Seismic Isolation In Advanced Ligo: Current Trends

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WHAT IS LIGO?

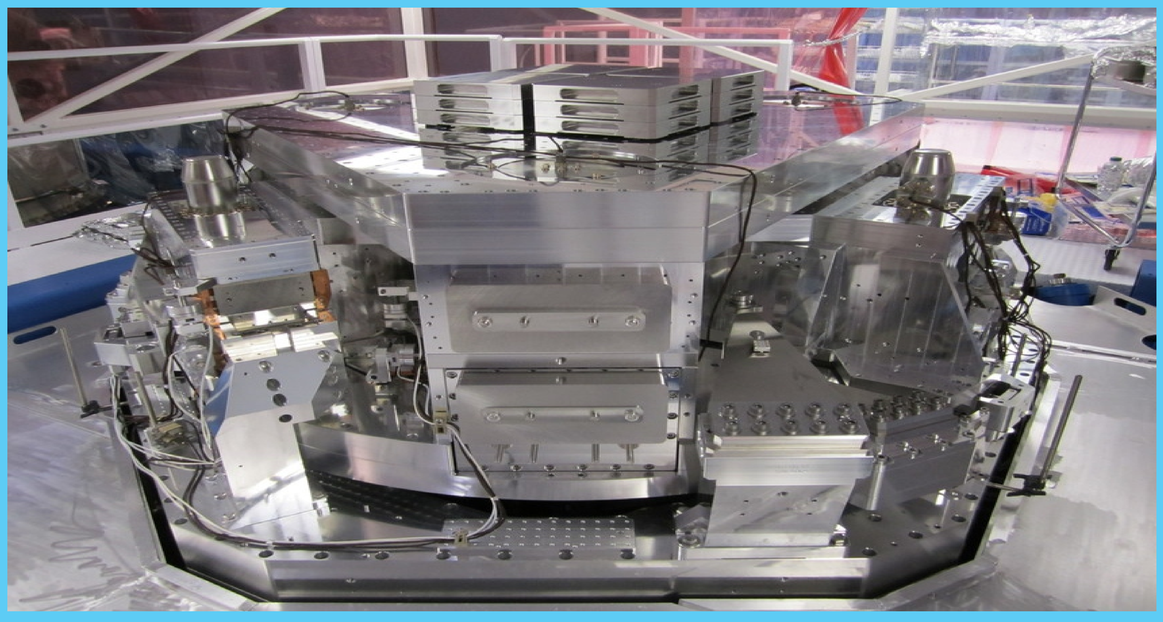
Gravitational Waves represent a new messenger for astronomy, carrying information about compact objects in the local Universe such as neutron stars and black holes. The excitement surrounding gravitational wave astrophysical observation stems from the significant differences between electromagnetic waves and gravitational waves, the need for experimental confirmation of the existence of gravitational waves and the desire to explore gravitational wave sources. The LIGO project is a National Science Foundation(NSF) sponsored project being managed jointly by the California Institute of Technology and the Massachusetts Institute of Technology. The LIGO detector senses the changes in space by comparing the lengths of two perpendicular arms using a Michelson interferometer. In order to detect cataclysmic astrophysical events, the initial LIGO detector was designed to sense a gravitationally induced strain of ~ 10^{-20}rms over a detection band of 40 Hz to 5 kHz and 10^{-21}rms in a few hundred Hz band near 100 Hz. This strain corresponds to a displacement over a 4km baseline, of only 10^{-18}m rms, or 1/1000 th the diameter of the nucleus of an atom. To date, the Laser Interferometer Gravitational-wave Observatory (LIGO) and the VIRGO detector have observed several transient gravitational-wave signals from merging stellar-mass black hole binaries and a binary neutron star system, and have recently finished the second observing run (O2) of the Advanced LIGO era.

WHAT DO YOU MEAN BY SEISMIC ISOLATION ?

Seismic isolation is a technique used to reduce the effects of ground shaking on structure, their components and protect them from damaging.This refers to the removal of unwanted vibrations due to ground activity ranging from traffic on nearby roads, weather patterns on the other side of the continent, ocean waves crashing on shore and of course nearly every significant earthquake on the planet. In general, there are two broad categories of methods or systems which achieve seismic isolation by damping the effect of vibrations. These are "active" and "passive" damping systems. An active damping system senses vibrations and then performs counter-motions to keep the system effectively vibration free. For example, noise cancelling headphones work on this method. A passive damping system uses the inertia of the system to configure a way to reduce the effect of vibrations.

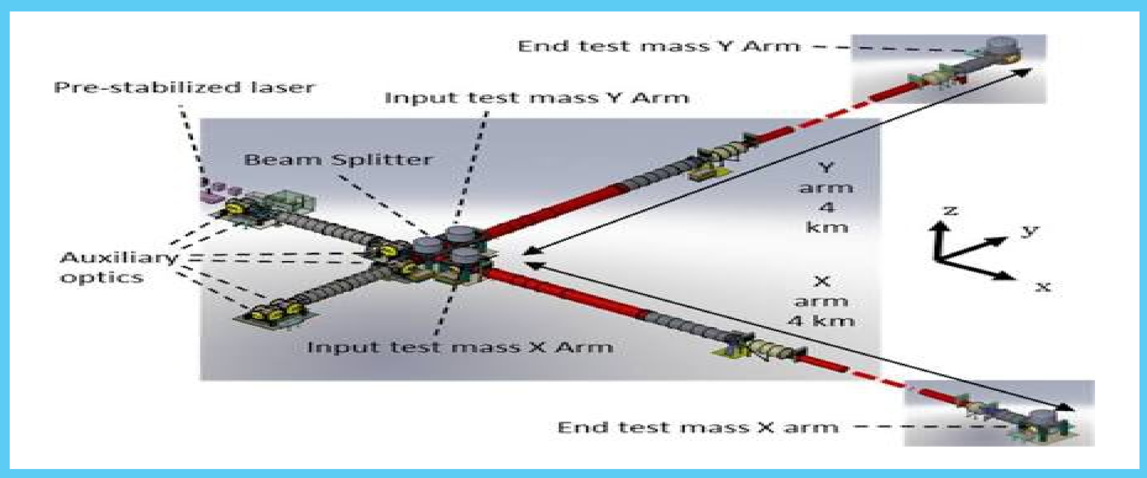
WHY LIGO NEEDS SEISMIC ISOLATION ?

The LIGO detector uses the principle of MICHELSON INTERFEROMETER to sense differential changes in two perpendicular arm lengths to search for strains in space produced by gravitational waves of astrophysical origin. Since gravitational waves will make themselves known through vibrations in LIGO's mirrors, the only way to make detection possible is to isolate LIGO's components from environmental vibrations to an unprecedented degree. The change in distance between LIGO's mirrors (test masses) when a gravitational wave passes will be on the order of 10^{-19}m. Since LIGO is designed to sense the smallest conceivable motion of mirrors, it is also extremely sensitive to all vibrations near(such as trucks driving on nearby roads) and far(earthquakes on the other side of the world). Without taking extraordinary measures, any number of Earthly vibrations could move LIGO's primary mirrors enough to mislead a gravitational wave signal, thus, isolating LIGO from as much environmental vibration as possible. This is the lynchpin in LIGO's quest to detect gravitational waves. A seismic isolation system serves to attenuate ground motion in the observation band(above 10 Hz) and also to reduce the motion in the "control band" (frequencies less than 10 Hz). It also provides the capability to align and position the load. The amplitude of seismic noise at the test mass must be equal to or less than the thermal noise of the system (10^{-19}m/Hz at 10 Hz) for the lowest frequencies where observation is planned.

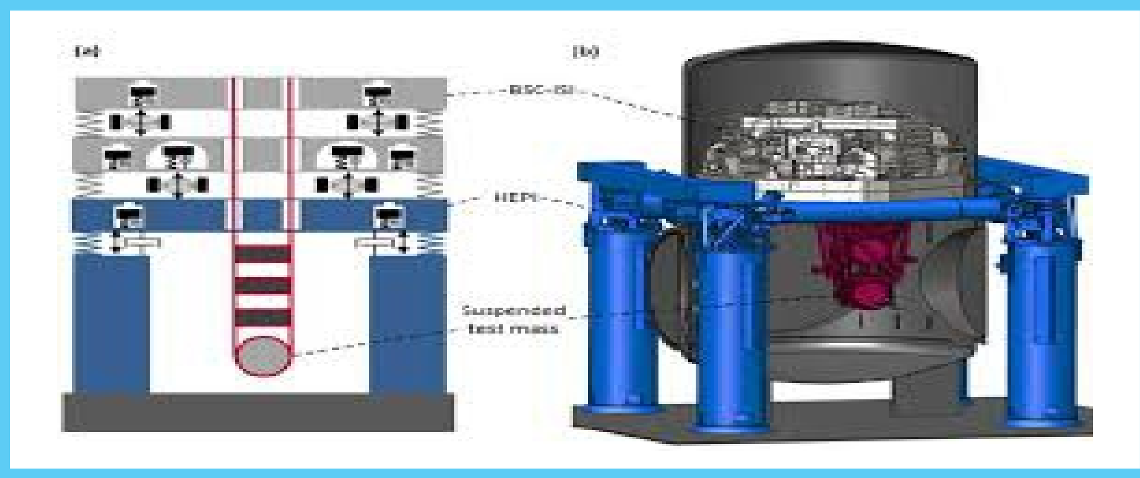


CURRENT TRENDS FOR SEISMIC ISOLATION IN ADVANCED LIGO

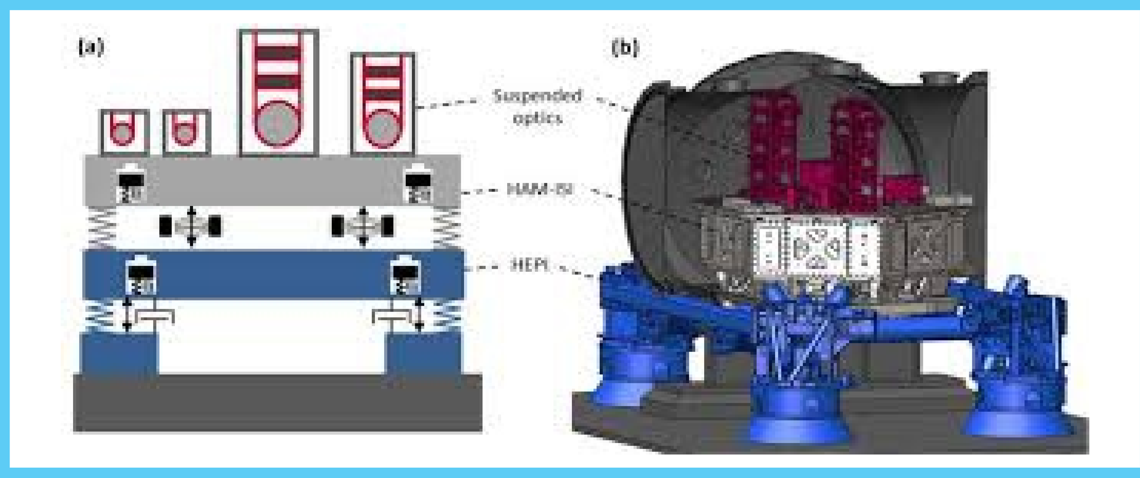
Advanced LIGO(aLIGO) consists of two 4 km interferometric detectors installed at the Hanford (WA) and Livingston (LA) sites in USA. A representation of the vacuum envelope and equipment hosting the instruments at the Livingstion site is shown in Fig. Each detector uses 11 vacuum tanks. Five of them are large BSC (Basic Symmetric Chambers) chambers (approximately 4.5 meters high, and 2.5 meters in diameter) housing the interferometer's core optics. Six of them are the smaller HAM (Horizontal Access Modules) chambers (approximately 2.5 meters high, and 2.5 meters width) housing the interferometer's auxiliary optics.



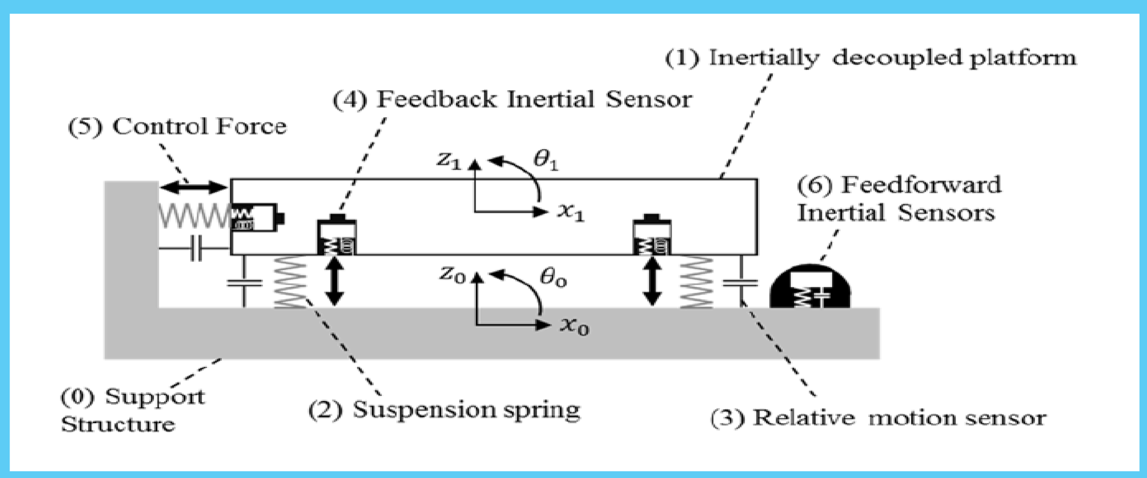
In the BSC chambers, three systems are cascaded to provide up to seven stages of seismic isolation to the core optics. A conceptual and a CAD model are shown in Fig. 3. As previously, the HEPI active platform provides the first stage of isolation. The second system is the Internal Seismic Isolation platform for BSC chambers (BSC-ISI). It provides two stages of isolation, each combining both active and passive isolation.



In the HAM chambers, three systems are cascaded to provide up to five stages of seismic isolation to each auxiliary optic. A conceptual and a Computer Aided Design (CAD) model are shown in Figure below. The first system is the Hydraulic External Pre-Isolator (HEPI). This platform provides one stage of active isolation. The second system is the Internal Seismic Isolation platform for HAM chambers (HAM-ISI). This system provides one stage of isolation combining active and passive isolation.

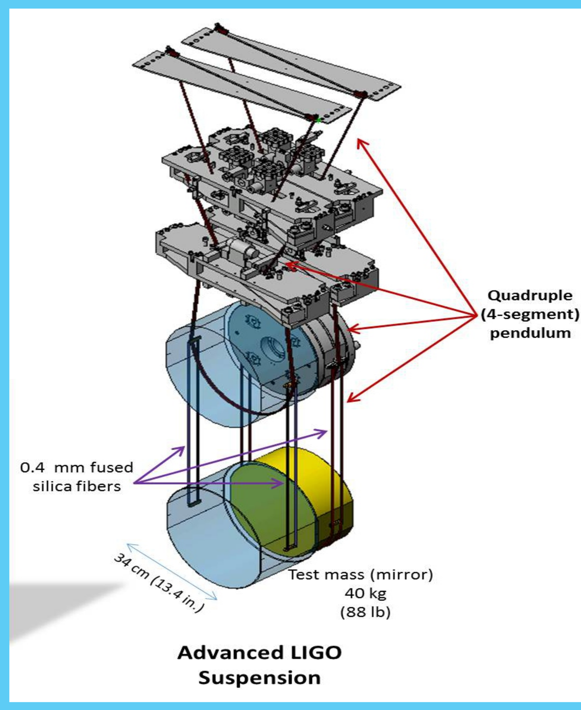


INERTIAL ISOLATION SYSTEM AND CONTROL INFRASTRUCTURE



The passive-active concept used in aLIGO isolation platforms can be summarized by the schematic shown in figure. The motion disturbance transmitted by the support structure is shown in grey (0). The isolation platform (1) is supported by suspension springs (2). Above the resonance frequency, the platform is inertially decoupled from the input stage and provides passive isolation. Relative sensors (3) are used to servo-position the platform with respect to the support structure at very-low frequencies. Inertial sensors (4) are used to provide active inertial isolation through feedback control. The signals from all the sensors are combined in a sensor fusion to drive the control forces (5). Additional performance is obtained using feedforward inertial sensors (6). The platforms are designed to minimize the cross couplings between the degrees of freedom (DOF). Each of the six DOF can be controlled using independent single input single output control loops.

COMPARISON BETWEEN iLIGO AND aLIGO



CHANGED COMPONENT	iLIGO	aLIGO	IMPACT OF CHANGE
Mirrors	25cmX10cm (11 kg)	34cmX20cm (40 kg)	Heavier the mirror difficult to disturb it. Greater area causes less deformation on heating.
Suspension	Single pendulum	Quadruple pendulum	Each additional pendulum reduces the motion transmitted to the mirror/test mass
Suspension	Metal fibres	Glass fibres	Molecules in metal jiggle a lot whereas molecules in silica are much less energetic
Seismic Isolation	Passive only	Passive and Active Isolation	Active isolation leads to multiple devices monitoring movement in hundreds of LIGO components and send signals to counter the motion.

FUTURE PROPOSITIONS

A 6-D INTERFEROMETRIC SYSTEM

During the first detections of gravitational waves from binary black hole and binary neutron star mergers, all significant signal-to-noise ratio got accumulated at frequencies above 20 Hz. The primary limitation of low frequency inertial isolation systems is tilt-to-horizontal coupling. To address this, Mow-Lowry and Martinov (2018) present an optical 6D seismometer. The core of this instrument is a reference mass that is softly suspended in all six degrees of freedom from an isolated platform. Its position relative to the platform is monitored using six interferometers. Figure below shows the design concept. Control forces are applied to the platform to stabilize the relative position effectively transferring the inertial stability of the reference mass to the platform. The advantage of this scheme is that no mechanical degrees of freedom are constrained. The proposed seismometer is capable of substantially reducing the motion of platforms at LIGO which will allow the observations of gravitational waves at 10Hz.

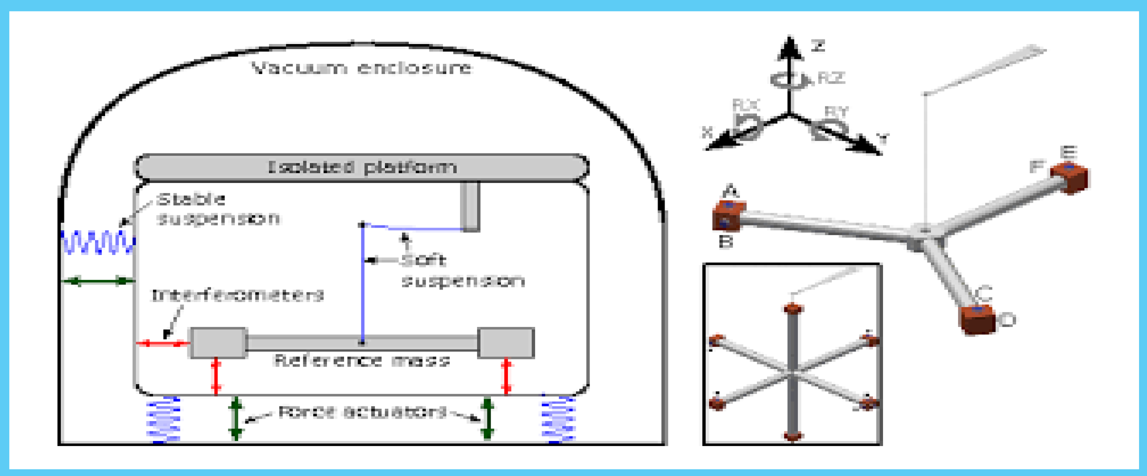


Figure above is a 2D representation of the isolation architecture(left) and a design concept for the reference mass and suspension (right). Letters indicate locations for interferometric sensing.In the inset on right is indicated an alternative configuration with equal moments of inertia in the three principal axes providing a first order reduction in Newtonian noise in tilting degrees of freedom at the expense of additional size and complexity.

LIGO LF : UPGRADE TO ADVANCED LIGO

Despite the sophistication of LIGO's seismic isolation, it does not significantly reduce the microseismic motion at nearly 0.2 Hz. This is due to tilt-to-horizontal coupling which causes the noise of the aLIGO inertial sensors to grow as 1/f^4 at low frequencies as shown in the figure. Above 1Hz, we require an improved sensitivity to reduce the direct coupling of the ground motion.LIGO-LF is an upgrade to Advanced LIGO that focusses on improving the sensitivity in the 5-30 Hz low-frequency band. LIGO-LF can reach fundamental limits set by quantum and thermal noises down to 5Hz. The upgrade's astrophysical implications are that a single LIGO-LF can detect mergers of stellar mass black holes out to a redshift of 6 and would be sensitive to intermediate mass black holes upto 2000 M_{sun}. One of the proposed approaches in LIGO-LF is to actively stabilize tilt motion using custom built tilt meters which can achieve the requirement below 0.5 Hz

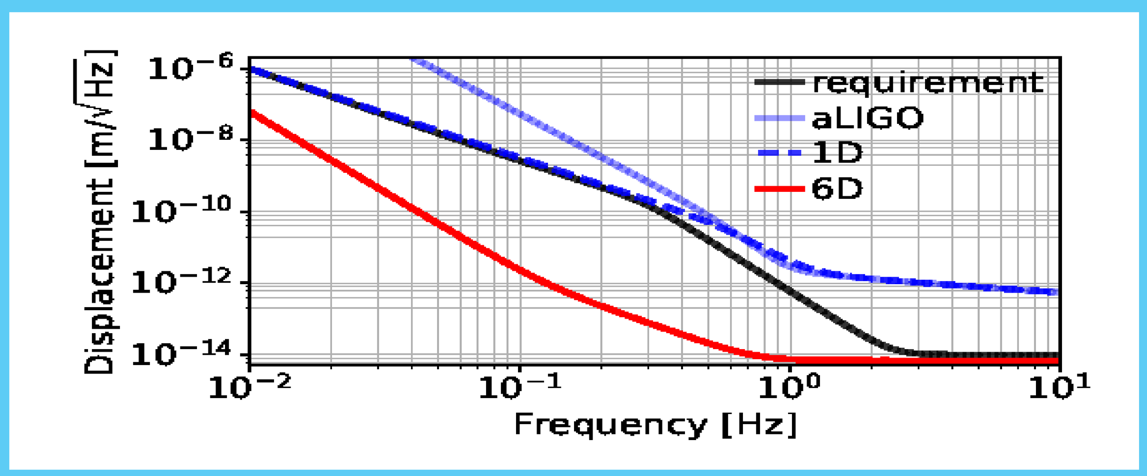


Figure Inertial sensor noise for aLIGO (blue line) and the requirement for Ligo-LF(black line). Custom tiltmeters can be used to improve aLIGO sensor noise