GWADW2022 - Approaching the low-frequency design sensitivity of ground-based detectors

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GatherTown and ZOOM

Book of Abstracts

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He-II filled marionette suspension for the cryogenic payload of the ET-LF interferometer

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Abstract. The low-frequency interferometer in the Einstein Telescope (ET-LF) shall be operated at test mass temperatures of 10 K to 20 K. Motivated by the potential of using superfluid helium (He-II) for cooling the test masses due to its exceptional heat transport properties and presumably low dissipative behaviour, we present the concept of integrating a double-walled He-II filled marionette suspension in the payload design. During the cool-down process, supercritical helium (He-I) at adjustable temperature flows in counter-flow through the double-walled suspension in order to cool the marionette. In steady-state operation, the suspension is filled with liquid He-II at rest, providing ultra-low noise cooling at 2 K via steady-state heat conduction. Considering the crucial role of the payload suspensions on the ET-LF sensitivity, we present the results of a thermal and mechanical feasibility analysis with particular
focus on suspension thermal noise.

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Characterisation of bonded silicon components towards assemblies for 3rd generation detectors

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A crucial milestone was recently completed in the IGR in the form of the first silicon suspension hanging on Hydroxide catalysis bonds and surviving cooling to cryogenics temperatures. Although the prototype allowed to validate multiple engineering concepts, it is expected that HCB won't meet the thermal noise requirements for the 3rd generation of gravitational waves detectors. For this reason, the focus is now placed on improving the bonding technique, and particularly on investigating direct bonding. A range of surface activation processes is studied with the help of a brand-new surface profiler to correlate surface property and bond quality. Bonded samples are prepared for strength and mechanical loss measurements. The testing processes have had to be re-thought to fit the new geometry used, and preliminary results on the effect of pre and post-processing are obtained.

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Sapphire suspension in KAGRA –Current design and perspective-

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Cooling mirrors and their suspensions are promising way to reduce thermal noise. To maximize the benefits of cooling, utilizing low mechanical loss material at cryogenic temperature is essential; therefore, KAGRA mirrors and their suspension fibers are made of sapphire. To achieve good cryogenic suspension, there are several technical difficulties because the suspension needs not only low mechanical loss for thermal noise reduction but also high thermal conductivity for keeping mirror temperature low. In this talk, we present a review of the current KAGRA sapphire suspension and its perspective.

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Sapphire technology for cryogenic detectors: new results from Lyon

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The institutes iLM and iP2i in Lyon are involved on a significant effort to develop the sapphire technology for the future cryogenic detectors. iLM is taking care of the crystalline growth of ultra-low level of optical absorption and mechanical losses of mirror substrates and last stage suspensions. iP2i through the platform LMA develops the ultra-low level of total optical losses of mirrors, working on aberration, scattering and absorption. The collaboration is finalising the development of a large oven able to grow 500kg sapphire ingots for the production of 450mm diameter mirrors. In parallel the investigation on the growth of ultra-low absorption sapphire is ongoing and the details on the most recent result of 10ppm/cm sapphire will be presented. The impact that this new advancement will have on the ET suspensions will be given too.

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A new approach for suspending cryogenic mirrors

Authors: Francesca Badaracco[1] ; Kazuhiro Agatsuma[2] ; Alessandro Bertolini[3] ; Andrea Chincarini[4] ; Joris van Heijningen[1] ; Luca Naticchioni[5] ; Paolo Ruggi[6] ; Stefano Selleri[7] ; Riccardo DeSalvo[8]

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The Einstein Telescope will increase the sensitivity to gravitational wave detections with respect to the current detectors, especially in the low-frequency band (down to 2 Hz). Reaching such sensitivities at low frequencies implies great technology challenges: in order to reduce the seismic and the thermal noise very soft suspensions and cryogenic temperatures are needed. A big challenge arises here: to bring and to keep a test mass at temperatures around 10 K we need to extract heat from it.

The only way to do this is via thermal conductivity of the test mass suspension elements. However, soft suspensions are non-compatible with the need of extracting heat which would require short suspensions with a large cross section. We propose here a new suspension morphology in order to allow a good heat extraction without spoiling the softness of the suspensions. This should provide a good solution to one of the biggest technological problems of building the Einstein Telescope.

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Silicon suspensions: thermal noise and mechanical properties

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The design of cryogenic suspensions for mass tests for future generation GW detectors is based on the balancing of several factors: mechanical properties, thermal conductivity, resonance frequencies, thermo-mechanical stress and generally any parameter that aims to reduce thermal noise of test masses. The talk will present the state of the art of studying the mechanical and thermal properties of silicon as a function of the orientation of the axes and how these can influence the design of a monolithic suspension. Furthermore, the measurements of the limit load on fibers produced at the maximum of the current technique will be described and compared with the expected limit load, trying to understand the limiting factors. Finally, we will describe the tests done so far to measure the mechanical dissipations of the mono-crystalline silicon fibers and the limits found.

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Thermal and mechanical simulation of the cryo-payload: status and preliminary results.

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In the design of the cryogenic payload, thermal and mechanical FEA models are used for optimizing the system both for its structural and thermal behavior. The thermal study is important to have the temperature distribution along the suspension wires and the thermal resistances of to the various interconnections between the parts of the suspension. The mechanical study gives the estimation of the losses present in the system. We will present the status of this combined method to have an estimation of the suspension thermal noise with the Levin method.

Plenary / 59

AdV+ low frequency noises challenges and plans

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Advanced Virgo Plus is a two step plan for improving the sensitivity of Advanced Virgo for the O4 and O5 observing runs. After discussing the low frequency noises that have limited AdV in O3, we will present the planned AdV+ upgrades and adjustments that aim at reducing the low frequency fundamental and technical noises for O4 and O5.

Plenary / 28

Approaches to low frequency noise in LIGO

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This talk will overview the current views of low frequency noise contributions in LIGO. This overview provides context to discuss potential upgrade options either to reduce direct noise contributions or to address underlying causes of complex bilinear noises.

Plenary / 6

Multi-messenger observations of gravitational-wave transients

Author: Alessandra Corsi[1]

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Starting from the example of GW170817, I will discuss prospects for multi-messenger gravitational-wave astronomy, highlighting opportunities to clarify currently open questions in the field, while expanding multi-messenger studies beyond the realm of compact binary mergers.

Plenary / 5

Observing black holes throughout the Universe

Author: Colpi Monica[1]

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I will overview how extending detector sensitivities at low gravitational wave frequencies will let us observe the first merging stellar black holes forming at cosmic dawn, and unveil the still elusive population of intermediate-mass black holes, which provides clues on the yet unknown origins of the massive black holes lurking at the centres of today's galaxies.

Plenary / 3

Introduction of the meeting

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Poster session I / 77

Low-frequency, high-resolution, optical inertial sensors

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Large-scale, high-end, scientific instruments see their performances significantly impaired by residual ground motion at low frequencies. Namely, recent development of gravitational wave detectors aims to detect gravitational waves whose strain is as low as 10-20 Hz-1/2 in the sub-Hz frequency range, while seismic noise can be 10 times larger in this frequency range. High performance active isolation strategy and seismic sensors are required to address this issue.
The Precision Mechatronics Laboratory, based in ULiège and ULB, Belgium, has a large experience in developing high-resolution optical inertial sensors intended to be used in active control. The latest inertial sensors, HINS and VINS, are based on an Long-range, Michelson-type, optical readout with a sensitivity of 2·10-13 m/√Hz at 1 Hz. They have a resolution of 2·10-12 m/√Hz at 1 Hz, 1·10-13 m/√Hz at 10 Hz and 3·10-14 m/√Hz at 100 Hz.
A new, compact, design of the sensors is being developed. The sensor is designed to fit a 10 x 10 x 10 cm box, reducing the original design of VINS by a factor of 8. The mechanics also features fused-silica joints for and reduced low-frequency thermal noise. Ringdown tests demonstrate a Q-factor of 2800 in open-air.

Poster session I / 65

Filter cavity longitudinal control for frequency dependent squeezing

Author: Barbara Garaventa[1]

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Broadband mitigation of quantum noise in interferometric gravitational-waves detectors can be achieved via frequency dependent squeezing (FDS) of the vacuum field at the dark port of the interferometer. This allows to reduce the vacuum field phase fluctuations at high frequency, where quantum shot noise dominates, and the amplitude fluctuation at low frequency, where the contribution of quantum radiation pressure noise is higher.
Advanced Virgo and Advanced LIGO will implement FDS during the O4 science run, by coupling a frequency-independent squeezed vacuum to an optical filter cavity (FC) with an optical pole in the audio domain. In such scheme, the crossover frequency where amplitude squeezing is converted into phase squeezing depends on the detuning between the FC resonance and the carrier field in the interferometer.
Coarse longitudinal control of the filter cavity can be easily achieved by means of an auxiliary field at the second harmonic of the IR carrier. However, the lock point accuracy is generally limited. An

accurate longitudinal control with an IR field is achieved with either a bright, subcarrier field or with the weak RF sidebands used for the coherent control of the squeezing ellipse angle. We propose an alternative solution overcoming some drawbacks of such schemes.

Poster session I / 75

Enhanced Baffles for future Gravitational wave Interferometers

Authors: Stefano Selleri[None] ; Riccardo DeSalvo[1]

[1] *University of Utah*

The problem of mitigating scattered light noise within interferometer arm tubes has been addressed via the insertion of baffles that intercept the stray rays which after interacting with the tube walls may be reinjected in the Fabry-Perot resonator, carrying the vibrational noise of the walls. Such a problem has been dealt with conical, serrated, baffles that may still be source of noise due to diffraction at their edges. Recently, helical baffles have been proposed, showing that diffraction is reduced and mechanical construction easier, not needing serration.

Poster session I / 73

Superconducting inertial sensor with low-noise actuators for gravitational-wave observatories

Author: E.C. Ferreira1[1]

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The cryogenic environment of gravitational-wave detectors, such as Einstein Telescope (ET), can be used in combination with superconducting materials to open up pathways to low-loss actuators and sensor mechanics.
We are developing a Cryogenic Superconducting Inertial Sensor (CSIS) with a displacement sensitivity of several fm/$\sqrt{\text{Hz}}$ at 0.5 Hz. Such highly sensitive device can monitor the effects of low-vibration cryocoolers applied to the penultimate stage of ET as well as possibly assist in the suspension control.
In CSIS, superconducting thin film spiral coils use the Meissner effect to form actuators as part of a force feedback sensing scheme. This actuator reduces losses of the sensor mechanics by not using magnets in the actuator, which greatly reduces viscous eddy current damping. We investigate properties as magnetic field and current density distribution of the coil by finite element analysis using COMSOL. The magnetic field and force applied by the actuators have also been simulated analytically and the results agree with COMSOL ones.
We also present results from the thin film fabrication process to produce 1 cm diameter coils. Superconducting thin films deposited on silicon substrate are being cryogenically tested.

Poster session I / 52

Optical simulations of stray light on instrumented baffles surrounding Virgo end mirrors during O5

Author: Marc Andrés Carcasona[1]

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As part of the second phase of Advanced Virgo update program, instrumented baffles are being constructed to be installed around the end mirrors in the main FP cavities, in continuation of what has been implemented for the input mode cleaner end mirror during phase I. According to the current design, these baffles will be equipped with more than 200 photosensors, allowing for real-time monitoring of the stray light around the mirrors. We present optical simulations of the light distribution in the detector's main cavities to assess the ability of the sensors to effectively monitor misalignment and defects on the mirrors' surface and to play a role in the pre-alignment of the interferometer. The effect of the backscattered light from the baffles is also computed and projected over the O5 sensitivity curve, to evaluate possible effects of the presence of instrumented baffles on the ultimate sensitivity of the detector.

Poster session I / 41

Tunable coherence for straylight suppression in high precision interferometers

Authors: Daniel Voigt[1] ; Oliver Gerberding[2]

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As straylight is a dominating limitation for the sensitivity of gravitational wave detectors, we investigate the use of tunable coherence in the form of phase modulation following a pseudo-random-sequence on the interferometer laser to break the coherence of the delayed straylight. Thereby, we aim to reduce its intrusive impact on the measurement by effectively realizing a pseudo white-light interferometer with tunable coherence length. While this has been proven to work with digital demodulation for multiplexing in digital interferometry, we now study optical demodulation at the signal ports of a Michelson-interferometer with higher modulation speeds to reduce the remaining coherence length. As a first step, we present results and estimated suppression factors from a numerical simulation in preparation of the experimental studies in a tabletop interferometer.

Poster session I / 9

Angled beam expander telescopes for the Michelson beams in third generation Gravitational Wave Observatories

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Third generation of Gravitational Wave detectors like the Einstein Telescope or the Cosmic Explorer will be Michelson interferometers with Fabry-Perot cavities in the arms,

using mirror test masses with diameter at the limit of technical feasibility. Unlike other detectors, the Einstein Telescope will have a 60° angle between the arms. Because of its larger incidence angle, at any given beam size, it would require beam splitters almost double in size and much heavier than the 90° case. It is proposed here to install beam expander telescopes with angled mirrors located inside the Michelson interferometer between the Fabry-Perot cavities and the beam splitter. Beyond reducing the beam sizes and the beam splitter to manageable sizes, the proposed solution allows to bring the optimal recombination angle to 90°. The proposed geometry offers a natural way to separate the beam splitters of different detectors into individual, smaller and more stable caverns, thus improving observatory observation-time efficiency, to provide needed beam diagnostic points and convenient degrees of freedom for beam alignment into both the Fabry-Perot cavities and the beam splitter, as well as to provide a method for maintaining optimal mode matching of the two arms onto the beam splitter without thermal compensation plates.

Poster session I / 24

Optimization of design parameters for Gravitational Wave detector DECIGO including fundamental noises

Author: Yuki Kawasaki[1]

Co-authors: Seiji Kawamura [1] ; Koji Nagano [2] ; Shuichiro Yokoyama [3] ; Bin Wu [1] ; Tomohiro Ishikawa [1] ; Shoki Iwaguchi [1] ; Ryuma Shimizu [1] ; Izumi Watanabe

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The DECi-hertz Interferometer Gravitational-Wave Observatory (DECIGO) is a space gravitational wave (GW) detector. DECIGO was originally designed to be sensitive enough to observe primordial GW background (PGW). However, due to the lowered upper limit of the PGW by the Planck observation, further improvement of the target sensitivity of DECIGO is required. In the previous studies, DECIGO's parameters were optimized to maximize the signal-to-noise ratio (SNR) of the PGW to quantum noise including the effect of diffraction loss. To simulate the SNR more realistically, we optimize DECIGO's parameters considering the GWs from double white dwarfs (DWDs) and the thermal noise of test masses. We consider two cases of the cutoff frequency of GWs from DWDs. In addition, we consider two kinds of thermal noise: thermal noise in a residual gas and internal thermal noise. To investigate how the mirror geometry affects the sensitivity, we calculate it by changing the mirror mass and thickness. As a result, we obtained the optimums for the parameters that maximize the SNR that depends on the mirror radius. This result shows that a thick mirror with a large radius gives a good SNR and enables us to optimize the design of DECIGO.

Poster session I / 15

Probing dipole radiation with the low-frequency gravitational-wave observatories

Authors: Junjie Zhao[1] ; Lijing Shao[None] ; Yong Gao[None] ; Chang Liu[None] ; Zhoujian Cao[None] ; Bo-Qiang Ma[None]

[1] *Beijing Normal University*

Atom-interferometer gravitational-wave (GW) observatory, as a new design of ground-based GW detector for the near future, is sensitive at a relatively low frequency for GW observations. Taking the proposed atom interferometer Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna

(ZAIGA), and its illustrative upgrade (Z+) as examples, we investigate how the atom interferometer will complement ground-based laser interferometers in testing the gravitational dipole radiation from binary neutron star (BNS) mergers. A test of such kind is important for a better understanding of the strong equivalence principle laying at the heart of Einstein's general relativity. To obtain a statistically sound result, we sample BNS systems according to their merger rate and population, from which we study the expected bounds on the parameterized dipole radiation parameter B. Extracting BNS parameters and the dipole radiation from the combination of ground-based laser interferometers and the atom-interferometer ZAIGA/Z+, we are entitled to obtain tighter bounds on B by a few times to a few orders of magnitude, compared to ground-based laser interferometers alone, ultimately reaching the levels of $|B| < 10^{-9}$ (with ZAIGA) and $|B| < 10^{-10}$ (with Z+).

Poster session I / 11

Electromagnetic Follow-up of Binary Neutron Star Mergers with Early Warnings from Decihertz Gravitational-wave Observatories

Authors: Yacheng Kang[1] ; Chang Liu[1] ; Lijing Shao[1]

[1] *Peking University*

We investigate the prospects of electromagnetic follow-up for binary neutron star (BNS) mergers, with the help of early warnings from decihertz gravitational-wave (GW) observatories, B-DECIGO and DO-Optimal. Extending Liu et al. (2022), we not only give quick assessments of joint short γ-ray burst (sGRB) detection rates for different γ-ray satellites and BNS population models, but also elaborate on the analyses and results on multi-band kilonova detections for survey telescopes with different limiting magnitudes. During an assumed 4-year mission time for decihertz GW observatories, we find that DO-Optimal performs better than B-DECIGO as a whole on the detection rate, and has a larger detectable distance for joint sGRB/kilonova searches. Taking the log-normal population model for BNS mergers and a one-day early-warning time as an example, we discuss the accuracy in localization and timing, as well as the redshift distributions for various synergy observations with electromagnetic facilities and decihertz GW detectors. Based on our analyses, we propose a feasible "wait-for" pattern as a novel detecting mode for future multi-messenger astrophysics.

Poster session I / 12

Prospects for Detecting Exoplanets around Double White Dwarfs with LISA and Taiji

Authors: Yacheng Kang[1] ; Chang Liu[1] ; Lijing Shao[1]

[1] *Peking University*

Recently, Tamanini & Danielski discussed the possibility of detecting circumbinary exoplanets (CBPs) orbiting double white dwarfs (DWDs) with the Laser Interferometer Space Antenna (LISA). Extending their methods and criteria, we discuss the prospects for detecting exoplanets around DWDs not only by LISA, but also by Taiji, a Chinese space-borne gravitational-wave (GW) mission. We first explore how different binary masses and mass ratios affect the abilities of LISA and Taiji to detect CBPs. Second, for certain known detached DWDs with high signal-to-noise ratios, we quantify the possibility of CBP detections around them. Third, based on the DWD population obtained from the Mock LISA Data Challenge, we present basic assessments of the CBP detections in our Galaxy during a 4 yr mission time for LISA and Taiji. We discuss the constraints on the detectable zone of each system. With the DWD population, we further inject two different planet distributions with an occurrence rate of 50% and constrain the total detection rates. We briefly discuss the prospects for detecting habitable CBPs around DWDs with a simplified model. These results can provide helpful

inputs for upcoming exoplanetary projects and help analyze planetary systems after the common envelope phase.

Poster session I / 18

Realistic Detection and Early Warning of Binary Neutron Stars with Decihertz Gravitational-wave Observatories

Authors: Chang Liu[1] ; Yacheng Kang[1] ; Lijing Shao[1]

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We investigated the detection and localization of binary neutron star (BNS) populations with decihertz gravitational-wave observatories in a realistic detecting strategy, including real-time observations and early warnings. Assuming 4 years' operation of B-DECIGO, we found that the detected BNSs can be divided into three categories: (a) sources that merge within 1 year, which could be localized with an uncertainty of $\Delta\Omega \sim 10^0$deg^2; (b) sources that merge in 1-4 years, which take up three quarters of the total events and yield the most precise angular resolution with $\Delta\Omega \sim 10^{-2}$deg^2 and time-of-merger accuracy with $\Delta t_c \sim 10^{-1}$s; and (c) sources that do not merge during the 4-yr mission window, which enable possible early warnings, with $\Delta\Omega \sim 10^{-1}$deg^2 and $\Delta t_c \sim 10^0$s. Furthermore, we compared the pros and cons of B-DECIGO with the Einstein Telescope, and explored the prospects of detections using 3 other decihertz observatories and 4 BNS population models. In realistic observing scenarios, we found that decihertz detectors could even provide early-warning alerts to a source decades before its merger while their localizations are still more accurate than ground-based facilities.

Poster session I / 25

Space gravitational wave antenna DECIGO

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DECi-hertz Interferometer Gravitational-wave Observatory (DECIGO) is a future Japanese space gravitational-wave antenna with a frequency band of 0.1 Hz to 10 Hz. DECIGO aims at detection of primordial gravitational waves, which could have been produced during the inflationary period right after the birth of the universe. There are many other scientific objectives of DECIGO, including the direct measurement of the acceleration of the expansion of the universe, and reliable and accurate predictions of the timing and locations of neutron star/black hole binary coalescences. DECIGO consists of four clusters of observatories placed in the heliocentric orbit. Each cluster consists of three spacecraft, which form three differential Fabry-Perot interferometers with an arm length of 1,000 km. Three clusters of DECIGO will be placed far from each other, and the fourth cluster will be placed in the same position as one of the three clusters to obtain the correlation signals for the detection of the primordial gravitational waves. In this presentation, we will explain the aimed sciences, the mechanical and optical design, and the current status of DECIGO.

Poster session I / 46

Space GW Antenna B-DECIGO

Authors: Masaki Ando[1] ; DECIGO group[None]

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B-DECIGO is a space gravitational wave antenna mission. While it is a precursor mission of DECIGO, we can expect fruitful sciences with B-DECIGO. One of the most exciting science cases is detection of compact binary system before merger. It will enlarge the possibility of multi-messenger astronomy with electro-magnetic wave observations at the time of merger. In this presentation , we will review the science cases and mission concept of B-DECIGO.

Poster session I / 56

Localization of gravitational waves using machine learning

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Co-authors: Yilun Hou [1] ; Kentaro Somiya [1] ; Hirotaka Takahashi [2]

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An observation of gravitational waves is a trigger of the multi-messenger search of an astronomical event. A combination of the data from two or three gravitational wave detectors indicates the location of a source and low-latency data analysis is key to transferring the information to other detectors sensitive at different wavelengths. In contrast to the current method, which relies on the matched-filtering technique, we proposed the use of machine learning that is much faster and possibly more accurate than matched filtering.
Our machine-learning method is a combination of the method proposed by Chatterjee *et al.* and a method using the temporal convolutional network.
We demonstrate the sky localization of a gravitational-wave source using four detectors: LIGO H1, LIGO L1, Virgo, and KAGRA, and compare the result in the case without KAGRA to examine the positive influence of having the fourth detector in the global gravitational-wave network.

Poster session I / 66

Practical quantum noise estimate of optical-spring quantum locking for space gravitational wave detector DECIGO

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The DECi-hertz Interferometer for Gravitational-wave Observatory(DECIGO) aims mainly at the detection of primordial gravitational waves (PGWs) originating from inflation. Recent observations by the Planck satellite and others have lowered the upper limit of PGWs. Thus, it is necessary to improve the target sensitivity of DECIGO. A newly proposed method to reduce the quantum noise of DECIGO is quantum locking with an optical spring. In this method, a short cavity is added to the main cavity, sharing one mirror of both cavities. The error signal in this auxiliary cavity is obtained properly in a homodyne detection, and fed back to the shared mirror to cancel the radiation pressure noise of the main cavity. In our previous study, the optimal sensitivity assuming ideal homodyne detection without any additional noise was obtained by simulation. In this study, we investigate a more realistic design, taking into account the mixture of the vacuum fluctuations incident to the homodyne detection system. In this poster, we explain the latest results of this investigation

Poster session I / 72

The Sar-Grav Laboratory at the Sos Enattos site, one of the quietest site in the 2-10 Hz frequency range

Author: Domenico D'Urso[1]

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Einstein Telescope (ET) will be the third generation of gravitational wave interferometer to be built in Europe. One of the sites candidates to host ET is located in Sardinia (Italy), near the Sos Enattos mine, where a seismometer's net already proves the quietness of the site. The Sar-Grav laboratory, a seed of ET, aims to host underground experiments, cryogenic payloads, low frequency and cryogenic sensor development that need low seismic and anthropogenic noise. On the surface there are a hangar of about 900 square meters, an optical laboratory and a control room; a 20 tons crane and cleaned rooms are planned to be installed. Underground, an area of 250 square meters and small experimental areas are planned to be built, while different stations at different depths are hosting sensors like seismometers and magnetometers. A fundamental physics experiment, Archimedes, is under installation in the surface area and will be moved underground in the future.
The site will host the test of the preliminary seismic isolation system, currently under studies , that will be designed to improve seismic attenuation in the low frequency region (0.1-10 Hz) and reduce the frequency of mechanical resonances.

Poster session I / 62

Gravitational wave sources in the low frequency region and their distances

Author: Rosa Poggiani[1]

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Pulsars are expected to be strong sources of low frequency gravitational waves in ground based interferometers. The knowledge of their distances is a key parameter to estimate the gravitational emission. The pulsar distances are usually estimated using dispersion measure. The Gaia data release provides information on the distance, kinematic and photometric properties of nearly two billions astronomical sources, among them some pulsars and accreting neutron star systems.
The Gaia based distances of some systems relevant for gravitational astronomy will be discussed.

Poster session I / 58

The Current Status of TOrsion-Bar Antenna (TOBA) Experiment

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Torsion-bar antenna (TOBA) is a ground-based gravity gradiometer proposed for measurement of gravity gradient fluctuations such as gravitational waves and gravity gradient noise. TOBA consists of two perpendicular torsion pendulum, and the low mechanical resonant frequency of torsion pendulums enables us to measure gravity gradient of frequencies around 0.1 Hz. TOBA aims to achieve the sensitivity 10ˆ(-19) / √Hz at 0.1 Hz.
For the final sensitivity goal we are developing a prototype Phase-III TOBA in order to investigate technical issues and establish noise reduction scheme. One of the key topic of Phase-III TOBA is cryogenic suspension system for the reduction of the thermal noise. Another key point is the readout system with monolithic interferometer. We will show the current situation of the developments and future upgrade plans for further improvement.

Poster session I / 16

Displacement-noise-free neutron interferometer for gravitational wave detection at low frequencies

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Co-authors: Atsushi Nishizawa [2] ; Yanbei Chen [3] ; Yuki Kawasaki [1] ; Masaaki Kitaguchi [4] ; Taigen Morimoto [1] ; Tomohiro Ishikawa [1] ; Bin Wu [1] ; Izumi Watanabe [1] ; Ryuma Shimizu [1] ; Hirohiko Shimizu [1] ; Yuta Michimura [5] ; Yutaka Yamagata [6] ; Seiji Kawamura [1]

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Improvement of the sensitivity of gravitational-waves (GWs) detectors at lower frequencies is still challenging on account of displacement noise sources, such as thermal noise, seismic noise, and radiation pressure noise. One of the solutions is the displacement-noise-free interferometer (DFI). At frequencies lower than 1Hz, however, the DFI has less sensitivity to GWs because the propagation time of light is much shorter than the period of the GWs. To resolve this problem, DFI with neutrons instead of laser, which is called a neutron DFI, was proposed. In a neutron DFI with neutrons propagating much more slowly than light, the neutron propagation time can be comparable to the period of GWs at lower frequencies. This enables us to cancel displacement noise without cancellation of the GW signals. Also, we proposed a simplification of the detector configuration by taking advantage of the ability to adjust the neutron speeds depending on the configuration. In our poster, we discuss the principle of the neutron DFI as well as a plan of the demonstration experiment.

Poster session I / 26

Current Status of Quantum Locking Experiment for Space Gravitational Wave Antenna DECIGO

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The DECi-hertz Interferometer Gravitational wave Observatory (DECIGO) is the future Japanese space mission with 1,000 km arm cavities. One of the main objectives of DECIGO is the detection of primordial gravitational waves (PGWs) produced in the inflation period. We should improve DECIGO's target sensitivity, which is limited by quantum noise, to enhance the possibility of the detection of PGWs.

The standard squeezing techniques to reduce the quantum noise are not effective because of the large diffraction loss in DECIGO due to the long arm length. Therefore, we proposed a new method, quantum locking with an optical spring, to reduce the quantum noise in a relatively broad frequency band. Quantum locking is the technique, in which each mirror of the long arm cavity (main cavity) is shared by two short-arm cavities (sub-cavities). Then the sub-cavities control the mirrors' motion of the main cavity. Interferometer signals obtained from the main cavity and the two sub-cavities can be combined to optimize the sensitivity of DECIGO.

In parallel with the theoretical analysis of the technique, we have been performing the experiment to verify the principle of the theory. In this poster session, we explain the current status of the quantum locking experiment.

Poster session III / 36

Cool-down studies of the low-frequency interferometer in the Einstein Telescope

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The low-frequency interferometer in the Einstein Telescope (ET-LF) shall be operated at temperatures of 10 K to 20 K. One cooling concept provides ultra-low noise cooling for steady-state detector operation using a He-II-filled suspension capillary, in which the heat transport takes place by steady-state heat conduction.
During cool-down, the double-walled capillary enables the flow of single-phase helium to a heat exchanger interface that is coupled by forced convection with the cryogenic infrastructure.
We present a first model of this interface, as well as corresponding thermal and fluid-dynamic numerical simulation results for a transient cool-down process.

Poster session III / 38

Design and Alignment of Compact Optical Heads for Test Mass Readout with Deep-Frequency Modulation

Authors: Meenakshi Mahesh[None] ; Oliver Gerberding[1]

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Improving the low-frequency range (1 - 10 Hz) of ground-based detectors requires compact interferometric sensors with high displacement sensitivity and dynamic. We combine Deep frequency modulation and compact interferometric techniques to develop a sensor for local test mass readout. We introduce an optical head design with on-axis beam topology realized in a Quasi-Monolithic component (QMC) comprised of cube beam splitters, which ensures beam transmission through perpendicular surfaces to keep angular alignment constant when operated in air or vacuum. This On-axis beam propagation should enable sub-picometer level displacement sensing and nano-radian tilt sensing with a high displacement range. We implemented and investigated a table-top model of

the QMC achieving high contrast values. The beam propagation and polarization effects in the QMC are analyzed and we present our current design for an integrated sensor.

Poster session III / 61

Silicon as a detector suspension material

Authors: Graeme Eddolls[1] ; Alan Cumming[1] ; Giles Hammond[1] ; Karen Haughian[1] ; Gregoire Lacaille[1] ; Iain Martin[1] ; Sheila Rowan[1] ; James Hough[2] ; Russell Jones[1]

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With the need to move to 3rd generation cryogenically cooled detectors, work is ongoing at Glasgow to investigate design, bonding and characterisation of silicon suspensions operating at cryogenic temperatures. Here we present an update on these activities, including the first demonstration of a bonded cryogenically cooled silicon suspension.

Poster session III / 37

Precision limits and a readout algorithm for DFM Interferometry

Authors: Tobias Eckhardt[1] ; Oliver Gerberding[1]

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Current gravitational wave detectors are limited by local sensor noise and other related technical noise sources at low frequencies below 10 Hz. We aim to use compact displacement sensors based on deep-frequency modulation interferometry for the local readout of test-masses to overcome these limitations.
In this poster I present our work on the readout of such compact displacement sensors. We analysed the limitations of such sensors by computing the Cramer-Rao lower bound of the phase estimate in the presence of common noise sources. And we developed a new algorithm to extract the interferometric phase in deep-frequency-modulation interferometry in a fast and non-recursive way.
First results show that our improved sensor can reach a higher precision than the currently ones used at the LIGO suspension while also having a larger dynamic range.

Poster session III / 30

Tonga's volcano eruption signals measured by the evironmental monitoring systems of KAGRA Observatory

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On January 15, 2022, at 04:14:45 (UTC), the undersea volcano of Hunga Tonga-Funga Ha'apai erupted and caused global seismic, atmospheric, and electromagnetic waves. They were transmitted to Kamioka, more than 8000 km away, and were observed by environmental sensors not only on the

ground but also inside KAGRA's underground facility. In this talk, these signals measured by KAGRA's environmental monitors and the transfer functions from the air-pressure wave in the atmosphere to the underground environmental disturbances (e.g., air-pressure, seismic motion) will be reported.

Poster session III / 43

Broadband quantum noise reduction for AdV+

Author: Marco Vardaro[1]

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Technical noise limits the low-frequency sensitivity of interferometric gravitational-wave detectors. Consequently, an effort has been made in recent decades to reduce them, which has led to the emergence of other limiting sources in the overall low-frequency noise budget. Among these noise sources there is the radiation pressure noise which, as demonstrated by LIGO and Virgo in the third observation run,, can deteriorate the low frequency sensitivity when large amounts of FIS is injected. In the next few years a huge work to improve the low frequency sensitivity of the gravitational wave interferometers is planned, therefore the quantum radiation pressure noise will limit the low frequency sensitivity even without FIS injection. For this reason, all collaborations are developing a frequency-dependent squeezing sources that should allow to fully benefit from the injection of squeezed states leading to a reduction of quantum noise in the whole detector bandwidth.
In this talk we present the status of the development and commissioning of the AdV+ frequency dependent squeezing source based on the filter cavity rotation method. Additionally to the reduction of the quantum noise at all frequencies, in the AdV+ FDS setup, a mitigation system for the stray light detrimental effect is also implemented.

Poster session III / 27

Compensating decoherence of squeezed light in cavity-enhanced quantum metrology

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Quantum states of light are being more commonly used to increase the sensitivity of various sensors. They allow to reach high sensitivity without using significant light power, and thus find application in various fields, from biological sensing to gravitational-wave detection. At the same time, these states are very fragile, and even a small amount of decoherence can significantly reduce their benefit. We propose a new approach that allows to compensate part of quantum decoherence, thus increasing the sensitivity beyond the previously established decoherence-induced quantum limit. To achieve this, we use an optimally tuned quantum squeezer placed directly inside the detector cavity. This squeezer operates to restore the externally injected squeezing or to amplify the signal, depending on the level of loss. It can be flexibly tuned to the optimal operation. We present the first experimental combination of intra-cavity and externally injected squeezing used to enhance detector's sensitivity. We demonstrate for the first time how optimal tuning allows to compensate quantum decoherence. Finally, we derive the new decoherence-induced quantum limit. Based on this approach, we develop the quantum expander for the detection bandwidth of GW detectors, which allows to significantly increase the sensitivity at high frequencies.

Poster session III / 32

Juggled interferometer for gravitational wave detection

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Juggled interferometer (JIFO) is a novel type of earthbound gravitational wave detector targeting a frequency band of 0.1–10 Hz. By using repeatedly free-falling test masses, JIFO can in principle decouple test masses from the seismically noisy environment and avoid suspension thermal noise in a straightforward manner. Since the test masses are in a weightless state, as is the case with space gravitational wave detectors, JIFO would be a good testbed for technologies of space projects.

Here, the concept of the Michelson-type JIFO is introduced. Then the experiment setup and the data readout method of a JIFO are discussed. Considering the displacement noise budget of the Einstein Telescope (ET), we show that the juggled test masses could significantly improve the sensitivity at 0.1-2.5 Hz even with discontinuous data. The science cases brought with the improved sensitivity would include detecting quasi-normal modes of black holes with 104-105 Msun, testing Brans-Dicke theory with black-hole and neutron-star inspirals, and detecting primordial-black-hole-related gravitational waves.

Poster session III / 39

SpicyPy: a common python tool for signal processing and control systems

Author: Artem Basalaev[1]

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Within gravitational wave research community (including but not limited to LIGO-Virgo-KAGRA, Einstein Telescope and LISA collaborations) a lot of work in understanding and improving the detectors involves signal processing and modelling of control systems. Historically, different software tools were used for these purposes. We believe that it is possible to create a single software tool that can be useful for many different applications in these domains. This would help to facilitate exchange of knowledge between collaborations, and could be used in teaching.

We aim to develop a python package intended as a general tool with a simple but powerful interface to facilitate control systems modelling, signal processing, and provide an interface between the two. It may rely on other well-known and tested packages already used for these applications, but it will abstract interactions with them with a unified interface. Potential applications include time series analysis, suspensions modelling, feeding sensor signals through a control system, and more. The project is a collaborative open-source effort across the groups from the start, and new contributors are always welcome. We are currently focused on compiling software requirements specification and are in discussions with researches from different collaborations to understand the most common potential applications.

Poster session III / 2

Substrate transferred aluminum gallium arsenide (AlGaAs) crystalline coatings

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Substrate-transferred crystalline coatings made from aluminum gallium arsenide (AlGaAs) have very low thermal noise compared to the ion beam deposited amorphous oxides used until now in gravitational wave detectors. AlGaAs coatings also show excellent optical properties and both thermal noise and optical performance has been demonstrated in other precision optics applications. The primary challenge to using AlGaAs coatings in future detectors is the coating diameter necessary and the large mass and thickness of the test mases. We present results on 10 cm diameter AlGaAs coatings and propose multiple pathways to implement AlGaAs coatings on upgrades to current detectors with up to 40 kg masses and on future detectors with larger masses. We also show schedule and budget plans that allow AlGaAs to be used in future gravitational wave detectors.

Poster session III / 47

Optical absorption of TiO_2 doped SiO_2 as a replacement high index coating material

Authors: Simon Tait[1] ; Ross Johnston[1] ; Iain Martin[1] ; Graeme McGhee[2] ; Peter Murray[2] ; Viola Spagnuolo[3] ; Jessica Steinlechner[3] ; Lukas Terkowski[4] ; Sheila Rowan[1] ; James Hough[2]

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The sensitivity of 3rd generation gravitational wave detectors is currently projected to be limited by the level of Brownian coating thermal noise produced from highly reflecting mirror coatings. In the current detectors layers of Ta_2O_5, a material with higher refractive index (n = 2.14), has higher levels of optical absorption compared the lower index layers of SiO_2 (n=1.44). To improve detector sensitivity and duty cycle, the optical and mechanical properties of new doped coating materials are being investigated. This work presents measurements of the optical absorption of SiO_2 and SiO_2 doped with TiO_2 layers as part of a highly reflecting coating stack. Utilising the photothermal common-path interferometry technique, we discuss the effects of heat treatment and crystallisation on the optical performance of the material compared to current aLIGO coatings.

Poster session III / 48

TiO_2:SiO_2 coating thermal noise and optical studies

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Current gravitational wave detectors are limited in their most sensitive frequency range by the mirror coating thermal noise which arises from the Brownian motion of the coating materials on the interferometer test mass optics. For the next generation detector upgrades and beyond, it is imperative to find coating materials/topologies that reduce this mechanical effect, whilst still meeting the desired optical requirements. Titania-doped silica had been identified as a coating material candidate which could potentially improve detector sensitivity.

We present here our investigations into the mechanical and optical properties of highly-reflective coating stacks made of pure SiO2 and TiO2 doped SiO2, deposited via ion beam sputtering (IBS). Two different concentrations of TiO2 doping in the high-refractive index layers of our coating stacks were investigated, with mechanical loss and optical absorption being measured through different steps of heat treatment for each, with the level of coating thermal noise being calculated from the former.

Poster session III / 13

Angular Signal Amplification with a Coupled Cavity for Torsion-Bar Antenna

Author: Yuka Oshima[1]

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Torsion-Bar Antenna (TOBA) is a ground-based gravitational wave detector using a torsion pendulum. The resonant frequency of torsional motion is ˜1 mHz, therefore TOBA has good design sensitivity of $10^{-19}\,/\sqrt{\mathrm{Hz}}$ at 0.1 Hz in low frequencies (0.1 Hz – 10 Hz). TOBA can detect intermediate mass black hole binary mergers, Newtonian noise, and so on. A prototype detector Phase-III TOBA with a 35 cm-scale pendulum is under development to demonstrate noise reduction. The target sensitivity is set to $10^{-15}\,/\sqrt{\mathrm{Hz}}$ at 0.1 Hz. To achieve our target sensitivity, we need to measure the pendulum rotation precisely. We propose a coupled wavefront sensor (Coupled WFS) as an angular sensor for Phase-III TOBA. In our method, an auxiliary cavity is used to compensate Gouy phase of a main cavity and enhance the first-order TEM modes in the main cavity. The experimental demonstration was successfully performed in 2021. In this workshop, we will show the principle and demonstration results of a Coupled WFS.

Poster session III / 44

Estimating the Newtonian noise of groundwater at the KAGRA

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Changes due to gravitational waves are very small, so noise is generated due to various factors. KAGRA was built 300 meters underground to reduce ground vibrations. The groundwater generated underground is discharged through pipes. The gravity gradient generated by the universal gravitation force due to the oscillation of the water surface through the pipe may cause the mirror of

KAGRA to shake and become a noise to the target sensitivity of KAGRA.
Our experiment was conducted using the simulation software Flow-3D in order to know the magnitude of Newtonian noise. The Newtonian noise was evaluated by calculating the waveform of the flowing water.

Poster session III / 45

Control of Dual-Pass Fabry-Perot Cavity for space gravitational wave antennas : DECIGO and B-DECIGO

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A dual-pass Fabry-Perot cavity will be used for DECIGO (DECi-hertz Interferometer Gravitational-wave observatory) and B-DECIGO. To detect gravitational waves, it is necessary to establish the method to control the dual-pass Fabry-Perot cavity. We can divide this issue in two parts, "Length control" and "Alignment control". For Length control, it is demonstrated that we can control the length of dual-pass Fabry Perot cavity with Pound-Drever-Hall technique. On the other hand, for Alignment control, though the method was already proposed (WaveFront Sensor and Beam Pointing Control), it is not demonstrated yet. Therefore, an experiment is needed for the demonstration.In this poster, we show the principle to control the dual-pass Fabry-Perot cavity in the direction of the angle and explain the experiment to demonstrate it.

Poster session III / 71

CO2 mode cleaner for Thermal Compensation System of Advanced Virgo+

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As planned for its fifth observation run O5, Advanced Virgo+ will have 80 Watts in main laser. The absorption of laser power in the interferometer's core optics leads to thermal effects causing optical aberrations, ultimately preventing interferometer's operation. To recover detector's ideal operation, Thermal Compensation System (TCS) is needed to correct wavefront distortions. In particular, to correct the axisymmetric part of the spurious thermal lens in the power recycling cavity, a heating pattern is projected on a compensation plate using Double Axicon System (DAS) where a 50 Watts CO2 laser beam is reshaped using axicons. Due to O5 stringent requirements on the residual of DAS correction, heating pattern distortions caused by the known amount of higher-order modes (HOM) in the CO2 beam cannot be tolerated. To remove these HOMs, we are constructing an optical mode cleaner which will allow us to retain 95% of the CO2 laser power for compensation with a strong reduction of HOM related residual correction. To our knowledge, this is the first time a mode cleaner is designed for a high power CO2 laser. We present here the requirements, motivation and current status of the work, discussing the issues related to the CO2 wavelength and power.

Poster session III / 63

Vibration analysis of ETpathfinder cryogenic heat-links

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The Einstein Telescope pathfinder (ETpathfinder) is a cryogenic testbed for the next generation of gravitational-waves antennas. To reach the target temperature of 18 K, ETpathfinder cryogenic payloads are designed to extract heat from the test masses by integrating low stiffness and highly conductive heat-links that connect to the cryocoolers. Since the interferometer test masses are very sensitive to mechanical vibrations, the noise from the cryocoolers through the heat conductor should be carefully monitored and controlled. This work presents the modeling and experimental measurements of the mechanical vibrations transferred by the heat-links in a dedicated payload setup. To investigate the stability criterion of the cold-head, seismic noise propagated via the heat-links is then projected to the displacement sensitivity of ETpathfinder.

Poster session III / 31

Measuring thermal noise in gram-scale Si flexures at 123 K

Author: Disha Kapasi[1]

[1] *Ms*

Future terrestrial gravitational wave detectors are limited by fundamental noise sources, one of which is the thermal noise arising in the test masses and suspensions in the frequency band where ground-based detectors are sensitive. To mitigate this noise, future detectors are envisioned to operate at cryogenic temperatures using silicon optics as test masses and silicon ribbons to suspend the test masses. Silicon ribbons resemble cantilever topology, and therefore studying the thermal noise in the flexing of a gram-scale silicon cantilever is analogous to the suspension thermal noise encountered in these ribbon suspensions. At the Australian National University, I have built an operational cryogenic infrastructure to measure the broadband thermal noise of silicon flexures at 123 K. In this talk, I will present initial results of our cool-down tests, thermal noise measurements from the experiment and future plans.

Poster session III / 17

Vibration Analysis of KAGRA Cryostat at Cryogenic Temperature

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Large-scale Cryogenic Gravitational-Wave Telescope, KAGRA is a second-generation gravitational-wave detector (GWD) located in Japan. The features that distinguish KAGRA from other GWDs are its underground location and cryogenic operation of the four main mirrors. The underground location provides a quiet site with low seismic noise, while the cryogenic operation cools the mirrors down to 20 K, reducing the thermal noises. However, cryocooler vibration and structural resonances of the cryostat can contaminate detector sensitivity as they couple to test mass through the heat-links. Monitoring and characterization of the vibration inside the cryostat is critical for the optimum noise performance of KAGRA.
In April, 2020 KAGRA conducted an international observation run, "O3GK" along with GEO600. During this run several noise sources were identified and a noise budget was prepared. However, as the mirrors were not cooled the noise transfer via heat-links was estimated based on room temperature, in vacuum vibration measurement performed 2.5 years before O3GK. During the upcoming observation run the mirrors will be cooled down, so we performed vibration analysis of the cooling system at cryogenic temperature to study its impact on detector sensitivity. In this poster, we describe the KAGRA cooling system and discuss the results of vibration analysis.

Review of LIGO's LF workshop / 29

Review of LIGO's LF workshop

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Scatter light for LF / 55

BRDF revisited

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Bidirectional Reflectance Distribution Function (BRDF) of LIGO and Virgo test masses quantifies the reflection of mirrors. It is related to the round trip loss (RTL) of the arm cavity and to various stray lights which induce noises in various ways. The available data of BRDF is limited and the RTL cannot be fully calculated by using existing BRDF data. This talk summarizes existing BRDF data of aLIGO, AdVirgo and 40m to characterize the overall view of BRDF and its applications to understand the cavity loss and to quantify stray light induced noises.

Scatter light for LF / 53

Stray Light Measurements With an Instrumented Baffle in the Advanced Virgo Input Mode Cleaner Cavity

Author: Giada Caneva Santoro[None]

In April 2021, a new instrumented baffle was installed surrounding the suspended end mirror of the Virgo's Input Mode Cleaner (IMC) cavity, as part of the phase I upgrade of the Advanced Virgo interferometer. The device is equipped with photo sensors that monitor the stray light inside the cavity. It serves as a demonstrator of the technology for the baffles that will monitor the stray light in the main arms, which will be installed during the phase II upgrade in the near future.
We will give an overview of the status of the instrumented baffle and its integration into the Virgo environment and present results on the measured scattered light distribution inside the cavity using data collected between spring 2021 and spring 2022, with Virgo in commissioning phase. The sensitivity and performance stability of the baffle is discussed and the data is compared to scattered light simulations.
These results will serve to calibrate the simulations and demonstrate the potential of instrumented baffles to detect defects in the mirrors and to improve the understanding of the scattered light inside ground-based gravitational wave experiments like Virgo.

Scatter light for LF / 23

Scattered light measurement and active mitigation for Advanced Virgo Plus

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Scattered light is a source of noise which limits the performance of current gravitational wave detectors.
In order to understand and mitigate this effect it is important to know quantitatively the amount of light backscattered by all the elements located on optical benches. To this purpose we built at LAPP an interferometric scattermeter with which the BRDF of the desired elements is measured.
In parallel, in Virgo we are working to mitigate the identified scattered light sources. On the one hand, we conducted a complete mitigation campaign of secondary beams, i.e. ghost beams, on all Virgo subsystems. As these unwanted beams propagate, they can produce scattered light that recombines with the interferometer beam. On the other hand, we developed a control loop to actively correct the stray light noise that was affecting the squeezing system. The principle of this system can be applied in other circumstances.

Scatter light for LF / 68

Fast Scattering transient noise at LIGO Livingston

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During the third Observing run, Fast Scattering was the most frequent source of transient noise at LIGO Livingston. The noise shows up as arches in time-frequency plane, usually separated by 0.25 sec (4 Hz) or 0.5 sec (2 Hz) from each other. This noise has been found to be correlated with elevated levels of ground motion in the anthropogenic and microseismic band. Depending on the amount of relative motion in these two bands, 2 Hz or 4 Hz fast scatter shows up. To localize the potential coupling to the detector, we examined the correlation between ground motion at End and Corner stations with the noise in DARM.

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ET at 3 Hz - can we break the 'controls noise' wall?

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The Einstein Telescope aims to have astrophysically interesting sensitivity at 3Hz. The performance goal is a factor of ˜10ˆ6 quieter than LIGO and Virgo at that frequency. This talk will present a recipe for addressing controls noise in a systematic manner at the design stage with supporting evidence from existing instruments.

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Closing remark

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Cosmic Explorer at low frequency

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This talk will discuss the problems that must be solved to achieve Cosmic Explorer's low frequency sensitivity goals.

Suspensions for LF / 4

The latest development in ALFRA, the UWA low-frequency rotational accelerometer

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Ground rotation sensors at low-frequency have a vital role in improving seismic isolation systems in advanced and 3G gravitational wave detectors. It was found that using seismometers as the sole source of ground motion measurement results in undistinguishable motion detection between horizontal and tilt motion, especially below 100 mHz. Therefore, pure angular motion measurement is necessary to separate tilt and translation to be applied as feedback in active isolation control. ALFRA is a low-frequency rotational accelerometer developed at the University of Western Australia (UWA) to detect ground tilt motion. It is a compact, inertial reference style rotation sensor that can be mounted in three orientations to detect ground tilt around a different axis of interest. A preliminary study of a prototype showed that ALFRA can achieve high readout sensitivity of few nrad/√Hz above 20 mHz and 0.1 nrad/√Hz above 50 mHz in measuring ground tilt. In this work, we will present our latest design for ALFRA and highlight several improvements that will be added to our previous design to enhance several aspects of the sensor and increase its sensitivity, usability, and convenience of adjustment.

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E-TEST: A Compact Isolation Concept for Future Einstein Telescope

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This study presents a low frequency isolation system in the framework of E-TEST project which is a research facility for Einstein Telescope. The isolation system combines a passive inverted pendulum and an active inertial platform. The design of this isolator allows reducing the overall height of the isolation system. We address the isolation system design, its dynamics and the control strategy applied. The simulation results show that the seismic noise could successfully be reduced by about 3 orders of magnitude at 1 Hz in horizontal when the control is applied. To avoid spoiling the performance at high frequency, the inertial platform is designed in such a way that the first flexible internal mode appears above 300 Hz.

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New Generation Superattenuators for Einstein Telescope

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Seismic noise and local disturbances are dominant noise below 10 Hz (0.1-10 Hz).With the introduction of high performance seismic isolation systems based on mechanical pendula,the 2nd generation GW antennas have reached the scientific goal of the direct observation of GW signals thanks to the extension of the frequency band down to 10 Hz. Now,the 3rd generation instrument era is approaching and the Einstein Telescope giant interferometer is becoming a reality with the possibility to install the detector in an underground site where seismic noise is 100 times smaller then on surface. Moreover,new available technologies and the experience acquired in operating advanced detectors are key points to further extend the detection bandwidth down to 2-3 Hz with the possibility to suspend cryogenic payload and then mitigating Thermal Noise too.In this talk, we present the

preliminary studies devoted to improve seismic attenuation performance of the Advanced VIRGO Superattenuator in the low frequency region.Following the experimental lines,we analyze the possibility to improve the vertical attenuation performance with a multistage pendulum chain equipped with magnetic anti-springs that is hung to a double Inverted Pendulum in nested configuration.The feedback control requirements and the possible strategies to be adopted for this last element, will be presented.

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Update on sensing seismic platform relative motion using Digital Interferometry

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The relative motion of seismic platforms, via coupling to the auxiliary length controls of the suspended optics, are predicted to be the limiting noise source for future gravitational-wave detectors at frequencies below 1 Hz. By measuring, then stabilizing this relative motion, the effective control feedback to the optics will be reduced and hence the noise coupling will be less, and potentially improve detector noise performance. The measurement of the relative motion with forms of suspension platform interferometry is an ongoing area of interest and research. Digitally-enhanced Interferometry is a decade-mature technique for sensing relative motion, by providing time-tagged pseudorandom phase modulation to isolate signals based on time-of-flight delay. The application of digitally-enhanced interferometry for suspension sensing is an active area of development within the Newtonian Noise research program at the Australian National University, and offers another potential method for sensing relative platform motion. We present an update on recent developments of digitally-enhanced interferometry towards suspension sensing and measurement.

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Introduction

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Newtonian Noise in the Einstein Telescope

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Newtonian noise (NN) was predicted to represent the very last sensitivity wall in Earth based gravitational wave detectors already by their first pioneers. Virgo will soon implement the first NN cancellation system ever and the knowledge we acquired during its development will be an asset in

evaluating what we need to reduce as much as possible the NN in the Einstein Telescope.
The problem here will be different given that the Einstein Telescope will be located underground, this will imply new difficulties that will contribute to spoil the NN cancellation capabilities. In this talk we will review the key points we must keep in mind to develop the NN cancellation system for the Einstein Telescope.

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Tunnel configurations and seismic isolation optimization in underground gravitational wave detectors

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Gravitational wave detectors like the Einstein Telescope (ET) will be built a few hundred meters underground to reduce both seismic and Newtonian noise. Underground facilities must be designed to take full advantage of the shielding properties of the rock mass to maximize the detector´s performance. A major issue with the ET design are the corner points, where caverns need to be excavated in stable and low permeability rock. This paper proposes a new topology that moves the top stages of the seismic attenuation chains and the re-combination of the beams of the Michelson interferometers in separate excavations far from the beam-line and equipment induced noise while the test mass mirrors remain in the main tunnels. Distributing the seismic attenuation chain components over multiple tunnel levels allows the use of arbitrarily long seismic attenuation chains that relegate the seismic noise at frequencies completely outside the low-frequency noise budget, thus keeping the door open for future Newtonian noise suppression methods. Separating the input-output and recombination optics of different detectors into separate caverns drastically improves the observatory detection efficiency and allows staged commissioning. The proposed scheme eliminates structural and instrumentation crowding while the reduced sizes of excavations require fewer support measures.

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Astigmatic mode mismatch sensing for the next gravitational wave detectors.

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One of the main limits of the Quantum Noise Reduction in Gravitational Wave detectors is the optical losses generated by the mismatch between the vacuum squeezed beam and the resonant cavities of the interferometer. In order to correct those aberrations, we need to be able to measure them. For this reason, different efforts have been made to develop wave-front sensing techniques to measure the mismatch between optical cavities.

However, the current technologies based on the spherical Gaussian Beam are not enough for the next generation of Gravitational Wave Detectors. In fact, the higher requirement on the optical losses imposes to compensate also the modematching generated by astigmatic aberrations, so a new generation of wavefront sensor technique is needed.

Here we will present an upgrade of the Mode Conversion Telescope technique that extends the mismatch measurement from the only symmetric aberrations to a complete characterisation of the mismatch between an astigmatic Gaussian beam and a resonance cavity. This extension uses four additional Quadrants Photodiodes sensors to detect the beat note between the Sidebands of the TEM00 and the second-order Hermite-Gauss mode TEM11 of the carrier. In particular, we will describe the method and present the first experimental results of this technique.

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Birefringence characterisation of KAGRA ITMs and simulation with FINESSE

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KAGRA is a cryogenic detector using sapphire mirrors as its test masses. The sapphire material was chosen mainly for its high thermal conductivity, low absorption and high transmittance of the 1064 nm laser. However, sapphire has a few disadvantages like birefringence. During the commissioning, we found out the interferometer had unexplained optical losses and beam distortions due to the birefringence effect from two input test masses. These issues degrade the detector controllability and sensitivity to the astronomical gravitational waves. In this talk, we would like to update our birefringence characterisation of KAGRA input test masses. We also proposed a method to model the impact of birefringence effect to the interferometer using the simulation software FINESSE.

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Low-frequency magnetic noise in terrestrial GW detectors: the case study of AdV+ Faraday isolator

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The coupling of environmental magnetic fields is a limiting factor for the lowfrequency sensitivity of future ground-based interferometers. Coupling can occur at various locations, such as actuation magnets of the mirror and optical benches isolation systems. Eddy currents in conductive parts can locally warp magnetic fields and enhance magnetic forces. A major goal for future detectors is to reduce magnetic fields and coupling with specific interferometer components. A characteristic example is the optical Faraday isolators, which are used to block reflected light beams by means of a magneto-optic crystal immersed in an intense static magnetic field. We present the study of a passive magnetic shield for the F I of the suspended detection bench of the AdV+ phase II detector. We illustrate the design optimization process and highlight critical points we faced and solved. We propose a procedure to measure the displacement of the bench due to an injected magnetic field coupling to the Faraday isolator.

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Demonstrating Interferometric Sensors to Improve Local Control of Suspended Optics

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Control noise dominates the low frequency spectrum of gravitational wave detectors. Improving sensors and hence local control will ease requirements for global control and reduce noise reinjected into the detector. Three Homodyne Quadrature Interferometers (HoQIs) were installed at the middle-mass of the beamsplitter triple suspension at AEI-Hannover's 10m prototype interferometer. HoQIs have compact baseplates designed to mount on the 'lower tablecloth' of the Big BeamSplitter Suspension (BBSS) for LIGO's A+ upgrade. Hollow, gold-coated retroreflectors mounted on the mass improve robustness to misalignment. The complete optical and electronic signal chain for in-vacuum use was tested. Signals were dominated by ground motion, but a level of ˜$3 \times 10^{-13}\mathrm{m}/\sqrt{\mathrm{Hz}}$ was seen at a few hundred Hz. The fringe visibility changed by less than 0.05 when we applied the largest possible vertical misalignment of 180um. The suspension is now ready to be tested in-vacuum. The benefits of using HoQI to damp resonance peaks in the BBSS have been modelled. We predict an improvement of factor 8 in peak suppression, and factor 60 lower RMS motion of the optic at 1Hz. If deployed on multiple suspensions, this can allow a reduction of auxiliary control bandwidths and associated noise in the 10-20Hz band.

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Low-Frequency control noise - Modelling ASC loops with Finesse

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The Einstein Telescope (ET) is a third-generation gravitational-wave detector, which is expected to be 1000 times more sensitive than current instruments at low frequencies. In this frequency range, detectors have been limited by technical noises. Alignment control is at the frontline of the limiting noises.

The amount of angular control noise chained to the sensitivity depends upon the bandwidth of the alignment control systems. By using low-bandwith control loops ET can keep the control noise below ET fundamental noises. We are building a model of such an alignment control scheme, using Finesse, a python-based interferometer simulation program.

We started with modelling Advanced Virgo's alignent control system, which incorporates high-finesse optical cavities and the last two stages of the super-attenuator. Control filters in the global basis have been implemented as used during O3 run and the resulting closed-loop MIMO matrix accounts for cross-coupled degrees of freedom, both in sensing and actuation. We will use this model to evaluate the alignment controllability of the Virgo opto-mechanical plant for O5 run, design the control strategy and test its noise performance. We will use the experience on validation from Virgo to design the alignment scheme for ET.