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LIGO-India Instrument Science White Paper 2024

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Introduction

The LIGO-India Instrument Science White paper outlines priority areas of interest for the LIGO-India project. To ensure that this white paper reflects the evolving priority areas as the project goes forward it may be revised periodically, say every 3 years. This Instrument science white paper identifies R&D topics at three levels; (a) projects that act as a seed activity for a new group which is starting a GW Experimental activity, (b) projects that lead to capacity enhancement of existing experimental groups to enable their participation in GW experimental activity and (c) projects that would enable new Indian groups to contribute to GW Instrument Science including Calibration, Newtonian noise, stray light mitigation, Det-char, etc. through LISC.

The topics of this White paper encompass site and facilities modeling for enhanced detector performance, modeling, simulation and process-optimisation related to the Vacuum system, design & development of vacuum system components for indigenisation, new designs for ultra-narrow linewidth oscillators, amplifier stages for the pre-stabilised laser system, core-optics characterisation, optical coatings development, ab-initio modeling for candidate low CTN coatings, suspensions modeling/prototyping, vibration-isolation, adaptive control systems, AI/ML based interferometer locking, stray light modeling/mitigation, calibration, etc. These topics of interest are classified into three broad areas (a) Topics related to the LIGO-Aundha Observatory (LAO) site and Facility (b) Topics related to LIGO-Aundha Detector - A1 and (c) Topics concerning long term research needed for next generation detectors.

The instrument science white paper is intended to be “harmonious” with the LIGO Instrument Science White paper and addresses topics not overly subscribed in the current LSC and those that are pertinent to the LIGO-India Project during the construction phase. The topics of the white paper have a significant number of R&D components to be able to attract research groups who may be interested in publishable results apart from the deliverables. The intent of choosing the topics is also to cover the various aspects of expertise required during the commissioning phase of the LIGO India project as the project hopes to draw on some of the project personnel trained as part of the R&D efforts to contribute to the commissioning effort.

The LIGO-India Project involves a baseline characterization of the site for establishing the parameters of the site before construction begins. This is required to ensure that the low-frequency noise quality of the site is retained by the facility that is built on the site and serves as an acceptance criteria for the facility. The building construction on the corner and end-stations would proceed in parallel and the vacuum chambers would be first installed in these buildings. One of the first detector subsystems to be installed will be the Physical Environment Monitoring (PEM) system which will happen concomitant with the Vacuum system installation. This will help identify ground and acoustic noise generated by various equipment as they are installed and their mitigation efforts. While the corner station and endstation detector equipment is being installed and commissioned, the beam-tube construction would proceed. The sequence of construction, installation and commissioning activities are scheduled so as to minimize project execution time. Once the vacuum system installation is completed and detector parts are installed, commissioning, engineering runs and the first science run would be undertaken in that order. After the first science run the Project would move into the Operations phase, which is expected to begin by 2030. The projects suggested in this White Paper may be seen in the light of this road-map and their relevance to the LIGO-India project may be weighed in relation to project timeline.

Research areas of interest

1. Site specific R&D, O&M and the Vacuum system

Several studies on the site, to establish the baseline seismic properties of the site before construction begins, were carried out by NGRI through a seismic survey and DCSEM through a geophysical survey. The information gleaned from these studies has been used in designing the buildings and the site layout. In addition to these studies, further work, which may guide the design of the buildings and mitigate the seismic degradation of the site due to the structures and machinery coming up may be needed. Some of these results may be needed quite soon, as we reach the end of the design phase and enter into site development. The studies in this section are divided into three kinds: (a) Those which solely pertain to the buildings and structures coming up on the site (b) Those which pertain to the facility maintenance and machinery that is going to be installed and (c) The vacuum system related studies.

a) Site characterisation studies

i) We have one weather station on the site presently and there is a need to install additional weather stations near both corner-station and end-station buildings. Studies of weather station data, which lead to a better understanding of the impact on the detector both at design phase (eg. humidity driven corrosion, diurnal and seasonal temperature fluctuations which load the air conditioning system) and during O&M phase (the wind driven building vibrations being transmitted to the suspensions, design of a wind fence) are needed.

ii) Seismic studies at the site (primarily data analysis): The existing one year of seismic data needs to be fully analyzed to determine and locate the sources of noise and the amount of noise generated by the anthropogenic noise such as roads, bridges and heavy vehicles moving on them. It is necessary to establish the present baseline noise levels so that we may observe the degradation of the site as facilities are developed. The goal is to ensure that the seismic noise of the operational observatory is not more than four times the baseline seismic noise of the site at present.. Subsequently, for modeling the propagation of seismic waves through the subsurface structures it is necessary to build a good model of the subsurface structure. One of the ways is to measure the velocity profile through subsurface structures and propagation constants for various frequencies at the site.

iii) Fiber-optics seismic sensors offer a distributed sensing of the strain along the arms which may be used in seismic feedforward and thus mitigate low frequency seismic effects in the interferometer. Commercial sensors are also available in this domain and may be deployed along the arms as the facility comes up to study these effects.

b) Facility related R&D

i) Wind induced vibrations

Endstation buildings, driven by wind buffetting, are known to introduce seismic noise into the interferometers in the USA. Studies utilising Computational Fluid Flow (CFD) to understand the nature of turbulence caused by the buildings was used to reshape the corners of VEA buildings to reduce the effects (TDCB project of BITS Hyderabad).

While the effects are expected to be reduced due brick and reinforced concrete construction of the LIGO-India buildings, detailed Finite Element Analysis (FEA) of buildings and their coupling to ground needs to be ascertained. These studies may further refine the design of the buildings and mitigate the effects of wind induced noise. If these are found to be significant, we may consider installing a wind fence at appropriate distance from the end station. Developing the FEA and CFD models of the wind fence may also be undertaken to determine optimal design and placement. Wind flowing over the undulating terrain may also pick up unusual seasonal behavior. Modeling wind velocity at the end-stations and the corner station using the data from the weather stations may help us to improve our designs and offer the possibility of local landscaping to further mitigate these effects.

ii) Physical Environment Monitoring (PEM)

Sensors need to be installed on the site as the buildings come up in order to monitor the increase in the seismic levels, temperature, magnetic field fluctuations, ground currents etc. Such continuous monitoring, while the construction is in progress may help us identify the causes and take corrective action as heavy machinery is installed. One such source is the Air Conditioning system (HVAC). The thermal stability to within 0.25 degC within the LVEA and VEA enclosures is hard to achieve in present day technology. The uncorrected temperature gradients across these enclosures have been shown to be strongly correlated to the drift of the alignments in the interferometer. Mitigating such effects, while not increasing the capacity of the HVAC, which in itself, is a source of local ground vibrations, is a challenge and needs further study. New techniques for monitoring of AC ground loop currents is needed to ensure that the EMI generated from these loops is minimized.

c) Vacuum System Maintenance and Troubleshooting

As observed at LLO, the 4 km long vacuum tubes may develop leaks in the long run. It is very difficult to detect these leaks and take corrective action unless some system is put in place right from the start. Along with addition of ports and pumps at regular intervals, which may be brought into service when required, we also need a well developed model for the vacuum system. Such a model, utilizing the data from the vacuum pressure sensors and residual gas analysers, may enable us to monitor the health of the vacuum system effectively and enable us to quickly locate the leaks with much less effort. Maintaining a low particle density along the length of the tube, not only to meet the requirements of the presently planned detector but also for the next upgrade (may be in about 15 years from now) would require us to pay close attention to the materials, the welding techniques and surface preparation techniques used to build the vacuum chambers and tubes. New techniques to reduce outgassing from the surfaces, improve measurements of hydrocarbon contamination and more efficient techniques for pumping hydrogen may need to be explored.

2) Aundha Detector related R&D

The 3rd Interferometer (3rd IFO) parts were placed in storage in 2016 at LHO and are waiting to be shipped to India. The present L1 and H1 detectors have seen many improvements and changes since then. LIGO-Aundha detector (A1) would need to be closely matched to L1 and H1. While the optical layout and subsystems of A1 are to be maintained the same as H1 (which more closely resembles the A1 due to the terrain and weather patterns near Aundha), it is quite likely that small differences may arise. Some of these would pertain to the specific manufacturing deviations of core-optics from design, or design layouts pertaining to the filter cavity etc. In addition, several changes have been introduced into LAO design following recommendations by LIGO-Lab USA. Due to these and many such reasons, A1 would be different in detail from the exiting detectors. Significant amount of work needs to be undertaken to implement these changes and ensure that A1 reaches a sensitivity comparable to that of L1 and H1. This section deals with all such research work, specifically focussed on attaining aLIGO design sensitivity in the A1 detector.

a) Interferometer modeling and noise budget estimations

Several different approaches in modelling the interferometer have been developed over the years. Finesse Simulation, is a frequency domain tool and has a well developed user group. An accurate optical model of the interferometer may be prepared and used to obtain the optical response of the detector. L1 and H1 models are maintained by the site personnel in collaboration with the LSC Finesse group. However, high spatial frequencies and their effects on the fields in the high power arm cavities modelled through the E2E simulation tool maintained at Caltech by Yamamoto et al. has been effectively used to identify hotspots on the mirrors. We need to develop expertise in this tool and develop a scalar propagation model of the A1 detector. While these two tools focus on the optical plant, the control system utilising the aLIGO Control and Data System (CDS) and the feedback servo-control techniques developed by the LIGO-Lab require a time domain tool to simulate the entire electro-optical system. These are computationally hard and big data problems due to the non-linear complexity of the optical system.

b) Simulation and Characterizations of backscatter

Scattered light within the vacuum chamber has proven to be a significant deterrent in improving the sensitivity of the detector. Over the past several years both L1 and H1 have been engaged in identifying ghost beams and diffuse scattered light finding their way back into the interfereometer and adding noise to the detection channel. Accurate scattering models and ray tracing models were built to diagnose this problem and prevent this light from reaching the sensing pathway. We would need to generate libraries of measured angle dependent scatter for materials in and near the optical path. We would also need to develop a PEM system capable of monitoring the scattered light, as the back scatter hot-spots are unique to each site. The information obtained from these PEM channels is then incorporated into interferometer simulations to identify the dominant channels of noise injection. These simulations require non-sequential field estimation and possibly some combination of non-sequential ray tracing and Hiro Yamamoto's SIS code. Identifying these hot-spots through characterisation of optics and simulating their effects beforehand would significantly speed up the commissioning of the detector.

c) Control loop analysis and troubleshooting

The Advanced LIGO detectors, and indeed all suspended-interferometer based detectors, are heavily dependent on finely tuned feedback control systems in order to maintain the interferometer at its working point, well within the linear regime of operation. A significant portion of the commissioning and operations manpower are devoted to develop the hundreds of control loops both at the level of individual sub-systems (suspensions, seismic isolators, stabilized lasers etc) as well as the global control of the interferometer. The technical noise at low-frequencies arising within these feedback control systems is one of the limiting noise sources in present day detectors. Efficient algorithms which may help us determine the plant transfer functions to a high precision, and quickly come up with a finely tuned control filter, would be very valuable tools. Optimal system identification using methods such as those advocated by Pintelon and Shoukens may be explored. Such modern control techniques may be developed and tested in existing detectors, well before A1 is ready for commissioning. In addition, the plant is not indeed time-invariant at the level of optimisation we are seeking. Recent development in Machine Learning (ML) and Artificial Intelligence may also be explored for designing adaptive control filters utilising free-running data, and a preset cost-function, to suggest in-situ changes to the filter parameters. Neural Network based Reinforcement Learning algorithms, which further optimise feedback loop design, may be explored.

Noise models for each of the LAO subsystems such as LSC , ASC, SEI, SUS, Aux Optics, PSL, OMC and so on, would be needed in order to estimate the noise sources contributing to the total noise of each subsystem. Such models enable us to identify and prioritise those noise sources which deserve our immediate attention (the loudest). Future searches for GW sources at high frequencies, ~1 FSR away at 37.5 kHz, may also require us to fine tune the control system in order to extend the detector sensitivity to this range and suppress noise at these frequencies.

d) Seismic isolation and suspensions

One of the persistent technical noise sources at frequencies below 30 Hz is seismic sensor noise. The low frequency noise, driven by the microseismic peak at 0.14 Hz, also gets upconverted to higher frequencies through nonlinear processes within the internal seismic isolators (ISI) of aLIGO. Sensing and attenuating the seismic peak from reaching the upper stages of ISI, especially during bad weather in the oceans, is very necessary. Presently aLIGO internal seismic isolators utilize several different sensors whose signals are carefully blended to give a unified broadband seismic sensitivity ranging from 0.005 Hz to about 100 Hz. Capacitance position sensors, broadband inertial sensors with force feedback and geophone signals are carefully blended and used within feedback loops. Each of these multistage seismic isolators use multiple such sensors to sense all the six degrees of freedom of the isolation platforms. These sensors ultimately limit the displacement noise that is finally achieved at the suspension points of the quadruple suspensions, which rest on these isolated platforms. Reducing seismic sensor noise therefore has a direct impact on the seismic noise attenuation of these platforms. Any future upgrade of the detector, which aims to extend its sensitivity to lower frequencies also needs to improve our capability to sense and attenuate motion at low frequencies. Besides decreasing the internal thermal noise of the sensors through proper choice of high-Q materials, one may also work on improving the electronics used by these sensors and the displacement sensors used to sense the inertial mass motion.

e) Optics and Coatings

i) Core optics

Coating thermal noise is a limiting noise source for all present day detectors in the range of 50 to 100 Hz. Globally many groups are proposing alternate coating recipes in order to minimise optical absorption, mechanical Q and thermal noise of these multi-layer dielectric coatings. The large number of parameters which need to be optimised has resulted in a large search space. Therefore multiple test facilities, where new coatings are tried and tested, is needed to explore this space and identify a suitable coating recipe. Some recent progress with crystalline AlGaAs coatings has shown promise, however scaling this technology to larger surfaces continues to be a challenge.

Parametric Instabilities (PI) in the interferometer arms, caused by excitation of body modes of the test-masses by radiation pressure noise is a show stopper unless these excitations are damped. One of the effective ways to damp them is to to use passive dampers placed on the test masses. This has been achieved for the lowest frequency body modes, however, in the near future we will also need to address the higher order body modes (HoM) by appropriately designed passive dampers.

ii) Auxiliary Optics

There are a multitude of problems in Auxilliary optics subsystem which require solving. Suppression higher order TEM mode content in the Pre-Mode-Cleaner (PMC), reduced beam pointing noise on the output beam of the PSL, increasing the control bandwidth of the PSL frequency and intensity noise loops, development of a fast shutter to protect the sensitive photodiodes in the dark port of the detector. Reduction of noise in the Angular sensors such as the Wavefront Sensors at low frequencies, low spatial frequency wavefront sensor to sense and filter higher order mode content, low-noise reference cavity for PSL with improved thermal control and vibration isolation are some of the problems which require our attention.

f) New Calibration Techniques

i) Photon calibrator is presently utilizes a complex system of comparisons to maintain a 1% level power calibration at 1W of laser light. It would be more convenient to have an absolute power calibration capacity at 1W of power. So far this power calibration was achieved within the USA with the help of NIST. LIGO-India makes it necessary to have an internally valid power calibration across many nations, so as to maintain an uniform, internationally recognized calibration.

g) CDS system and DAQ system

i) The CDS system presently uses custom built firmware on General Standards ADC and DAC cards in order to communicate with them. The newer version of CDS permit us to use alternate DAQ cards and develop drivers from them in the Debian OS. Many of the software tools developed by the LIGO community over the years is being ported to modern software like Python, this is an ongoing effort. These extensive software tools require considerable mathematical analysis to ensure that they yield accurate computational results. The CDS also requires a new timing system which recovers from synchronization errors quickly and maintains a robust timing system across the globe between L1, H1 and A1 as well as other gravitational wave detectors.

ii) Improving the RTCG and parser: The realtime code generator (RTCG) is continually being improved to achieve better performance and requires regular maintenance. The parser also needs such developmental effort. Some of the glitches observed in the data stream are suspected to be from the RTCG code and this needs to be investigated. Similarly the digital filters extensively used in the CDS filter banks) required attention to ensure they are not adding noise to the signals being processed.

h) Investigating new hardware (Timing cards, ADC, DAC cards etc)

In the present detectors the DAC noise is far above suspension thermal noise or Newtonian gravity noise. A new architecture for the DAQ system utilizing FPGA based controls of various important control loops such as the intensify stabilisation servo (ISS), pre-mode-cleaner (PMC), frequency stabilization servo (FSS), common mode servo board (CMB), arm length stabilisation (ALS) and its associated DAC noise are some of the Data Acquisition and digital control system related improvements needed.

The upconversion of low-frequency noise to higher frequencies is not chiefly due to the digital-to-analog ‘staircase’ pattern, but rather has to do with timing mismatches when many bits are flipped. One approach to resolve this problem may be to develop a low latency, low noise DAC or fix by software feedforward. Significant improvement may be made in low-noise analogue electronics through RFI mitigation, which presently causes wandering lines in the pulsar searches. This effect probably arises from beating of RF oscillators’ radiation in nonlinear electronics elements (“VCO whistles” in data analysis of glitches). One way to get around this problem is to send RF local oscillator excitations over Optical Fibers and collect the signals from the RF photodetectors over fiber. These and such solutions are not found as “off the shelf products” and therefore need development.

i) Detector Characterization which is IFO operations focussed

i) A Global Diagnostic System (GDS), which is capable of capturing malfunctions of the interferometer in realtime and providing enough diagnostic information to help us to trouble shoot is very much needed. Such a software tool should enable us to perform tasks such as automated servo tuning (we may find examples within the aero-space industry), automatic noise budget estimation, identify noise sources and pathways through which noise couples to controlled parameters. To achieve this additional instrumentation for collecting diagnostic information may be needed.

ii) Detector Characterisation effort also requires software capable of monitoring the various data channels and flagging data for various categories of vetos in real time.

3) Long term detector upgrades and GW Instrument Science

Gravitational Wave International Committee (GWIC) has published a report for future 3rd generation detectors and identified R&D required for developing the technology needed for these detectors [3] The timescale for development of these detectors being about 15 to 20 years, much of the technology development for them has to start now in order to meet that timeline. GWIC also has identified the readiness of available technology today and therefore where additional manpower needs to be deployed. Crucial areas of interest from a LIGO-India perspective are cryogenic suspensions operating test-masses at 20 K and associated cryogenic technology for sensors and actuators to reduce thermal noise in these systems. Future detectors may utilize high power CW lasers at 1.5 and 2 microns wavelengths in conjunction with silicon and sapphire test masses with appropriate low thermal loss coatings. Improved low-noise 1064 nm laser amplified by a Fiber amplifier to deliver the needed 200 Watts of power continue to be of interest for the next upgrade. Simulation and noise budgeting of a 3rd generation detector, which may be housed in the LIGO-India facility in the future, are crucial for guiding the technological development. Studies in non-equilibrium Statistical Mechanics and theoretical investigations in fluctuations of Young's Modulus (an interdisciplinary field at the interface between condensed matter physics and material science) are necessary to improve our understanding of thermo-elastic properties in materials at low temperatures.

References:

1) Instr Sci White Papers(2024, 2022-23, 2021)
2) Operations White Papers (2024, 2022-23, 2021)
3) R&D for next generation of ground based gravitational wave detectors