismic isolation system supports the test mass suspension (from ref. [26]).

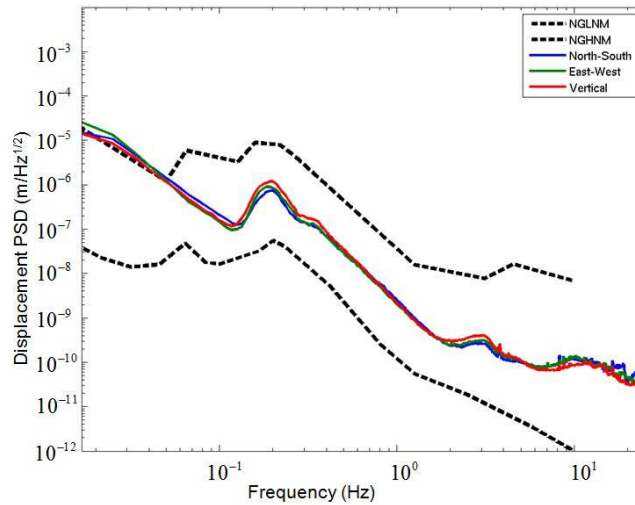


Figure 7: Measured ground noise power spectral density during quiet times at a typical site in India, pre-selected using seismic zone maps (prepared by Rajesh Nayak and Supriyo Mitra, IndIGO consortium. More detailed and updated information is available at www.gw-indigo.org).

9 The era of LIGO-India operation and GW astronomy

India already has a strong community of young GW researchers involved in data analysis and source modeling aspects. Therefore, the user community for LIGO-data within India is substantial and will grow further. In fact, it was this aspect that was the initial driving force behind IndIGO and LIGO-India. One focus for theoretical developments will be strategies for handling independent noise from the different detectors, especially multi-detector coherent searches for sources where the data from different detectors in the network is combined and analyzed with the phase information (aperture synthesis), instead of just coincidences in time. The goal is efficient coherent search for GW signal from binary mergers using data from global detector network. The interface of cosmology (through CMBR) and GW is another key area of interest here. What is envisaged is an integrated environment for astronomy data storage and handling, more or less mirroring the evolving vision within the GW community that GW astronomy will need simultaneous and triggered observations by different types of telescopes and detectors, spanning the electromagnetic spectrum, as well as arrays of cosmic ray detectors. An advanced data centre with large computing power and storage is integral part of the LIGO-India plan and the first stage of the centre is being set up at IUCAA, Pune. This data centre with several hundred Terabytes storage and about 100 Tflops peak computing power is now operational and will eventually serve, with appropriate upgrades, as a Tier-2 data archival and computing centre for signals from the global GW detector network.

10 Summary

I have sketched some key developments on the large canvas of the LIGO-India project, the extend of which is vast, transformational for Indian science, technology and higher education, and rejuvenating for Indian physics and astronomy.

11 Acknowledgments

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