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REVIEW ARTICLE

# Concepts and research for future detectors

## Summary of the Amaldi 10 C4 session

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**Abstract** Technologies, design aspects and recent progresses for future gravitational wave (GW) detectors are mentioned in this summary of the C4 session of the Amaldi 10 conference.

**Keywords** Gravitational-wave detectors · Quantum noise · Seismic noise · Optics · Interferometer · Amaldi 10 proceedings

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## 1 Introduction

The future of gravitational wave (GW) detectors lies in routine GW astronomy. The generation of advanced GW detectors will allow us to detect GWs within the next 5 years. Many technical improvements of the first generation are required and are currently being implemented to reach this goal, such as increasing the laser power, using larger and better optics, improving the suspension and seismic isolation systems, implementing new optical schemes such as signal recycling, and upgrading many auxiliary subsystems. Meanwhile investigations have probed the potential for even further improvements. A so-called "strawman design effort" has shown that a combination of currently known, but partly ambitious technologies used in the existing infrastructures may eventually gain another factor of three in sensitivity with respect to the advanced detectors. The Einstein telescope (ET), a concept for a European third generation GW Observatory, which has been studied in a pan-European effort from 2008 to 2011, follows a different route. ET will provide a new underground infrastructure capable of hosting three 10 km detectors, which will mostly be based on driving mature, proven technologies to their physical limits. This, in comparison to the advanced detectors, will gain an order of magnitude in sensitivity and low frequency cut-off. Technologies, which are common to ET and the Japanese *KAGRA* project, such

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as underground and cryogenic techniques, are currently being studied in the Euro-Japanese *ELiTES* project. Technologies and materials that have not reached a sufficiently mature level so far are investigated in a European wide R&D project: *ET R&D*. Some of this work and potential methods pointing even further into the future are summarised in the following sections. (based on the talk of H. Lück on Future GW detectors: Concepts and developments).

## 2 Contributed talks

### 2.1 Optical absorption studies of high resistivity float zone silicon (A. S. Bell)

We used the technique known as Photothermal Commonpath Interferometry to study optical absorption and the effects of change in free carrier density in high purity silicon at 1,550 nm, towards the use of this material in future detectors. Refractive index changes in a substrate caused by a focussed pump beam are encoded as phase changes in a weaker, more collimated probe beam. In addition to the well known change in refractive index due to heating of the sample, in semiconductors such as silicon there are also changes due to the creation of free carriers by two-photon absorption of the pump light. The relative size of these effects for a fixed pump power varies as the beam area. The experimental parameters we used for our initial measurements limited our sensitivity to linear absorption to 100 ppm/cm, due to two-photon absorption. We measured four different samples of single crystal, float zone silicon with resistivities of $>4{,}000\,\Omega$ cm from three different vendors. They all had linear absorptions less than our measurement sensitivity. In one sample, we measured absorption due to surface contamination of around 350 ppm. We are continuing our investigations using a photothermal deflection technique, using a much larger pump beam size to reduce or eliminate the two-photon effects, and allow us to reach around 1 ppm/cm sensitivity.

### 2.2 Single sideband tilt interferometer (D. Blair)

The phenomenon of three mode interactions, first predicted in the context of parametric instability in long baseline GW detectors, couple mechanical vibrations into a single sideband consisting of an optical cavity transverse mode. The process can happen in a single arm cavity or in a complete signal recycling interferometer. Experiments at Gingin have observed an interaction where an acoustic mode that mimics a tilt vibration is resonantly coupled to the $TEM_{01}$ transverse mode. Results demonstrate the intrinsic high sensitivity of this three-mode tilt sensor [1,2] The question arises: could a long baseline interferometer be configured to be sensitive to GWs through the angular component of the GW strain, which has angular amplitude $\theta$ equal to the strain amplitude $h$? If such a sensor could be included in an existing interferometer vacuum system it would immediately create a dual polarization instrument which could extract full waveform information. We conclude that a tilt interferometer based on this principle would be sensitive to GWs. To our knowledge it is the first example of a single sideband interferometer, which as shown in [3], can in principle extract much more energy from a GW than does a conventional interferometer. Unfortunately the tilt interferometer is intrinsically more sensitive to thermal noise since the thermal displacement noise creates tilts across the short test mass baseline. Thus it would not be competitive with conventional detectors. However it could have applications for high frequency GW detection, and can encourage further investigation of single side band detectors.

### 2.3 First observation of three-mode parametric instability in a free-space optical cavity (X. Chen)

Three-mode opto-mechanical parametric interaction in a high finesse optical cavity occurs when the two optical modes couple to an appropriate mechanical mode of the mirrors which have low losses. The phenomenon is highly likely to occur and lead to instability in the advanced GW detectors because they use high finesse cavity, high laser power and low loss mirrors. Braginsky et al. [4].

We use a tabletop cavity with a silicon nitride membrane acting as a resonator in the middle to study the parametric instability, for the purpose of understanding the phenomena and developing control schemes for large scaled GW detectors. The $TEM_{00}$ and $TEM_{20}$ mode are coupled to the mechanical 26 mode (1,718 kHz) and lead to exponential growth of oscillation amplitude. We observed spontaneous parametric interaction and parametric instability with different laser powers levels and different ring-up time. The experimental result also shows that the parametric instability may not lead to cavity unlock.

### 2.4 Detuned Sagnac speedmeter for the 3rd generation gravity wave detectors (S. L. Danilishin)

Sensitivity potential of conventional Michelson gravitational-wave interferometers will be exhausted in the next generation of detectors, which sensitivity shall be limited by quantum noise over a wide signal frequency band. The third generation detectors must employ novel techniques and topologies opening the way to sensitivities well below the standard quantum limit [5]. Sagnac speedmeter interferometer is one of the most promising candidates.

Here we investigate sensitivity limits of signal-recycled Sagnac interferometer with frequency dependent input squeezing and devise the optimal configuration thereof. As a benchmark system we chose the design developed by Strawman Red Team at the LIGO 3 Strawman Design workshop [6]. As expected, Sagnac interferometer outperforms Michelson at frequencies below 100 Hz due to inherently lower susceptibility to radiation pressure noise. This feature of Sagnac also yields much relaxed constraints on input filter cavity bandwidth ($\gamma_{FC}/2\pi > 270$ Hz compared to $\sim$17 Hz for Michelson) as it only has to rotate squeezed light phase in the high-frequency shot noise-dominated region. Moreover, interferometer bandwidth can be further increased, using the combination of weak signal recycling (transmissivity of SR mirror $T_{SRM} \sim 90\,\%$) with small detuning (SR cavity phase shift $\sim 12^\circ$) and increased arm cavity bandwidth. This is a unique feature of Sagnac interferometer where, unlike Michelson interferometer, detuning of signal recycling cavity creates two purely optical resonances in the transfer function and no optical spring, responsible for narrowband features in Michelson detuned SR sensitivity curves.

### 2.5 Juggling interferometer for the detection of GWs (D. Friedrich)

We investigate a novel type of earthbound GW detector targeting a frequency band around 1 Hz to complement currently build advanced detectors and open the possibility to detect for instance intermediate mass black hole binaries. Our approach utilizes free falling test masses in a laser interferometer to decouple their motion from the seismically noisy environment. By repeatedly realizing free fall conditions one can in principle extend the measurement time beyond that of a single free fall event, thereby increasing the frequency resolution. In this type of measurement -we name this a juggling interferometer—the initial conditions of the test masses, such as their microscopic position and initial velocity, will vary in each measurement cycle. As a consequence, the measurement process will not be continuous anymore. Based on numerical simulations, we show that continuous signals can be extracted from the discontinuous data to a given extent by detrending displacement data as well as the filter templates for each measurement cycle. In parallel we have started setting up a prototype experiment to demonstrate our proposed procedure.

### 2.6 Laguerre–Gauss laser mode research for future GW detectors (P. Fulda)

The use of higher-order Laguerre–Gauss (LG) laser modes has been suggested as a technique for reducing the test-mass thermal noise limit in future GW detectors. The speaker presented a synopsis of the research program led by the University of Birmingham into assessing the technical feasibility of implementing this technology in future gravitational wave detectors. This program included an initial simulation investigation, table-top demonstrations of LG mode interferometry and a detailed study of the LG mode degeneracy problem in high-finesse optical cavities. More recently a study of LG mode compatibility with a 10 m suspended prototype interferometer was made in collaboration with the University of Glasgow, as well as a study of high-power $LG_{33}$ mode generation in collaboration with the Hannover AEI.

The problem of higher-order LG mode degeneracy in optical cavities remains the biggest challenge facing implementation of this technology. However, recent studies of adaptive mirror shaping techniques have shown positive results with regards to ameliorating this problem [7]. See [8] for further details.

### 2.7 On the feasibility of a vacuum birefringence measurement at a gravitational-wave detector (H. Grote)

The reported work deals with the possibility to use ground-based GW detectors for fundamental physics measurements, other than detecting GWs. Here we investigated the feasibility to measure the birefringence of the quantum vacuum, an effect predicted by QED, but not observed by any experiment to date. For this measurement it would be necessary to equip a section of one beam tube of a GW detector (such as LIGO, Virgo, GEO 600, KAGRA, ET,...) with a facility producing a magnetic field $B$ perpendicular to the beam tube. The field $B$ would have to be modulated in strength or direction in order to produce an equivalent phase shift modulation in the light passing the beam tube (as predicted by QED). We investigated the possible use of solenoid electro-magnets, pulsed magnets, and permanent magnets and concluded that permanent magnets are the most feasible option to date. We determined the minimal magnetic aperture necessary for this type of experiment to be around 60–90 mm, depending on the type of GW detector. Further, we estimated measurement times for the basic QED effect, for a given GW detector sensitivity, magnet strength, and length of the section with applied B-field. A setup with a minimum of two rotating permanent magnets in a Halbach configuration is proposed. With the example of two magnets of 0.5 m length each, and a magnetic field strength of $B = 2$ T, the integration time to measure the basic QED effect would be about 4 months. This is valid for a signal-to-noise ratio of unity, assuming a peak displacement sensitivity of the GW detector of $1.6 \times 10^{-20}$ m/$\sqrt{\text{Hz}}$ at the frequency of interest.

## 2.8 Research at LMA toward third generation GW interferometer (J. Degallaix)

An intensive research effort is on going at LMA in order to characterize coating and substrates for third generation interferometers. The samples under test are placed within a cryostat [9] and currently three characterisation experiments are taking place at low temperature: (1) *Coating mechanical loss measurement on silicon cantilevers.* We reported on the low-frequency measurements of the mechanical loss of a high-reflectivity multilayer dielectric coating of fused silica and titanium-doped tantala, in the 10–300 K temperature range. The coating loss presents a maxima around 30 K with loss around $10^{-3}$, a value roughly three times higher compared to what is measured at room temperature. (2) *Coating mechanical loss measurement on disks.* Coating loss angle is also measured on 3 in. diameter disks resting on a sphere. This new setup eliminates the need of clamping which increases the repeatability of the measurement. Results of the loss angle of a uncoated and a fused-silica coated silicon disk were presented. (3) *Silicon optical absorption measurement.* Using the photodeflection technique, we demonstrate that the optical absorption of silicon at 1,550 nm is proportional to the density of free carrier. Preliminary measurement have shown no decrease of the absorption at low temperature.

## 2.9 Optimal network configurations for future GW detectors (P. Raffai)

We have carried out numerical analyses aiming to find optimal site locations for hypothetical networks of 1–3 triangular gravitational-wave detectors using a geomap of allowed sites. The analyses were based on three multidetector figures of merit (FoMs) characterizing the networks' capability of reconstructing signal polarization, and their accuracy in source localization and source parameter reconstruction. We have also defined a combined FoM that takes into account the three FoMs with equal weight. We have found that based on the combined metric, placing the first detector to Australia provides the most options for optimal site selection when extending the network with a second instrument. In Raffai et al. [10] we have suggested geographical regions where a potential second and third detector could be placed to get optimal network performance in terms of our FoMs. We have also given the optimal two-detector networks for each FoM separately in example cases where the location of the first detector has been predetermined. We have used a similar approach to find the optimal location and orientation for the proposed LIGO-India detector within a five-detector network with Advanced LIGO Hanford and Livingston, Advanced Virgo, and KAGRA. We have found that the FoMs do not change greatly in sites within India, though the network can suffer a significant loss in reconstructing signal polarizations if the orientation angle of an L-shaped LIGO-India is not set to the optimal value of $\sim 58.2^\circ(+k \times 90^\circ)$ (measured counterclockwise from East to the bisector of the arms).

### 2.10 Optical tuning and displacement noise of a macroscopic mechanical resonator (B. J. J. Slagmolen)

Macroscopic opto-mechanical resonators are being used to measure radiation pressure shot noise [11]. When placed within an optical cavity, the behaviour of the mechanical resonator can be modified to shift its resonant frequency and to dampen or enhance its quality factor. When measuring the radiation pressure shot noise the challenge is to circumvent or mitigate the thermal noise of these mechanical systems.

We present results of the thermal noise displacement of an aluminium mechanical flexure resonator. The thermal noise displacement is a combination of a structural and thermo-elastic damping mechanism. The thermo-elastic damping exhibits a velocity damped behaviour, and has a relaxation frequency at which the thermo-elastic damping is at a maximum. Away from this relaxation frequency the mechanical flexure resonator displays structural damping. In addition to these results, we present servo controlled optical spring effects. By modifying the locking point, we introduced an optical spring effect and were able to shift the resonant frequency of the resonator. Also, by controlling the phase of the feedback signal at the resonant frequency, we commanded the rigidity of the optical spring and accordingly introduced optical damping.

### 2.11 Anomalous dynamical back-action in interferometers: beyond the scaling law (S. P. Tarabrin)

We analyze the dynamical optomechanical back-action in signal-recycled interferometers that are operated off dark port. In particular, we consider a Michelson–Sagnac interferometer with a semitransparent micromechanical membrane positioned in one of its arms, and a Michelson interferometer as a special case of Michelson–Sagnac interferometer with the absolutely reflective membrane. We show in [12] that the dynamical back-action in these interferometers operated off dark port exhibits certain anomalous features, as compared to the well-studied (within the scope of the scaling law) canonical form of dynamical back-action on dark port. In particular, optical damping in a Michelson–Sagnac interferometer acquires a non-zero value on cavity resonance, and additional stability/instability regions on either side of the resonance, revealing new regimes of cooling/heating of micromechanical oscillators. In a free-mass Michelson interferometer, for a certain region of parameters we predict a stable single-carrier optical spring (positive spring *and* positive damping), which can be utilized for the reduction of quantum noise in future-generation gravitational-wave detectors. We also present experimental evidence of the observation of the anomalous region of instability in a 10 cm-scale Michelson–Sagnac interferometer, predicted by our theoretical model.

### 2.12 Realistic polarising Sagnac topology with DC readout for future GW detectors (M. Wang)

Current GW detectors under construction are based on the Michelson topology; even future GW detectors, such as the Einstein telescope [13] was initially designed to host Michelson interferometers. We investigate the feasibility of implementing an alternative topology—a polarising Sagnac—for future GW detectors, in particular the low-frequency interferometers of the Einstein telescope [14]. We consider several important practical issues of such a scheme, including optical losses and the non-perfect polarising optics, and propose a new method for the generation of a local oscillator field similar to the DC readout scheme of current detectors. We show that this scheme combined with squeezed vacuum input could provide a similar level of radiation pressure suppression but does not require the signal recycling mirror nor auxiliary filter cavities.

## 3 Contributed posters

### 3.1 Long term seismic characterization of candidate sites for the ET: preliminary analysis and results in Sos Enattos Mine (F. Acernese)

The knowledge of seismic behavior at different underground levels is essential for the characterization of candidates sites to host third generation of gravitational wave detectors, like the Einstein telescope (ET). For this aim we started a campaign of measurements in the Sos Enattos mine, Sardinia (IT), implementing a modular monitoring system composed by three stations connected among them through optical fibers: the first one, located at ground level (338 m above sea level), is equipped with an weather monitoring system; the second one, at about −84 m underground level, and the third one, at about −111 m underground level, are each equipped with an environmental monitoring system and with several high sensitive seismometers (horizontal inertial sensor developed by University of Salerno [15] and Trillium240 broadband seismometer by Nanometrics©). Furthermore data concerning the sea condition are provided by the Servizio Meteorologico dell'Aeronautica Militare. From analysis of the first six months, we can affirm that no significant differences has been found at two different underground levels but in worst days significant correlation has been found between the spectral peak of the sea waves offshore and of main microseismic peak when it increases from $10^{-13}$ to $10^{-12}\,m^2/s^4/Hz$. Considering these preliminary results, future improvements regard the installation of a clock server to perform an accurate correlation analysis, the extension of the network of sensors for space correlation measurements, and the improvement of the sea monitoring.

### 3.2 A new control approach for the design and implementation of low frequency large band seismic suspensions and inertial platforms (F. Barone)

An innovative application of open-loop monolithic folded pendulum (FP) sensors [15] is the control of large band multi-stage suspensions and/or inertial platforms in the band $0.01-10$ Hz. In fact, their high sensitivity ($10^{-9}\,m/\sqrt{Hz}$ with optical lever readout, $10^{-11}\,m/\sqrt{Hz}$ with LVDT readout, $10^{-14}\,m/\sqrt{Hz}$ with laser interferometric readout), coupled to their large measurement band $10^{-7}-10$ Hz (mainly due to the open-loop configuration—no force feed-back—that dramatically reduces the electronic noise), their resonance frequency tunability in the range ($0.07-1$ Hz), their low thermal noise (measured loss angle $<6\times10^{-5}$ for Al7075-T6) and their very good immunity to environmental noises are characteristics very effective for this control typology. Three FP sensors (FP 2009 version in open-loop configuration with an optical lever readout) have been used for a test of control of the top stage (Filter Zero) of a mechanical four-stage suspension located in the VIRGO-Napoli laboratory [16]. The obtained error signals, characterized by a SNR better than LVDTs, were largely sufficient for the inertial damping of the Filter Zero resonances ($\approx$25 dB). This preliminary test demonstrates that optimised FP sensors can be very effective for the inertial damping of multi-stage mechanical suspensions and/or inertial platforms.

### 3.3 Low frequency/high sensitivity triaxial monolithic sensor (F. Barone)

The triaxial inertial sensor consists of three monodimensional fully symmetric monolithic open-loop folded pendulum (FP), installed in homogeneous-triaxial geometry, for the evaluation of the horizontal and the vertical components of the acceleration using a classical rotation matrix [17]. Therefore, it is a very compact and light sensor, suitable also for ultra-high vacuum and criogenic applications, whose sensitivity is mainly determined by the FP components natural resonance frequencies and by the sensitivity of their optical readouts.

The characteristics of the triaxial sensor are directly related to its FP components, that we report here for the UNISA FP—2010 version [17]): weight $<1.5$ kg, volume equal to $140\times134\times40\,mm^3$, resonance frequency tunable in the range $0.07-1$ Hz, large measurement band ($10^{-7}-10$ Hz) (measured with coherence analysis) and low thermal noise ($Q>14{,}000$ at $10^{-5}$ mbar that shows a very low loss angle $\approx6\times10^{-5}$ for Al7075-T6 symmetric monolithic FP). The measured sensitivity curve with interferometric readout ($10^{-12}\,m/Hz^{1/2}$ in the band $0.1-100$ Hz), is expected to largely improve with the new version of symmetric monolithic FP (UNISA FP—2013 version [17], that shows already a higher readout sensitivity (better than $10^{-14}\,m/Hz^{1/2}$ in the same band).

### 3.4 Digital control and data system of the AEI 10 m prototype interferometer (M. Born)

The AEI 10 m Prototype Interferometer [18] is currently set up in Hannover. All subsystems such as the 35 W laser, the seismic attenuation system (SAS) and the Suspension Platform Interferometer (SPI) are controlled by an Advanced LIGO digital control and data system (CDS) [19]. This Linux based CDS is currently running control loops on five front-end computers. Loops that include sensors and actuators connected to different computers are closed by a fast PCIe network connection. Data acquisition is done by a separate frame-builder computer with 60 TB of disk space. Currently, about 200 fast ADC/DAC channels at 65 kHz sampling rate and about 10,000 slow channels (16 Hz) produce 60 GB/day. In addition to the standard CDS features, we developed a digital interface for an AEI LISA Pathfinder Phasemeter. This microcontroller based interface delivers phase data of 20 photo diodes from the SPI at a rate of 614 Hz. The upsampling to the 2,048 Hz of the control loop is done by a simple zero-order hold. For low-noise upsampling, the implementation of a poly-phase FIR filter is planned. Ongoing is the integration of subsystems of the Prototype Interferometer into the CDS as they are set up. Further planned enhancements are the implementation of the new aLIGO timing system and of our DC power supply load monitoring.

### 3.5 The AEI-SAS: Seismic isolation for the 10 m prototype interferometer (G. Bergmann)

A 10 m arm length prototype interferometer is currently being set up at the AEI in Hannover, Germany. This facility will not only be used for developing novel techniques for future GW detectors, but furthermore it will provide a platform for high precision experiments such as measuring the standard quantum limit (SQL) of interferometry. To achieve the high requirements on displacement noise for these experiments very good isolation from seismic motion is required.

The first stage of seismic isolation for the 10 m prototype interferometer is a set of passively isolated optical tables. Geometric anti-spring filters provide vertical attenuation, and the tables are mounted on inverted pendulum legs which provide isolation in horizontal direction. Purely mechanically passive attenuation of more than 60 dB below 10 Hz was shown in first experiments. The table motion agrees very well with the predicted performance. Several sensors and a Suspension Platform Interferometer will be used to measure the residual table motion. These signals will be used for actively controling the tables. This will even improve the passive table's performance around its fundamental resonances. Currently two out of three tables are installed in the vacuum envelope.

### 3.6 Modelling mirror surface distortion effects in low-loss, near-unstable Fabry–Perot cavities poster (D. Brown)

Gravitational wave detectors utilise optical cavities in multiple ways. When squeezed light is injected to reduce the quantum noise, optical losses can significantly degrade its effect, in particular losses in the filter cavities such as from surface defects. At the same time, thermal noise can be reduced by increasing the spot size on the mirrors leading to near-instable cavity geometries. Experiments such as the 10 m AEI prototype are planning to use near-instable cavities [20] in the future. We use numerical modelling software FINESSE [21] to investigate such low-loss, near-instable cavities with nanoscale defects present on the mirror surfaces and the effect they have on the cavity performance along with the possible effects measurable via an optical experiment. The numerical results are a preliminary investigation for an unstable cavity experiment currently being conducted [22]. It was found certain mirrors will produce a measureable cavity finesse differences that can be used to study how mirror surface distortions will effect near-instable cavities.

### 3.7 Non-ideal coherent noise cancellation for quantum optical systems (T. Denker)

The future generation of laser interferometric GW detectors will be limited in sensitivity by radiation pressure noise (RPN) in the frequency range from 10 to 100 Hz. Next to shot noise this is the other fundamental noise source caused by the quantum nature of light [23]. The temporally statistically distributed photons of a light field push on a cavity mirror and the back action caused by the restoring force imprints a phase shift on the light field. This effect acts as a phase modulation, masking the effect of a GW. To reduce the effect of RPN we want to employ coherent control schemes [24] and present a possible experimental realisation of coherent feed-forward [25]. It consists of a meter cavity with an opto-mechanically coupled mirror that exerts back action on the cavity light field due to RPN. To eliminate the back action an auxiliary cavity that acts as a virtual negative mass oscillator is introduced to destructively interfere with the RPN before the resulting light field leaves the meter cavity. The coupling between the two cavities can be realised by a beamsplitter and an optical parametric amplifier (OPA) in the auxiliary cavity which produces the required anti-noise. By choosing the right parameters for the OPA and appropriate efficiencies it is possible to achieve radiation pressure noise cancellation. My poster is about theoretical possibilities and limitations.

### 3.8 Results of the medium size ring-lasers G-Pisa and GP2 (A. Di Virgilio)

Ring Lasers are instruments based on the Sagnac effect, able to measure the absolute angular rotation rate. Presently, in this field, they are the most sensitive device, and are used for: inertial navigation, geodesy, geophysics and as well fundamental physics [26]. They can be used as well as tilt-meter with nano-radiant sensitivity, and large bandwidth. They can have a very large bandwidth, from several kHz down below μHz. The systematics of the laser set the limit of the low frequency response; as an example the backscattering noise, which can be understood and off-line subtracted. Our prototype G-Pisa [27], has been operating for several months inside the Virgo's central area, during the latest scientific run, with two different orientations (vertical and horizontal), with a sensitivity about $2{-}3 \times 10^{-9}\mathrm{rad/s}/\sqrt{\mathrm{Hz}}$. They could be used for future generation of GW antennas as environmental monitors and to improve the performance of the suspensions. The sensitivity depends on the size of the instrument, very sensitive device cannot be much less than 4m in perimeter. G-Pisa has a perimeter of 5.4 m.

### 3.9 Study of six mechanical two-mode impedance matchers on a spherical GW detector using FEM (C. Frajuca)

A spherical gravitational wave (GW) detector has a heavy ball-shaped mass which vibrates when a GW passes through it. Such motion is monitored by transducers [28]. One of such detectors is Schenberg [29]—will have resonant frequencies around 3.2 kHz making the transducer development for this higher frequency detector somewhat more complex. In this work we present a series of finite study elements of a sphere coupled to two-mode mechanical oscillators that will work as mechanical impedance matchers between the sphere and the microwave transducer. This work reports improvements made in the modelling of mechanical impedance matchers using finite elements method when shell elements type were used instead of tetrahedron elements type, showing that method works as a very good approximation. We found that the normal modes of the coupled system are not exactly degenerative, although theoretical calculation predicts that they should be. We showed that it is not straight forward to find a mechanical oscillator with a frequency near the one of the spheres quadrupole modes and which will work as a good impedance matcher for a spherical gravitational wave detector. When these matchers were attached to the sphere we noticed that the quintuplet modes showed different bandwidths, this lack of degeneracy of the quintuplets may be due to the asymmetry created by the presence of the resonators in only one of the spheres hemisphere.

### 3.10 Comparison of Michelson- and Sagnac-interferometers regarding their susceptibility to mirror imperfections (S. H. Huttner)

In recent years the Sagnac-interferometer has become of interest to the GW community. We set up FINESSE models to compare the sensitivity of these two designs to imperfections of the mirrors. Our Sagnac model had rectangular (10 km × 1.5 m) ring-cavities in the arms where the light runs both clock- and anti-clock wise (which requires toric mirrors: different radius of curvatures in the x- and y-direction), whereas the Michelson model contained 10 km long linear Fabry–Pérot cavities. We chose to model the interferometers with light in the $LG_{33}$ mode which is of interest to reduce thermal noise, but has a lower tolerance to mirror surface errors.

We started from the mode-matched and perfectly aligned case with undistorted optical modes and perfect symmetry between the arms. We slightly misaligned one cavity mirror in each arm (0.1 μdeg) and separately introduced curvature errors to the same mirrors (1 %). In each case the imperfections were applied in both the common and differential modes (i.e. with the same or opposite sign in the two arms). To assess the effect of the imperfections on performance, the changes in circulating power in the arm cavities, power at the dark ports of the interferometers and peak sensitivity were compared.

It was found that the designs showed broadly similar (within a factor of 2) susceptibility to both errors, with the exception that the Sagnac design exhibited approximately eight times greater tolerance of differential misalignment.

### 3.11 An optical spring with an intra-cavity squeezer (J. Kato)

The sensitivity of GW detectors will be limited by quantum noise. An optical spring and squeezing are candidates to reduce the quantum noise. The optical spring in the detector is generated by detuning the signal recycling cavity and it amplifies the signal at the resonance. The quantum noise is attributed to the vacuum entering the interferometer from the anti-symmetric port. When the vacuum is squeezed, the sensitivity of the detector is improved at the high frequencies. This improvement can be obtained also by increasing the laser power, but squeezing is not of benefit to the detuned interferometer because it has almost the same effect as changing the reflectivity of the signal recycling mirror and it does not amplify the effective power. Methods to use the optical spring and squeezing compatibly have not been clearly established. We propose to put a non-linear crystal in the signal recycling cavity so that the optical parametric oscillator works as a signal amplifier. This intra-cavity squeezer effectively increases the laser power like the squeezing vacuum injection and it is compatible with the optical spring. The amplifier shift the spring frequency due to effective power up.

An experiment to measure the frequency shift is in progress. We are constructing a tabletop interferometer, which is a dual recycling Michelson interferometer with folding arms like GEO600. The end masses are 200 mg and sustained by piano wires. The Michelson interferometer and the power recycling cavity have been locked. We are currently working on the signal recycling mirror.

### 3.12 Design and development of a Suspension Platform Interferometer for the AEI 10 m Prototype Interferometer (S. Köhlenbeck)

The AEI 10 m Prototype is low noise test bed for advanced GW detector developments and measurements at and beyond the Standard Quantum Limit. To reach the necessary sensitivity for those experiments an ultra high vacuum system will be equipped with three passively seismic isolated optical benches separated by over 10 m. Below 0.1 Hz an additional system is required to stabilize the relative displacement of the three optical benches. The suspension platform interferometer (SPI) was designed to measure the displacement of the optical benches and use the obtained signals in a feedback control system. The requirements were set to $100\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ for the longitudinal degree of freedom and for the angular to $10\,\mathrm{nrad}/\sqrt{\mathrm{Hz}}$ in between 100 and 10 mHz. Two optical benches are already installed and working. The SPI is a quasi-monolithic assembly of four heterodyne Mach–Zehnder interferometers on a low thermal expansion glass plate (Clearceram-Z HS). It is mounted on the central optical bench and the interferometer connecting the optical benches is also installed. The light is prepared outside the vacuum system and brought into it by optical fibers. The performance of the SPI is limited to $1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ at 100 mHz and $1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ at 10 mHz. To reduce the noise in the interferometers an optical pathlength difference stabilization will be implemented.

The feedback system to reduce the inter table motion was tested and the applied filters will be further optimized.

### 3.13 Coupling of longitudinal phase shift from sidemotion of waveguides (S. Leavey)

One way of potentially reducing mirror coating thermal noise is through the use of waveguide mirrors, which use a periodic grating structure etched onto a region of highly reflective material. High reflection is produced without multiple coatings, potentially reducing noise [30].

Previous efforts with 2nd order Littrow configurations found that an additional phase effect is produced on the reflected light [31,32], resulting in stringent technical requirements. Recent simulations of a 0th order waveguide [33] have shown that this effect can be avoided. The authors aim to demonstrate this result experimentally.

The group at the University of Glasgow, in collaboration with Universität Jena and the Albert-Einstein-Institut, Hannover, is undertaking measurements using a waveguide mirror tuned for 1,064 nm light. It has been suspended as the input mirror in a 10 m Fabry–Perot cavity kept on resonance using the Pound-Driver-Hall technique, with finesse 75. The dielectric end mirror is rotated at a frequency of 70 Hz to scan the cavity light across the waveguide to produce sidemotion, and the longitudinal signal is read out via an RF photodiode. At the time of writing, the first results are being analysed.

### 3.14 Control of the angular motion of the tiny 20 mg suspended mirror in the high power cavity for QRPN measurement (M. Nakano)

In advanced GW detectors such as KAGRA, the quantum radiation pressure noise (QRPN) is expected to limit the sensitivity in lower frequency band. Hence, the development of experimental techniques to reduce the QRPN is highly interesting. We challenge to construct a table-top system to observe the QRPN and verify a technique to reduce it by taking advantage of the phenomenon called “ponderomotive squeezing”. We are developing a Fabry Perot Michelson interferometer using 20 mg suspended end mirrors to observe QRPN. The cavity was locked stably at low light power, but at higher laser power angular instability due to opto-mechanical coupling will occur. The control scheme, we are investigating to stabilize the cavity at high laser power, uses the alignment of the front mirror to change the optical axis. This angular control scheme is simulated using an analytical opto-mechanical model. In previous experiment, at low light power we succeeded in reducing angular motion of the small end mirror by applying feedback. The simulated angular behavior of the optical cavity agreed with this result. With this simulation model, we found that we have to optimize the feedback filter to observe QRPN; otherwise the sensor noise of the quadrant photo detector to detect the beam spot position on the small mirror could prevent the observation of QRPN. We plan to optimize the feedback filter based on this model to meet the requirements set by QRPN.

### 3.15 Noise modelling for atom interferometry (R. N. Palmer)

Atom interferometry can measure gravity with potentially very high precision [34], and has been proposed as an 0.01–1 Hz GW detector [35]. However, reaching this precision requires careful minimisation of many noise sources [36,37]. In particular, we consider noises caused by imperfect control of the atom clouds' position and size, which include wavefront distortion and Coriolis (rotation) effects. These noises can be suppressed by selecting atoms near a fixed position using a smaller detection beam [36], or subtracted off by measuring the position and phase gradient using an imaging detector [38].

We develop a computer model of atom interferometry and its errors, analogous to existing tools for optical interferometry, and apply it to both these schemes. We find that imaging detection gives the lowest noise, as it does not rely on throwing atoms away and hence increasing shot noise.

### 3.16 Active damping of triple-suspended mirror for the 10 m prototype via modern control techniques (D. Schuette)

Modern control techniques ease the design process of feedback loops needed to control and stabilise complex systems [39]. We show that active damping of the suspensions can be accomplished via an Linear Quadratic Gaussian controller. This controller combines a linear quadratic regulator (LQR) and a linear time-invariant Kalman filter. The LQR characterises the overall system dynamics, including unwanted cross-correlations for the six degrees of freedom in form of a state space model. The LQR solves a cost functional minimising the quadratic sum of the position fluctuations of the suspended mirror for a specific control energy. The Kalman filter optimally estimates non-measurable variables and adds white Gaussian noise to the measured signals. To determine the frequency response of the system we set up an optical lever to read out the motion of the lower stage after introducing a signal at the top stage. This readout also provides the possibility to identify non-ideal suspension setups [40]. As a result the combination of passive damping, suspension design realised by the 10 m prototype group, and active damping of the eigenmodes of the triple pendulum should enable the desired performance for interferometric measurements at the Standard Quantum Limit.

### 3.17 Dynamic tuning for a signal recycled interferometer (D. Simakov)

In this poster I've presented the studies of a particular method of detection of chirp signals from coalescing compact binary stars—the so-called dynamical tuning, i.e. amplification of the signal via tracking of its instantaneous frequency by the tuning of the signal-recycled detector. The layout of the detector and the fine tuning of the arm lengths divides the detector in two distinctive modes: a power and a signal recycling modes. The stationary operational mode requires conventionally the frequency domain model. The quasi-stationary approximation applicable for for describing of the dynamical tuning only to some extend. A time-domain consideration developed for signal-recycled interferometers, in particular GEO 600, describes the signal and noise evolution in the non-stationary detector. Its non-stationarity is caused by motion of the signal recycling mirror, whose position defines the tuning of the detector. We prove that the shot noise from the dark port and optic al losses remains white independently from the value of losses and from the motion of the SRM. The analysis of the transient effects was performed, including study of the detector response to the step-wise change of the GW amplitude and frequency, and of the the SRM position. The analysis shows that during the perfect tracking of the chirp frequency only transients from amplitude changes arise, and also from the imperfectness of this frequency tracking. The signal-to-noise-ratio gain, calculated for this method of detection is ~16 for a shot-noise limited detector and ~4 for a detector with both shot and thermal noise. It is possible to develop the time-domain model for the more common configuration with the Fabry–Perot cavity in arm.

### 3.18 Development of a low-frequency gravitational-force sensor (B. J. J. Slagmolen)

We present the design concept of a low-frequency gravitational-force sensor. The sensor is targeted for sensing the Newtonian noise due to atmospheric and seismic disturbances at frequencies below 10 Hz. The sensitivity of future GW detectors will be limited by these noise contributions. The low-frequency gravitational-force sensor can provide an independent measure of the Newtonian noise to validate the estimator in a future implementation of a Newtonian noise cancellation system. Other sources of gravitational-forces can potentially be investigated, such as the gravitational inverse-square law [41] and potentially discrepancies in big G [42].

The sensor design is based on a torsion bar antennae, developed by Ando [43]. The low-frequency gravitational-force sensor consists of two perpendicular beams, independently suspended as torsion pendulums. They share the same suspension point, and have their axis of rotation co-linear and the center-of-mass co-incident. An incoming gravitational force, perpendicular to the plane of the two suspended beams, will rotate the beams differentially. The linear distance between the ends of the two beams, will change and are measured using a Michelson interferometer. Any linear pendulum motion between the two beams will be registered as a common mode motion, to which the Michelson is mostly insensitive. The sensitivity to gravitational forces is modelled, based on a metre-scale prototype design.

### 3.19 Optical absorption measurements on a crystalline silicon test mass at 1,550 nm (J. Steinlechner)

The initial and advanced (2nd) generations of laser-interferometric GW detectors employ fused silica (FS) as test-mass material and are operated at a wavelength of 1,064 nm. Already the 2nd generation will be limited by thermal noise in a wide frequency band. An approach to reduce this noise is to cool the test masses to cryogenic temperatures. Since the mechanical Q-factor of FS decreases by orders of magnitude at low temperatures, it is not suitable as test-mass material in cryogenically cooled GW detectors.

For the European 3rd generation GW detector ET it was proposed to use crystalline silicon (c-Si) as test-mass material. Due to it's extremely high absorption at 1,064 nm, the employment of c-Si will enforce a wavelength change, e.g. to 1,550 nm. The goal of this work was a measurement of the optical absorption of c-Si at 1,550 nm as a function of optical intensity. Our measurement technique provides the full information about the optical round-trip loss. Both, the bulk absorption and the absorption in the crystal surfaces were determined in one joint measurement. A non-linear absorption was observed for intensities above a few kW/cm$^2$. In addition we observed an intensity-independent offset that possibly arises from absorption in the crystal surfaces and was estimated to 800 ppm/surface.

### 3.20 Quantum-dense readout for GW detectors (S. Steinlechner)

Quantum metrology uses entanglement to improve the sensitivity of measurement devices. While up to now only a single observable was considered, additional information might be contained in its orthogonal observable. This information is inaccessible with current techniques such as (single-mode) squeezing of light. In a table-top laser interferometer, we demonstrate a new quantum-dense readout scheme [44]. This readout provides information about two non-commuting observables, with uncertainties below the meter's quantum ground state. We show how the additional quadrature information can be used to identify parasitic stray-light interferences. Parasitic interferences arise from scattered and frequency-shifted photons inside the detector and affect the sensitivity of high-power interferometry devices, such as GW detectors. Our readout scheme employs a two-mode squeezed state of light, prepared from two individually squeezed states. One mode, the meter mode, is injected into the interferometer dark port via a polarizing beam splitter and Faraday rotator. The interferometer output is then overlapped at a 50:50 beam splitter with the second, reference mode. In each of the two beam splitter outputs, a balanced homodyne detector detects one of the two readout quadratures which are oriented along the initial squeezing ellipses.

Using this novel quantum-dense readout scheme, we were able to readout two orthogonal quadratures with about 6 dB simultaneous quantum-noise squeezing. With the help of sinusoidal test signals, we showed how science signal and parasitic signals can be distinguished, creating a novel veto channel against stray-light induced disturbances in gw detectors.

### 3.21 A path length modulation technique for frequency shifting scatter induced noise in squeezing measurements (A. R. Wade)

Spurious scattered light reflections couple low frequency environmental noise into the homodyne measurement of squeezed light states. We present a technique for frequency shifting contributions of scattered-induced noise in squeezed light measurements. By pre-modulating the pump path length at the start of the squeezing apparatus followed by a matched anti-symmetric post-modulation, a vacuum squeezing ellipse is kept in a fixed quadrature whilst modulating the phase of scattered reflections originating between the two points of modulation. A 500 Hz sinusoidal path length dither is implemented, matching the phase and depth of dither of two mirrors. We show a 20 dB reduction in scatter-induced noise in a balanced homodyne measurement of a squeezed vacuum state, recovering squeezing down to 1 Hz.

A path length modulation technique that actively reduces contributions from scatter within a squeezing apparatus path is potentially useful for squeezing deployments to laser interferometer gravitation wave detectors, where it is desirable to frequency shift spurious back reflections coupling in through a squeezing injection port. Such a technique offers advantages of improving scatter immunity without the need for lossy isolating optics that degrade squeezing. For further details refer to [45].

### 3.22 A coating thermal noise interferometer for the 10 m prototype (T. Westphal)

Coating thermal noise (CTN) is becoming a more and more significant noise source as the sensitivity of interferometry is pushed to its limits [46]. It arises from mechanical loss of thin films in dielectric coatings. Deeper understanding and verification of its theory, such as frequency dependence of losses, requires direct (off-resonant) observation. The AEI 10 m Prototype facility provides all ingredients required for an experiment in a frequency range of special importance for earth bound GW detectors [18]. A pre-isolated platform shows two to three orders of magnitude attenuated seismic noise inside an ultra-high vacuum system. Up to 10 W highly frequency and intensity stabilized laser light at 1,064 nm will be available for experiments. A CTN-interferometer is being constructed at the 10 m Prototype facility. The interferometer is designed to be dominated by CTN from 10 Hz to about 50 kHz, limited by seismic noise at low frequencies and shot noise (photon counting noise) at high frequencies. This is achieved by means of a small spot size on the probe mirror. The size can be tuned over a wide range (100–3 $\mu$m) to investigate the predicted scaling with spot size. The first of three identical suspensions has been set up. Digitally controlled actuation as well as active damping in vacuum were successfully demonstrated.

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