Vibration isolation systems for the beam splitter and signal recycling mirrors of the KAGRA gravitational wave detector

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	Abstract.
205	KAGRA is an underground interferometric gravitational wave detector which is currently being commissioned. This detector relies on high-performance vibration- isolation systems to suspend its key optical components. These suspensions come in three different configurations, of which the Type B is used for the beam splitter and signal recycling mirrors. The Type B suspension comprises the performance three three different configurations.
210	geometric anti-spring filters for vertical isolation and one inverted pendulum for horizontal isolation. The payload comprises the optic, its marionette and their recoil masses, which hold local displacement sensors and coil magnet actuators used for damping the resonant modes of oscillation of the suspension itself. The beam splitter
215	version has a modified lower section to accommodate a wider optical component. The payload is also equipped with an optical lever, used to monitor and control the position of the suspended optics from the ground. All four suspensions have now been installed in vacuum chambers. We describe the mechanical, electrical and control design, and the measured performance compared to requirements.

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1. Introduction

The detection of gravitational waves (GWs) from a black-hole binary inspiral event by the two LIGO detectors [1], and subsequent observations of further such events and a neutron-star binary inspiral in conjunction with the Virgo detector and non-GW 225 telescopes [2, 3] have ushered in an exciting new era in astronomy. In order to improve the localization of sources, it is highly desirable to add further km-scale detectors to the network. LIGO-India is planned to come online on 2025 [4], and the Japanese detector KAGRA has had its first observation run together with GEO600 from the 7th to the 21st of April 2020. This run is known as O3GK and we will refer to it throughout the 230 text. Besides improving the localization of GWs sources, KAGRA also has the goal of introducing new technologies leading to the next generation of detectors. For instance, in order to reduce the thermal noise, the test masses, which are sensitive to GWs, are cooled down to 20 K [5]. Also, the detector is built underground where the seismic motion is between 10 and 100 times lower depending on the frequency range [6]. 235

Low seismicity allows us to design vibration isolation systems which require smaller amounts of feedback correction, thus decreasing the injected control noise, which may be harmful for the detector sensitivity. This article describes one such vibration isolation system used for the Beam Splitter (BS) and the three Signal Recycling (SR) Mirrors (SR2, SR3 and SRM). Sec. 2 provides an overview of the different types

- of suspensions used in KAGRA together with requirements. Sec. 3 describes the mechanical components employed in the suspension and Sec. 4 describes the sensors and actuators used locally to damp resonant modes of the suspension. Sec. 5 explains the topology of the control system. Sec. 6 reports the performance at low frequencies,
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where stability is important in order to acquire and keep the lock of the interferometer. Finally, Sec. 7 reports the result of a numerical estimation of the control noise injected within the observation frequency band.

2. Overview of vibration isolation systems in KAGRA

As is standard for interferometric GW detectors, the main optics are suspended as the lowest level in a multi-stage pendulum system, which provides vibration isolation from seismic background and thermal noise that would otherwise compromise performance. KAGRA suspensions rely on passive vibration isolation at high frequencies within the interferometer observation band and active control at lower frequencies where the resonant motion of the suspension needs to be damped. Passive vibration isolation ²⁵⁵ relies on the fact that the transfer function from ground motion to the load motion of a multi-stage oscillator decreases as f^{-2n} above its resonant frequencies, where f is the input frequency, and n is the number of stages. Active damping of resonant motion at low frequencies is achieved at each stage by measuring the motion and by applying forces with local sensors and actuators.

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Four main types of suspensions are used in KAGRA. Figure 1(a) shows their layout



Figure 1: Layout of the main optics and their vibration isolation systems used in KAGRA [7].

and Fig. 1(b) shows a 3D CAD rendering of each type. Type-A suspensions [8, 9] are used for the most critical optics, namely the input and end test masses, which define the arms of the Fabry-Perot-Michelson interferometer and react to the GW. Each Type-A system has an inverted pendulum (IP) stage for horizontal isolation, five stages of geometric anti-spring (GAS) filters for vertical isolation and from it hangs the cryogenic payload. [5]. Type-B suspensions, described in more detail below, are used for the BS and the three SR mirrors. They have an IP stage, three levels of GAS filters and a room-temperature payload [10]. Type-Bp suspensions are used for the three power recycling mirrors. They have two levels of GAS filters, with an extra recoil mass around the lower one as a partial substitute for an IP [7]. Type-C suspensions [11] are used for the input and output mode cleaners and are based closely on the design used for the TAMA300 interferometer [12].

Table 1 shows the performance requirements for the Type-B suspension. The

Quantity	Beam Splitter	Signal Recycling Mirror
Damping time	60 s	
RMS longitudinal displacement	$4 \times 10^{-7} \mathrm{~m}$	
RMS velocity	$5 \times 10^{-7} \text{ m/s}$	
RMS angular fluctuation	1×10^{-6} rad	
Displacement spectral	$2 \times 10^{-18} m/\sqrt{11}$	$2 \times 10^{-18} m / \sqrt{H_{\pi}}$
density at 10 Hz	3×10 III/ $\sqrt{\text{Hz}}$	2×10^{-1} III/V Hz

Table 1: Required upper limits for the motion of the optics hanging from Type-B suspensions [6, 13].

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damping time refers to the time it takes for the active control system to damp any resonant motion which may be involuntarily excited. The 60 second limit was set to permit quick recovery of the alignment of the interferometer. The RMS values of the longitudinal and angular displacements and longitudinal velocity concern the low frequency regime where stability is necessary to acquire and keep the optical cavity lock. Finally, the displacement spectral density at 10 Hz is the requirement within the interferometer observation band.

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3. Mechanical design of the Type-B suspension

Figure 2 shows the Type-B suspension (SR variant) within the vacuum chamber and a supporting outer frame[‡]. The chamber and the frame are shown in semi-transparent gray and the suspension in opaque color. The lower part of the frame and some parts of the chamber extend beyond the limits in the diagram. The IP, in the top section of 285 the tank, is supported by the rigid frame A' on the outside of the tank via three jacks B' entering through flexible belows so that the frame and tank are largely mechanically decoupled and the height and levelness of the IP can be adjusted. The IP stage has three flexible legs D', two of which appear in the diagram, and the resonant frequency can be tuned by adding arc-shaped weights around the edge of the IP table E'. The baseline design has 172 kg of arc weights for the BS and 103 kg for the SRs. By increasing this by about 25-35%, the resonant frequency can be adjusted to a suitable value. We require a frequency less than 80 mHz to give adequate isolation of the microseismic peak. A frequency of 40 mHz is achievable with some care but does not leave enough margin for small temperature changes and we generally work around 65 mHz. The IP has three 295 assemblies F' arranged circumferentially around the outside, each one comprising a LVDT (Linear Variable Differential Transformer) displacement sensor and a coil-magnet actuator. Next to each LVDT/actuator assembly there is a horizontal Fishing Rod (FR) unit, with a pair of soft, opposed, auxiliary springs (whose curve resembles that of a

fishing rod) on a motor-driven base to apply DC position adjustments. The IP also has

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‡ Primed labels are used to to avoid conflict with the names of other parameters.



Figure 2: The Type-B suspension (SR variant). Primed labels are used to to avoid conflict with the names of other parameters. A': supporting outer frame, B': jack, C': IP base, D': IP leg, E': IP table, F': LVDT, coil-magnet actuator and horizontal fishing rod, G': geophone, H': Top GAS filter blades, I': various components (see text), J': Security Structure, K': Standard GAS filter F1, L': maraging steel rod, M': magnetic damper, N': Bottom Filter, O': moving masses to adjust BF pitch and roll, P': IRM, Q': Mirror or beam splitter, R': RM, S': optical table, T': cable clamps, U': spring blade assemblies for the optical table suspension, V': magnetic damper for the optical table suspension, V'': iron ring with magnets, W': suspension point (see text).

three geophones G' (velocity sensors) arranged circumferentially around the edge of the IP table.

The Top GAS filter (F0) H' is mounted on the movable IP table and supports the hanging chain, while the Security Structure (SS) J', which surrounds and protects the chain, is attached to the fixed underside of the IP C'. The assembly I' comprises 305 the keystone, a motor-driven rotary bearing to allow yaw adjustments of the chain, a LVDT for sensing vertical displacement, a coil magnet-actuator and a vertical motordriven Fishing Rod for DC position adjustment. The keystone is a component at the geometrical centre of the GAS filter structure onto which all the spring blades are clamped [14].

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The second GAS filter K', called the Standard Filter (SF, a.k.a. F1), is suspended by a maraging steel rod L' from the keystone of F0. At the hooking ends, the rod has a thickness of 3 mm. The term "standard" refers to the structure of all the filters that are neither on the IP table nor at the bottom interfacing with the payload. In Type-B we have only one of this type of filter but as shown in Fig. 1, in Type-A suspensions 315 four are used. As it will be described in Sec. 6 this particular SF has two ring segments of copper plates M' on its upper surface, which interacts with a ring with magnets hanging via thin rods from the underside of the IP C' to give eddy-current damping of the fundamental yaw mode and other pendulum modes of the chain. This sub-assembly is called the Magnetic Damper (MD).

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The third GAS filter N', called the Bottom Filter (BF), is suspended with a maraging steel rod from the SF. At the hooking ends, the rod has a thickness of 2.5 mm. The BF has four large sliding masses O' on the top surface, two motor-driven, to allow for pitch/roll adjustment of the BF, and a motor-driven rotary bearings in its keystone to allow yaw adjustments of the IM stage below.

All the GAS filters have configurable numbers of blades. All BF and F0 units use three blades but with different widths according to load. The SFs in the SR suspensions use four blades whereas the one for BS uses six due to the heavier load. GAS filters F1 and BF also have LVDT displacement sensors, coil-magnet actuators acting on the keystones, and vertical motor-driven Fishing Rods for DC position adjustment.

From the BF hangs the payload. The IM (Intermediate Mass) is suspended by a central maraging steel rod from the keystone of the BF, and the Intermediate Recoil Mass (IRM) P' is suspended by three thin rods from the base of the BF. At the hooking ends, the central rod has a thickness of 2 mm and the other three rods have uniform thickness of 2 mm. As shown in Fig. 3(a) the IRM encloses the IM on the top and 335 sides. A section of the IRM has been removed from the diagram in order to show the IM and the wire clamp, which is shown in more detail in Fig. 3(b). The IM works as the marionette of the optic. On the inside it has two motor-driven sliding masses to allow for pitch and roll adjustments independent of the IRM, whose pitch, roll and yaw track the BF. Details of such system can be found in Ref. [10]. The IRM holds 340 six displacement sensors, each one paired with a coil-magnet actuator into a unit called OSEM, which stands for Optical Sensor and Electromagnetic Actuator [15]. As will be



Figure 3: Some details of the SR payload.

explained in more detail in Sec. 4.1, the displacement sensor is a shadow sensor in which a flag mounted on the moving IM obstructs the path between an LED and a photodiode. The coil acts on a magnet in the flag assembly mounted on the IM. OSEMs are used for actively damping the resonant motion of the suspension. From the viewpoint shown in Fig. 3(a) there is another OSEM at the back side of the IRM and the remaining one is on the section which was removed from the diagram to show the IM.

As shown in Fig. 2 the optic (BS or SR2/SR3/SRM) Q' and the RM (Recoil Mass) ³⁵⁰ R' both hang from the IM. As suggested in Figs. 3(a) and 3(c) they are both suspended by two loops of wire held by clamps at the IM, one of which is shown in Fig. 3(b). A double clamp arrangement is used: the primary clamps are tightened to a modest torque (2 N.m) to locate the wire, and the secondary clamps are tightened rather more firmly

(10 N.m., the maximum recommended for the M6 screws) to support the load. The wire standoffs for the optics are shown in Fig. 3(d). They are modelled on the aLIGO design: 355 each side of the optic has a sapphire prism with two laser ablated grooves for the primary standoff, and a similar prism of machined stainless steel for the secondary. Both sets are applied with Master Bond EP30-2 adhesive with 5% by weight of silica beads with a diameter of 120 μ m, added to reduce the risk of cracks from temperature changes [16].

As depicted in Fig. 3(e) the RM uses a simple grooved cylindrical metal wire standoff 360 and a PEEK clamp. For hanging the BS and SR optics 0.3 mm and 0.2 mm diameter piano wire is used respectively and for the RMs 0.65 mm and 0.60 mm diameter tungsten wire is used for BS and SR respectively. The piano wire employed was manufactured according the JIS SWP-A norm, which allows the alloy to have between 0.80% and 0.85% of carbon, which is similar to C85 steel. The particular lot used had 0.82% of 365 carbon.

The RM mostly encloses the optic except at the front and back, and has four coils that act on magnet-standoff assemblies attached to the optic using EP30-2 with beads as above. This arrangement is shown in Fig. 3(f). The original design called for four full OSEMs with displacement sensors on the RM, but the magnet-flag assemblies needed 370 to be very long and proved impractically easy to damage, so we elected to eliminate the shadow sensors and flags and rely on the optical lever (OL) for longitudinal, pitch and yaw position sensing. This allowed us to greatly reduce the area of adhesive and increase the freedom of movement before there was risk of touching.

Cables are guided to the upper part of the chamber following paths close to the 375 axial centre of the suspension in order to minimize the possible torques they may apply. Some of the clamping points are labeled T' in Fig. 2. Only a few are shown but there are many in all stages. The importance of robust cable clamping and routing is due to the fact that the suspension is very soft and small changes in the position of the cables may easily produce an unwanted displacement of the optic. Such changes may 380 be produced by an accidental excitation from the control system or by an earthquake. Along the suspension the cables are clamped around the stages and are fixed on cable clamps which attach to the suspension rods. Cables are routed so as not touch each other or other components between clamping points, and when going from a clamping point on the suspension rod to an upper stage a particularly large amount of slack was 385 given in order to avoid introducing any additional stiffness.

The optical table S' shown in Fig. 2 supports auxiliary optical components like scattered-light baffles, and injection and pick-up mirrors. Each such table has its own separate suspension. At the top are three copper-beryllium spring blades indicated by U, from which the copper ring V' hangs. The ring V' is set in close proximity of ring V'', which has magnets on its lower side and hangs from from hooking points W' on the vacuum chamber. The optical table hangs from ring V', and eddy-current damping between the rings passively damps the resonant motion of the whole optical

An important parameter of the IM marionette is the coupling from translation 395

table suspension.

degrees of freedom to rotational ones. In the nominal mechanical design of the IM, the vertical position of the centre of mass (COM) coincides with the horizontal plane of actuation of the OSEMs, configuration which is expected to minimize the couplings. However, in the real system such a coincidence does not happen due to manufacturing tolerances and also as a consequence of having to use additional ballast mass on the 400 IM in order to reach the load the upper BF requires. In principle, during assembly the coupling can be measured when applying forces onto the IM with the actuators, and then minimized by changing the distribution of mass of the IM [17]. However, the IRM encloses the IM almost entirely, configuration that prevents further manipulation of the ballast masses once the IRM has been assembled with the OSEMs. Given this constraint, 405 the strategy has been to reduce the actuation couplings in software by calculating a diagonalization transformation in which additional forces and torques are applied in order to reduce the coupling displacements [18]. In a prototype experiment previously reported [10], the coupling factors from longitudinal to all others DoF were reduced to less than 0.01 in units of either $\mu m/\mu m$ or $\mu rad/\mu m$ at frequencies of a few tens of mHz. In the case of the mirror, the wire prism standoffs were glued in line with the COM in longitudinal and vertical. Due to the wedges of the mirrors, the COMs do not coincide

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1.5 mm. The CM of the RM does coincide with the geometrical centre. The separation
between the wires holding the mirrors is 10 mm and for the ones holding the RM it is
20 mm. For O3GK, diagonalization of the IM and RM DoF was not carried out due to time constraints.

with the transverse geometrical centres. For instance, in SR2 the CM is nominally off by

4. Sensors and actuators for control

As pointed out in Sec. 2 the vibration isolation system relies on local sensors and actuators to actively damp the resonant motion of the suspension. For the purposes 420 of active control, all the motor-driven adjustments (fishing rods, moving ballast masses, rotary bearings etc.) mentioned above are considered fixed, and only the non-contacting sensors and actuators are used. These sensors are three L-4C geophones from Sercel and three LVDTs with coil-magnet actuators at the IP [19, 20], one LVDT with coilmagnet actuator at each of F0, F1 and BF, six OSEMs at the IM, and four coil-magnet actuators plus an OL mounted on the ground for the optic. The number of sensors and actuators were chosen so they could be diagonalized to L (longitudinal), T (transverse), V (vertical), R (roll), P (pitch) and Y (yaw) at the IM; L, T and Y at the IP; and L, P and Y at the optic; the damping then is calculated in the diagonalized basis. For the most part the diagonalization is straightforward, being based on the known geometry 430 of the sensors and actuators, but that for the OL is more involved and is described in section 4.3. Additionally, for the IP, the position signals from the LVDTs and the velocity signals from the geophones are combined via frequency-dependent blending to give lower-noise position signals. The LVDTs are known to be more sensitive sensors at low frequencies where active control is necessary to suppress position drifts. See section 435



Figure 4: Diagram (a) shows how the flag (in blue) mounted on the moving IM creates a shadow on the photodiode. The plot shown in (b) is the sensitivity of the OSEMs used in SRM suspension.

5 for more details on the control system. This section describes the OSEMs, LVDTs and geophones.

4.1. OSEMs

Each OSEM has a coil for magnetic actuation and the LED and photodiode of a shadow sensor for displacement. A cross section view is shown in Fig. 4(a). Six OSEMs are 440 used on the IRM. At corresponding positions on the IRM there are PEEK pedestals, each holding an actuation magnet and a thin, flat, aluminium shadow-sensor flag. The dimensions are chosen so that when the flag tip is midway between the LED and photodiode, the magnet is at the point of maximum field gradient of the coil. The flag assembly is self-assembling via the force of the magnet on ferromagnetic inserts in 445 the flag base and pedestal tip, which makes them resistant to permanent damage in the case of a knock. Each pedestal has a second, oppositely oriented magnet at the base to cancel the overall dipole moment of the IM. As shown in Fig. 3(a), each OSEM is mounted on a panel with screws that have in-out range for adjusting its position with respect to the tip of the flag. In turn, each panel is mounted on the IRM with screws 450 in oversized holes that provide range for lateral alignment. Both types of adjustment happen after the masses are hung. Before installation in the suspension, each OSEM was calibrated in an optical table by moving a dummy flag with a micrometer. This process

⁴⁵⁵ and the linear range in units of displacement. The displacement sensitivity§ of some OSEMs were also measured by rigidly fixing the OSEM body and the flag at nominal relative positions. Across the 24 OSEMs in all Type-B, most have linear ranges close

yields the calibration factor, typically in units of displacement per count of the ADC,

§ In this paper we call *sensitivity* to the smallest amount of a quantity a sensor can measure. It is determined by the total noise and is typically expressed in units of an amplitude spectral density, e.g. m/\sqrt{Hz} for a displacement sensor.



As depicted in (a) the LVDT and the coil-magnet actuator are mounted Figure 5: coaxially with the suspension rod. Fig. (b) shows that the RMS values integrated from 100 Hz down to 1 mHz are below 200 nm.

to 800 μ m and 870 μ m with one outlier at 750 μ m and two at 950 μ m. Fig. 4(b) shows the displacement sensitivity of six OSEMs as amplitude spectral densities. With small differences between the six samples the sensitivity is close to 9×10^{-9} m/ $\sqrt{\text{Hz}}$ at 0.1 Hz 460 and 3×10^{-9} m/ $\sqrt{\text{Hz}}$ at 1 Hz. Typical RMS values integrated from 100 Hz down to a few tens of mHz are close to 20×10^{-9} m.

4.2. LVDT

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LVDTs quantify displacement using the change in the mutual inductance between a single primary coil and a double secondary coil with the two halves counter-wound, which move with respect to each other [19]. Fig. 5(a) shows the cross section of one of the LVDTs used in a GAS filter. This view corresponds to the region referred to as I'in Fig. 2. The primary coil is wound around a PEEK former attached to the keystone of the GAS filter. The coil is oriented coaxially with the suspension rod which also hangs from the keystone. The secondary coils are fixed on the GAS filter base plate. 470 The primary coil is driven with an AC signal of constant amplitude and frequency, and the induced voltage in the secondary is demodulated using the excitation signal as a reference, and passed through a low pass filter. The resulting DC voltage is proportional to the core displacement. Fig. 5(a) also depicts the coil-magnet actuator. The actuation coil is wound on the same former as the LVDT primary coil and moves together with the keystone. The magnets and an iron yoke, used to guide the magnetic field lines in

a suitable manner, are fixed to the GAS filter base plate. The yoke has a central hole for the suspension rod to go through.



Figure 6: The plane of incidence of the OL is vertical. The beam enters and leaves the the vacuum chamber through the depicted viewports.

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The LVDT units used in Type-B suspensions provide linear outputs along ranges that vary from several to many millimetres in order to accommodate the relatively large displacements that the GAS filters may experience due to their low resonant frequencies. As an example of their sensitivity, Fig. 5(b) shows the displacement spectral density of the six LVDTs used in the SR2 suspension. As with the OSEMs, the sensitivity was measured after locking the keystones. Some LVDTs are more sensitive than others due to differences in calibration and linear range. The least sensitive device is the one for 485 the Top Filter with 1×10^{-7} m/ $\sqrt{\text{Hz}}$ at 0.1 Hz and 5×10^{-8} m/ $\sqrt{\text{Hz}}$ at 1 Hz. All RMS values integrated from 100 Hz down to 1 mHz are below 200×10^{-9} m.

4.3. Optical lever

An OL is used to measure the displacement of the suspended optical component from the ground in order to damp the resonant motion of the suspension in L, P and Y, and 490 to set the orientation of the mirror in P and Y, using the IM as a marionette in order to keep the alignment of the mirror [21]. So far the lock has been acquired and kept by means of the OL, but in a more advanced operation stage it is planned to use wave-front sensing because it produces signals coherent with the main interferometer beam.

The working principle of the OL is that the motion of the mirror will produce both 495 angular and lateral displacement of a reflected light beam incident upon it, from which both longitudinal and angular displacements of mirrors can be determined. In all Type-B suspensions the plane of incidence of the OL beam is vertical. Figure 6 shows the typical propagation path of the beam in the case of the SR suspensions. The emitter optics are mounted on a breadboard located on a pylon rigidly fixed onto the floor and 500 the receiving optics are on a breadboard fixed onto the outer frame, both sets outside of the vacuum chamber. The emitter set comprises a superluminescent diode (SLD) light source connected to a collimator via an optic fibre. At the receiving end, the OL beam reflected by the mirror is divided by a non-polarizing beam splitter and sent along two paths. One path leads directly to a quadrant photodiode (QPD), which senses primarily mirror angle (P, Y). The other path takes to a lens and then to a QPD placed at the image plane of the mirror, which senses primarily L. The three degrees of freedom can then be mathematically decoupled further in real-time.

In reality, however, the optical components are not perfectly aligned and additional mechanisms of coupling between L, P and Y arise. For instance, when the beam 510 is not reflected at the very centre of the mirror, a coupling from pitch and yaw to longitudinal appears. A detailed description of many mechanisms of coupling and methods of diagonalization can be found elsewhere [21]. Briefly, diagonalization is achieved by separately exciting in L, P and Y with white noise and examining the behavior of the different transfer functions at the resonance frequencies. For example, it 515 is expected that at the resonance frequency for P the mirror is not moving significantly in L and Y and, therefore, any apparent coupling belongs to the sensor itself and can be removed mathematically in real time. Rather than applying an excitation at a particular frequency, white noise was used in order to distinguish resonant motion from motion produced by actuation coil imbalance as the latter is expected to be frequency independent and, therefore, its effect appears as white noise. Calibration into micrometers is achieved by measuring the position of the optical components on the breadboard and assuming 3D-CAD values for the larger and harder dimensions to

measure inside the vacuum chamber. The response of the QPDs to beam displacements in micrometers was also carefully measured by moving the QPD with a micrometer stage with a still beam. After diagonalization and calibration, typical values of cross-coupling factors were approximately equal or less than 0.01 in units of either $\mu rad/\mu m$, $\mu m/\mu rad$ or $\mu rad/\mu rad$, with a few outliers reaching 0.02 in the same units. In order to test the OL readout, the whole GAS filter chain and the payload were moved using the IP in

L and Y by amounts also measured by the calibrated IP-LVDTs. The values reported by the OL and IP-LVDTs were consistent with each other within 10%. It is important to point out that the drawback of using QPDs as beam position sensors is their limited linear usable range, which affects the recovery time of the local control system when the mirrors move too far away from the centre after a large accidental excitation. For

example, in the case of the SR2 suspension the linear range is approximately $\pm 180 \ \mu m$ in $L, \pm 120 \ \mu rad$ in P and $\pm 180 \ \mu rad$ in Y. A strategy that would straightforwardly increase the angular measuring range would be to place the lens before the beam splitter, keeping the length sensing QPD at the image plane of the suspended mirror and placing the angle-sensing QPD at the focal plane of the lens [22, p. 23]. This change would decrease the sensitivity, which may be an acceptable compromise.

4.4. Inertial sensors

As pointed out in Sec. 2, the Type-B system relies on passive vibration isolation within the GW observation band at 10 Hz and above. However, at lower frequencies the passive approach is not expected to be enough when intense oceanic weather increases the microseismic motion of Honshu island at frequencies of 200 mHz and below. In these 545 conditions, active damping is necessary. Because LVDTs do not measure the IP motion with respect to an inertial reference frame but from the moving ground, the motion of the IP produced by ground motion must also be measured with an inertial sensor in order to create an appropriate feedback signal. Within a geophone the test mass is part of a harmonic oscillator subject to viscous damping. A permanent magnet is attached 550 to the case and a pick-up coil is attached to the test mass. Relative motion between the two produces an electromotive force proportional to the velocity. As shown in Fig. 2, to sense motion in L, P and Y, each IP (E') uses three geophones (G'). The model used is the L-4C manufactured by Sercel. Each geophone is in air within a hermetically sealed pod that is in turn placed on the IP table in vacuum. The responsivity, defined 555 as the transfer function from velocity to output voltage, has a particular mathematical form and is fully determined by the resonance frequency of the oscillator ω_0 , a damping coefficient ζ and the responsivity factor G, which is the proportionality constant between the velocity and electromotive force generated [23]. For each geophone these parameters were determined with a least-square-fit of the measured transfer function from the 560 readout of a Trillium 120QA seismometer calibrated in m/s to the geophone voltage output. Typical resonance frequencies are above 1 Hz, with high coherence values in the calibration measurement down to 100 mHz. The sensitivity of the geophones were also measured using a three channel correlation analysis [24]. Fig. 7 shows the sensitivity of the geophones used in SR2 suspension together with a theoretical estimate of one of them 565 [23, 25]. The predicted sensitivity takes into account the Johnson thermal noise of the resistance of the pick-up coil, the thermal noise of the inner test mass suspension and the electronic noise of an output preamplifier used to preserve the signal-to-noise ratio in the digitalization process at the ADC. The preamplifier is built with the low voltage noise operational amplifier CS3001. The theoretical calculation reveals the preamplifier noise is dominant and its amplitude coincides with a previously measured value [6, 25]. As it can be seen from the plot below 9 Hz the measured values of the geophone sensitivity are higher than the predicted ones. For instance, at 200 mHz the measured noise is larger by a factor of 3.6. We are currently in the process of identifying the source of this discrepancy. The figure also depicts the free swing displacement spectral density 575 in IP-L measured by the geophones. The IP resonance can be seen at 70 mHz and the pendulum modes of the chain can be seen at 400 mHz and at 670 mHz, with the value of the noise floor consistent with the geophone noise. In the same plot, the sensitivity of one of the IP-LVDTs is shown for the purposes of comparison.



Figure 7: The measured sensitivities of the geophones are higher than expected. The measurement of IP-L free swing motion during a seismically quiet day yields a similar noise level.

5. Control system 580

The aim of the local control at low frequencies is twofold: to continuously keep the mirror in an appropriate position in order to allow and maintain the alignment of the interferometer, and to suppress the resonant motion of the suspension itself. Quantitatively, this means achieving a performance compatible with the requirement, listed in Table 1, for the conditions in which the global control using interferometer 585 signals are engaged and the mirrors are locked in their respective optical cavities. Besides the expected challenges posed by this goal, the control scheme faces the additional challenge of keeping the control noise injected into the interferometer observation band to an acceptable level to allow KAGRA to reach its ultimate sensitivity. In this section, local control systems that were used during O3GK are described.

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Suspensions are controlled by real-time computers similar to those used at LIGO. The signals are acquired by an analog to digital converter (ADC) at 2 kHz. In software, feedback signals are created by applying active control filters to the input signals. Using a digital to analog converter (DAC) the feedback is then passed to coil drivers and thence to the actuators.

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Each Type-B suspension has fifteen DoF upon which it is possible to actuate: three at the IP (L, T, Y), one at each GAS Filter, six at the IM (L, T, V, R, P, Y) and three at the suspended optic (L, P, Y). Real displacement sensors and actuators (i.e. LVDTs in IP, shadow sensors in OSEMs and QPDs in the OL and their associated coil-magnet

actuators) are mapped into these DoF via diagonalization matrices. In terms of well 600 known categories, assuming that these DoFs are minimally coupled in both sensing and actuation, this transformation converts the multiple-input-multiple-output (MIMO) control problem to multiple single-input-single-output (SISO) problems. In this scheme the inputs are the desired values of each DoF and the outputs are their actual values delivered by the control system. 605

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A suitable filter design must find a balance between the different competing physical elements affecting the output. Figure 8 shows block diagrams of the control system with these additional elements. The IP and the three GAS filters can be described with the same generic diagram shown in figure (a). The subscript i refers to one of IP, F0, F1 or BF. The diagram for the payload is depicted in figure (b). Parameters called out with the same letter as in (a), but with the subscripts IM and OPT, refer to analogous quantities at the IM and mirror levels respectively. Each DoF is subjected to an external disturbance D_i . At the IP and F0, the origin of the disturbance is the ground motion, and, at lower stages, the disturbance is the amount of ground motion which is not filtered out by upper stages. In diagram (a) the disturbance is explicitly represented

- as $D_i = C_i^{\rm u} X_i^{\rm u}$, where $C_i^{\rm u}$ is the transfer function from the displacement of the upper stage $X_i^{\rm u}$ to the displacement of the current stage X_i . Also, since each control loop utilizes feedback signals derived from the sensors, the signals are inevitably coupled to sensor noise N_i . Control loops also have setpoints R_i to bring each stage to a position suitable for the interferometer alignment. The plant, which represents the dynamics of
- 620 the system via its transfer function, is referred to as P_i and the controller as K_i . All these blocks can be easily identified in the diagrams of the IM and mirror levels in (b). The difference is that position of the mirror X_{OPT} , measured by the OL, is fed into the IM control filter for DC positioning of the mirror using the setpoint R_{OPT} .
- The goal is to design a filter K_i that minimizes the coupling from the noise N_i and 625 from the disturbance D_i to the displacement X_i , while keeping the displacement at the setpoint R_i , which is typically just a DC offset. The displacement X_i can be written as a linear combination of R_i , D_i , and N_i as

$$X_{i} = \frac{K_{i}P_{i}}{1 + K_{i}P_{i}} R_{i} + \frac{1}{1 + K_{i}P_{i}} D_{i} - \frac{K_{i}P_{i}}{1 + K_{i}P_{i}} N_{i}.$$
(1)

- For DoFs with DC setpoints, the control filter includes an integrator, which has a f^{-1} 630 frequency dependence and a very high gain at very low frequencies. In this frequency regime the integrator dominates over other terms present in the filter and the open loop gain $K_i P_i \gg 1$, making the displacement X_i track the setpoint R_i . In order to guarantee stability, the unity gain frequency (UGF) of the DC control loop is set to around 10 mHz in the IP, which is far below the frequency of the first resonance of the plant (as will be 635
- seen in Fig. 11). At the GAS filters the UGF of the integrator was set to around 100 mHz, lower than the resonances of the GAS filter chain, which lie between 200 mHz and 1 Hz. Stability of the stand-alone DC control loop also requires reducing the open loop gain at the resonant frequencies with notches in the filter. At higher frequencies, the displacement is dominated by the disturbance D_i and the sensor noise N_i . Assuming 640



Figure 8: Block diagrams of the local control system of the Type-B suspension. Diagram (a) describes either the IP, F0, F1 or BF stages. Diagram (b) describes the payload.

that the disturbance and noise are not correlated, the power spectral density of the displacement reads

$$\left\langle X_i^2 \right\rangle = \left| \frac{1}{1 + K_i P_i} \right|^2 \left\langle D_i^2 \right\rangle + \left| \frac{K_i P_i}{1 + K_i P_i} \right|^2 \left\langle N_i^2 \right\rangle,\tag{2}$$

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where the DC term related with R_i has been dropped. It can be immediately seen that it is impossible to minimize the displacement value to zero for any control filter K_i . This is due to the complementary nature of the coupling terms $\frac{1}{1+K_iP_i} + \frac{K_iP_i}{1+K_iP_i} = 1$, which means that they cannot be minimized simultaneously. Therefore, it is important to design K_i in such a way that the control system is able to suppress the disturbance D_i while at the same time avoiding the introduction of too much noise. Resonant motion excited by the external disturbance $X_i^{\rm u}$ is suppressed with damping proportional to the 650 velocity. In frequency space this means that the filter K_i is proportional to the frequency f. At very low frequencies this term has a negligible gain compared with the dominant integration term. As the frequency increases the open loop gain also increases such that $|K_i P_i| \gg 1$ at the resonances, implying that the disturbance D_i is suppressed by roughly

a factor of $|K_iP_i|$. At frequencies higher than the resonant frequencies, the sensor noise 655 will typically dominate. With $|K_i P_i| \gg 1$, the displacement value converges to the readout noise value. Therefore, the control filter K_i must be rolled off with a low-pass filter such that the noise coupling $\left|\frac{K_i P_i}{1+K_i P_i}\right| \ll 1$ at the interferometer observation band, which begins at 10 Hz. In filters used for O3GK the roll-off was implemented with a few simple poles, however, an optimal implementation should use steeper low-pass filters 660 like Butterworth or similar. The trade-off of low-pass filters is that they introduce a negative phase shift in the open loop transfer function $K_i P_i$, and this additional phase may compromise the stability if the filter cut-off frequency is too close to UGF. So, in general, the design of a suitable controller K_i is a trade-off between disturbance rejection, noise attenuation, and stability. In general, higher-order roll-off is needed at 665 lower stages because the control noise is not passively attenuated as much as the control noise from upper stages.

Displacement parameters $X_i^{\rm u}$, D_i and X_i are given with respect to an inertial reference frame. The LVDTs and OSEMs, however, are mounted on mechanical stages that move in a such a way that they cannot be considered inertial reference frames. In the diagrams in Fig. 8 the motion of the sensors themselves must be taken into account as a component of the noise N_i . Thus, the noise N_i is the addition of the intrinsic readout noise (Figs. 5(b) and 4(b)) and the displacement of the stage upon which the sensor is mounted. In the case of the IP and F0 the LVDTs are directly mounted on the ground and, therefore, their readouts are directly affected by seismic motion. In order to prevent excessive injection of microseismc motion at the IP along L and T, the control filters were designed such that the control band does not include the frequency of the microseismic peak. As a trade-off, some resonances sensed at the IP at higher frequencies were not actively damped.

- In the future, the control strategy will make use of sensor correction and sensor blending techniques. Sensor correction refers to the subtraction of the ground motion contribution from the readout of the IP and F0 LVDTs using the signal of a nearby seismometer mounted on the ground. This would allow us to use a higher gain for active isolation from seismic motion and also for damping for resonances at higher frequencies. Sensor blending refers to the simultaneous use of the LVDTs and the geophones within the IP control loop. LVDTs and geophones have different advantages over different frequency bands due to their different intrinsic sensitivities. Namely, as shown in Fig. 7, at low frequencies the LVDTs are more sensitive whereas the geophones are better sensors at higher frequencies. Therefore, a blended sensor uses the geophones
- to sense the IP motion produced by the microseismic peak at around 200 mHz and use the LVDTs at lower frequencies where the geophones are too noisy. As suggested above, above the resonant frequency of the IP the LVDTs have the additional disadvantage of being limited by ground motion because they are mounted on the ground and the IP tends to be mechanically isolated from it. The geophones, on the contrary, are inertial sensors and are not limited by ground motion. They directly measure the velocity of
- the IP table with respect to an inertial reference frame. At frequencies closer to the

resonant frequency and below it the coupling of the IP to the ground increases making the contribution of the ground motion to the LVDT signal less important allowing us to measure the IP position with respect to the ground more effectively. For O3GK sensor blending was not implemented due to the excess of noise in geophones referred to in Sec. 4.4.

6. Performance at low frequencies

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This section reports the measured performance at low frequencies during the commissioning and the O3GK observation campaigns in 2020. During this stage the aim was to achieve a minimum level of stability for the interferometer to function rather 705 than to reach the ultimate performance of the suspension. The scope of the control system used during the measurements reported in this section did not reach the full extent described in Sec. 5 mainly due to time restrictions. Moreover, implementing the damping with the blended sensor was not possible at the time due to an excess of noise in the geophone channels, an issue which is currently under investigation. In the 710 IP and all stages of vertical attenuation shown in Fig. 2, DC position control and AC damping control were implemented according to the guidelines given in Sec. 5. The IP used only LVDTs with low control gain above the IP resonant frequencies in order to minimize the injection of ground motion. In Sec. 7 the numerically calculated behaviour of the suspension with a more favorable implementation of the control system for the 715 interferometer sensitivity will be reported.

The behaviour of the suspensions at low frequencies determines whether the main interferometer control system is able to acquire and maintain the lock. It also determines how fast the interferometer locking conditions can be recovered after an unlock event ⁷²⁰ involving the overall suspension. Disturbances may be external, like human activity or an earthquake, or produced internally as an accidental excitation of a subsystem of the control system itself. In this frequency regime the performance can be characterized by the behaviour of specific subsystems upon different conditions, all of which are described in this section.

Besides the devices used for active control described in Sec. 4, the Type-B suspension also has a passive eddy current damper [26] for the lowest yaw resonant mode at 55 mHz. According to our rigid body simulations of the whole suspension [27, 6], the IP does not participate in this mode but only the stages that hang from the IP table, so no actuators are able to damp it. This torsion mode can be easily

excited by the IP motion or may also be excited by the radiation pressure produced by the laser impinging on the suspended mirror [28]. As shown in Fig. 9 the magnetic damper comprises two copper ring segments fixed on top of the F1 GAS filter and an iron ring with magnets attached to its bottom in close proximity to the copper ring. The magnets are not visible in this view but the three maraging steel rods holding the iron ring from the IP table are clearly seen. The height of the iron ring can be adjusted

by moving the upper attachment points of the three suspension rods to the IP table.



Figure 9: The iron ring with magnets attached underneath hangs right above the copper ring on top of the SF. The magnets cannot be seen from this upper view.

The hooks are threaded and are inserted into threaded holes in the table. The copper segments and the iron ring are coated with nickel plating to make them UHV compatible. During assembly, outside of the vacuum chamber, the gap between the magnets and the copper segments was measured with a non-magnetic ruler with sub-millimetre scale and, once inside the chamber, the position of the hooks was adjusted with a vernier caliper, yielding an uncertainty of the order of ± 0.3 mm.

- The goal is to set the position of the iron ring with respect to the copper segments so as to achieve underdamped oscillations with a decay time below 60 seconds in order to yield a fast recovery of the aligned state whenever an excitation arises. Figure 10 745 shows the decaying yaw displacement of the mirror, measured by the OL, for three different positions of the iron ring in the SR3 suspension. The torsion mode was excited with sinusoidal actuation applied in yaw using the IP coil-magnet actuators. After waiting for a few seconds for the motion to become large enough, the excitation was suddenly interrupted and the yaw displacement was measured with the OL. The envelope 750 of the damped oscillation was calculated using the Hilbert Transform and a decaying exponential $\exp(-t/\tau)$ was fitted to the envelope where t is time and τ is the decay time. From the top plot to the bottom one, the gap between the lower face of the magnets and the upper surface of the copper ring is 8.5 mm, 5.5 mm and 3 mm with decay times of 94, 27 and 17 seconds respectively. Whereas the plot for the gap of 8.5 mm clearly shows 755 such a configuration is not suitable, the other plots offer more interesting information about the other two configurations. In both of them the damped oscillation at 55 mHz is clearly seen together with components at higher frequencies. Such components correspond to resonant modes which are excited in the same process as the 55 mHz yaw mode and which the damper ring is not designed to damp. These modes are meant to 760
- be damped by the active control system instead, which during these measurements was off. The exact modes which were excited and their amplitudes were not reproducible



Figure 10: Torsion mode amplitude decay, measured by the OL, for different positions of the MD. The values of the height refer to the gap between the magnets and the copper ring.

in the different measurements. We remark that during the measurements reported in Fig. 10 the OL signals were not optimally diagonalized and, therefore, a certain amount of pitch and longitudinal displacement should be also expected to be seen in yaw. In 765 the middle plot, additional to the damped 55 mHz motion, oscillations at 149 mHz and 1 Hz are clearly seen. Both correspond to yaw modes of the IM, RM and mirror, which the damper ring cannot damp and whose decay times are reported below. In the bottom plot it is clear that the 55 mHz motion damps rather quickly making clearly visible the 1 Hz oscillation. Oscillations in the frequency neighborhood of 149 mHz can 770 be seen below 80 seconds. The configuration selected had the magnets on the iron ring 5.5 mm above the copper ring and a decay time of 27 seconds. Possibly the decay time could have been further improved but we also wanted a gap large enough to ensure the magnets and the copper plates would not touch each other during subsequent work involving the Top Filter, whose LVDT has a total linear range of ± 4 mm. 775

Besides continuously damping possible excitations produced by persistent microseismic motion the active control system also aims to damp sudden temporary disturbances. The figure of merit is the decay time of the resonant motion once the excitation has ceased. Fig. 11 shows the values of the decay times for 25 different modes according to frequency. The horizontal line indicates the 60-second limit set to achieve



Figure 11: Decay times of 25 resonant modes of the SR2 suspension according to frequency. With the control on their values are below 60 seconds.

fast recovery of interferometer operation. The resonant frequencies were identified from force to displacement transfer function measurements or from free swing displacement amplitude spectral densities. As with previous reports [10, 7], each mode was excited with the actuators at the relevant stage and its displacement was measured with the devices described in Sec. 4. The envelope of the damped oscillation was also calculated 785 using the Hilbert Transform and then a decaying exponential was fitted to the envelope in order to estimate the decay time. As can be seen in Fig. 11, with the control system on all the decay times are below the limit. The decay times of the payload yaw modes at 149 mHz and 1 Hz, which are present in the mirror displacement plots shown in Fig. 10, have decay times of 4.8 s and 3.5 s respectively when active damping is used. Current 790 efforts include the blending of LVDTs and geophones in order to achieve a sensor with better sensitivity in the region of the microseismic peak and above, and also the redesign of some filters to have a higher unity gain frequency. Therefore, the decay times of some of the modes are likely to become smaller in the future.

⁷⁹⁵ As stated in Table 1 the RMS displacement and velocity of the mirror with the control system should be small enough to allow the lock acquisition of the interferometer optical cavity. Fig. 12 shows the residual displacement and velocity of the SR2 mirror measured by the OL on March 2020 just before O3GK observation campaign, together with ground motion data. This measurement provides upper limits only due to the fact that the OL is mounted on the ground and therefore is expected to be limited by seismic motion. The RMS displacement integrated from 10 Hz down to 10 mHz is 2.7×10^{-7} m in L, 1.8×10^{-8} rad in P and in 6.2×10^{-9} rad in Y. The corresponding RMS velocities are 3.0×10^{-7} m/s in L, 6.6×10^{-8} rad/s in P and 1.4×10^{-7} rad/s in Y. All these quantities are below the requirement shown in Table 1. Notice that above 700 mHz the ground motion does not limit the OL measurement. On days of bad weather, the



Figure 12: The RMS displacement (a) and RMS velocities (b) of the SR2 mirror measured by the OL are below the requirement listed in Table 1. The apparent increase of the ground motion displacement below 60 mHz is due to noise in the seismometer.

contribution of the microseismic motion to the readout of the OL increases. This in turn yields a higher upper limit estimate of the residual motion of the suspended mirror thus making the comparison with the requirement difficult. In these conditions the only alternative is to use the main interferometer as a displacement sensor to characterize the performance of the overall suspension.

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Long term stability of the mirror position and orientation is also important for the operation of the interferometer. Besides the obvious need to keep the orientation and longitudinal position of the optic constant, the height of the SRs should also be controlled due to the radius of curvature of the front faces of the mirrors (the BS is flat). The IPs and GAS filters are very sensitive to temperature changes due to the 815 change of Young's modulus of maraging steel. For the Virgo Superattenuator, which uses maraging steel in its Magnetic Anti-Spring Filters, the temperature is kept within 0.2 °C [29] because those devices do not have coil-magnet actuators [30]. In KAGRA all GAS filters have coil-magnet actuators and together with the LVDTs the keystone positions are kept constant with DC control loops. In order to assess stability the hourly 820 mean positions of the IP and GAS filters of the SR2 suspension were examined for a period of two months in which the temperature of the clean booth changed by 1.1 °C. Figure 13 shows the position values after the removal of large excursion data points which suggested the presence of an external excitation. The positions of the IP, F0 and BF do not track the temperature trend but cluster around the set point with small 825 standard deviations, which are represented in Fig. 13 with red lines. For IP-L, F0 and BF the standard deviations are 81 nm, 11 nm and 36 nm respectively. F1 GAS does have a trend resembling the temperature trend but its position only changes by 17 nm during this period. These values are smaller than the integrated RMS values reported



Figure 13: Hourly average of the positions of SR2 IP and GAS filters over a span of sixty days in which the temperature changed by 1.1 °C. The DC control loops keep the values around small neighborhoods with standard deviation values represented by the red lines.

in Sec. 4.2 because the hourly mean averages out high frequency noise which is the main contributor to the values plotted in Fig. 5.

7. Numerically calculated performance

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This section reports the result of a numerical calculation showing it is possible to meet the requirement listed in Table 1 for the residual motion of the optic within the interferometer observation band at 10 Hz and above along the longitudinal degree of freedom. The calculation is based on the rigid body model [27, 6] developed for KAGRA's suspension design. The residual motion of the optic includes the contributions of ground motion and sensor noise injected by control loops.

This calculation does not consider the damping of the microseimic peak at the IP ⁸⁴⁰ using the currently installed geophones. Their noise level only allows blending with the LVDTs at frequencies which are too high to use them appropriately for damping at 200 mHz. Nevertheless, the frequency band in which the geophones will be used

goes up to above 640 mHz where the second pendulum mode of the chain is. Because this frequency is relatively low and also because the IP is far away from the optic, the control noise injected by such a subsystem is not expected to be a problem at 10 Hz. It 845 is worth mentioning that in a Type-B suspension prototype test in Tokyo, damping with the geophones experimentally achieved a reduction by a factor of 2 in the RMS velocity of the IP compared to the uncontrolled free swing case [6]. The numerical estimate considers a safety overall 1% coupling from the vertical degrees of freedom into the main longitudinal one including a fraction of 0.33% accounting for the 1/300 rad slope of the 850 KAGRA tunnel. The amount of ground motion used was the 90 percentile amplitude spectral density. Figure 14(a) shows the residual motion of the mirror. The requirement at 10 Hz and above is shown in dark green and the requirement for the integrated RMS displacement is shown in orange only at low frequencies. In both cases the calculated displacement is below the requirement. The calculated integrated RMS displacement is 855 2.7×10^{-7} m and the displacement spectral density is 4×10^{-18} m/ $\sqrt{\text{Hz}}$ at 11.48 Hz at its closest point to the requirement value. At this frequency there is a vertical resonance of the IM, RM and optic. The control loops considered are the DC position and AC damping control for the IP using the LVDTs, DC position control for the three GAS filters and AC damping control for the F0 Top GAS filter. DC control loops have UGFs 860 of around 10 mHz and all filters have been rolled-off to minimize the contribution of injected sensor noise. In order to allow the suspension to reach a performance compatible with the requirement using only local sensors, the use of the IM OSEM displacement sensors and the OL is not considered as they introduce too much noise. In a later stage of development, we hope to either replace these sensors or mix them with more sensitive 865 interferometric devices such as wave-front sensors and the main interferometer itself. The major contributions to the integrated RMS are the ground motion injected via the IP LVDTs and the pendulum mode sensed by the IP just above 400 mHz. The latter is also a consequence of not using the inertial sensors for damping. The LVDTs make it necessary to limit the unity gain frequency of the IP control filter to below 100 mHz 870 in order to avoid introducing an even larger amount of ground motion, thus leaving the resonance undamped. This condition becomes manifest in the decay times reported for this mode in Fig. 11. With the control on and off the decay times are above 50 seconds with no significant difference between the two. Figure 14(a) includes the contributions of the IP and GAS Filter sensor noise, which refers to LVDT intrinsic readout noise 875 propagated through the control filters and the plant. The peaks in the contribution of the GAS Filter plot come from damping the modes at 218 mHz and 588 mHz. Figure 14(b) shows the simulated residual motion of the mirror with the same configuration of the control system, but calculated using the ground motion data shown in Fig. 12(a). The blue line is the OL measurement from the same figure, which is shown again for the 880 purposes of comparison. At low frequencies the calculated displacement is consistent with the OL measurement given the fact that the OL is mounted directly on the ground and is therefore affected by its motion. Notice, additionally, that unlike the behaviour shown in Fig. 12, with the control system configuration used in the calculation, above



Figure 14: Graph (a) shows the calculated residual motion of the SR2 mirror. The integrated RMS motion is below the requirement of 4×10^{-7} m and the residual motion at 10 Hz is below the requirement of $2.54 \times 10^{-18} \,\mathrm{m}/\sqrt{\mathrm{Hz}}$. Graph (b) shows the calculated residual motion using the ground motion data reported in Fig. 12(a). Again, the apparent increase of the ground motion displacement below 60 mHz is due to noise in the seismometer.

700 mHz the residual motion is below the ground motion. 885

8. Conclusions and Future work

The previous sections describe the mechanical components of the Type-B suspension, its measured behaviour at low frequencies and report a numerical estimate of the residual motion at 10 Hz where the observation band of the main interferometer begins. The higher part of the suspension comprises an IP and three GAS filters with typical 890 resonance frequencies around 65 mHz and a few hundreds of mHz respectively at the time of initial tuning. Displacement control at each of these stages is achieved with coilmagnet actuators and LVDTs with resolutions below 200 nm. The payload comprises the suspended optic, its marionette IM and their respective recoil masses. The damping at the IM is achieved with OSEMs whose displacement sensors have resolutions close to 20 nm.

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Two important features of the suspension were experimentally verified. The first is decay times of resonant motion shorter than a minute. This was achieved using active damping with LVDTs and OSEMs and passive damping with the magnetic damper ring above the Standard Filter F1. One minute at the longest was the requirement set for a quick recovery of the conditions necessary for interferometer alignment. The second feature is low enough amplitudes of the residual motion of the suspended mirror to allow the interferometer to acquire lock. Such a residual motion was measured with the OL at low frequencies with the control on, and its value is below the requirement shown in

Table 1. 905

Another very important requirement set for the residual motion of the mirror is having amplitudes low enough for the interferometer to reach its ultimate sensitivity at 10 Hz and above. Due to time restrictions imposed by the O3GK calendar, it was impossible to experimentally measure the mirror displacement using the interferometer as a displacement sensor. Neither was there time for the fine tuning of the control system 910 for it to deliver low amounts of injected control noise. Therefore, in this paper we present instead a numerical estimation based on the rigid body model of the suspension using a control configuration favorable in terms of control noise. According to this calculation, the Type-B suspension is indeed potentially capable of meeting the requirement shown in Table 1. From the experimental point of view, however, the challenge in creating the 915 conditions to realize such a result remain.

Diagonalization of the IM sensors and actuators is necessary. In the mirror stage only the actuators remain to be diagonalized. Increasing the measuring range of the OL would allow the control system to effectively act upon large amplitude motion. In future upgrades the damping of the IP with inertial sensors is necessary. The 920 noise in the currently installed geophones is such that the blending frequency is too high to effectively damp the microseismic peak. Besides experimentally identifying the dominant noise source and mitigating its effect, another course of action has been the development of a more sensitive seismometer whose prototype is currently under test [31]. Performance can also be improved by the subtraction of ground motion 925 from the IP and F0 LVDTs, as they move together with the ground, horizontally and vertically respectively. This technique is referred to as sensor correction; it has been implemented in Type-A suspensions already [9] and is currently being implemented in Type-B systems. Another outstanding item is the measurement of the transfer function from ground motion to optic displacement using the interferometer as a sensor.

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