Study report on a reconsideration of the LCGT bandwidth for low-frequency measurements

LCGT-LF Special Working Group

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1 Background

A comparison of the LCGT sensitivity curve at low frequencies with other second-generation detectors shows little advantage of its being located underground or operated in a cryogenic temperature. Regarding suspension thermal noise, the advantage of the low temperature is compensated by a thicker fiber to extract the heat from the mirror. It was thus pointed out at the LCGT External Review in March 2011 that LCGT might put more significance on the global gravitational-wave network if it lowers the target frequencies by decreasing the power and accordingly the fiber thickness.

The purpose of this special working group is to explore a possible low-frequency configuration (LCGT-LF), to investigate its pros and cons, and to make a recommendation on the observational bandwidth. The investigation includes scientific benefits of the gravitational-wave sources at each frequency band and technical feasibility of the new configuration. It is an additional role of the special working group to explain the benefit of the underground location and the cryogenic operation.

2 Overview

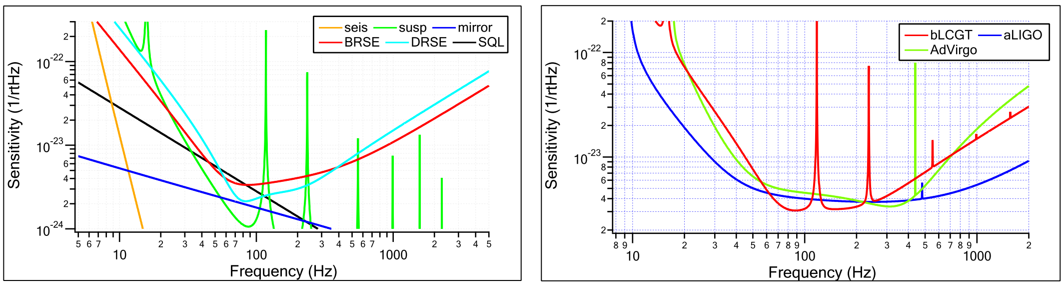

Figure 1: bLCGT noise budget (*left panel*) and comparison of the sensitivity with aLIGO and AdVirgo (*right panel*).

Figure 1 shows the bLCGT noise budget in the left panel and the sensitivity curve compared with Advanced LIGO (aLIGO) and Advanced Virgo (AdVirgo) in the right panel. The cryogenic operation allows LCGT to reach the lowest level in the sensitivity spectrum with a detuned configuration, and the inspiral range for the neutron-star binaries is almost as high as aLIGO in spite of the difference of the baseline length (the inspiral ranges are 309 Mpc for aLIGO, 242 Mpc for AdVirgo, and 273 Mpc for LCGT). On the other hand, the bandwidth of LCGT is narrower than the other two and the sensitivity curve looks ugly for a couple of thick peaks in the middle of the observation band.

The contribution of suspension thermal noise to the LCGT sensitivity is only 10 % or so in the current configuration, but it is apparently the limiting factor that forbids the LCGT to shift the target to lower frequencies. There is a big gap between seismic noise and suspension thermal noise, which would mean that LCGT is not making the most use of its underground location. In LCGT-LF, the suspension fibers should be replaced to make a room to detect gravitational waves at around a few ten Hz. The ugly peaks at 117 Hz and 235 Hz could be moved away from the observation band at the same time.

Let us show an example LCGT-LF sensitivity in the next section and discuss the science we may obtain and we may lose with the new configuration. This LCGT-LF is a narrow-band configuration; the bandwidth is narrow but the sensitivity at around a few ten Hz is remarkably better than bLCGT or other detectors. We will show later an alternative design with the broadband configuration (LCGT-LF(2)).

3 LCGT-LF

3.1 Sensitivity

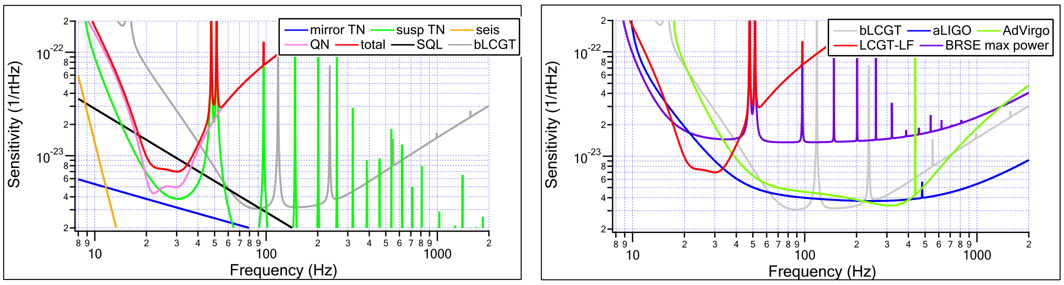

Figure 2: LCGT-LF noise budget (*left panel*) and comparison of the sensitivity with aLIGO and AdVirgo (*right panel*).

Figure 2 shows the sensitivity curve of LCGT-LF. The interferometer parameters are shown in Table 1. It turns out that thin fibers are not useful for the low-frequency measurement since the vertical resonance peak at 117 Hz comes down with the decreasing fiber thickness. Note that the violin modes go away to higher frequencies. We have to use longer fibers. The fiber thickness and length are tuned in such a way that the vertical peak and the first violin mode frequencies almost coincide. There is a room between the peaks and the suspension thermal noise floor, which we can make the most use of by tuning the optical parameters.

The purple curve shows the sensitivity of LCGT-LF in the BRSE operation, aiming at a broad range of observation with low inspiral range to compensate the narrow-band observation.

	bLCGT	LCGT-LF	LCGT-LF(2)
fiber length	0.3 m	1.2 m	0.3 m
fiber thickness	1.6 mm	1.4 mm	0.6 mm
input power	75 W	1.5 W	15 W
finesse	1550	1050	1550
SRM reflectivity	85 %	88 %	85 %
detune phase	3.5 deg	32.4 deg	0 (BRSE)
mirror temperature	20 K	20 K	32 K

Table 1: Changed parameters for LCGT-LF and LCGT-LF(2). The other parameters are unchanged from bLCGT.

One can choose either operation mode. It will take some time to adjust the interferometer to the other mode but it can be done without opening the vacuum or warming up the mirrors. The maximum power to keep the temperature at 20 K can be injected into the interferometer; the incident power levels are 1.5 W for the narrow-band operation and 12 W for the BRSE operation.

Inspiral range for neutron-star binaries is 196 Mpc. The contribution of suspension thermal noise here is about 30 %. The circulating laser power has been reduced but the target frequency band has been lowered so that the contribution of suspension thermal noise has rather increased.

At around 20 Hz, the LCGT-LF sensitivity is better than aLIGO by a factor of 2 and better than AdVirgo by a factor of 8. Let us see if these differences are large enough for LCGT-LF to put something significant to the network.

3.2 High-frequency and low-frequency sources

NS-NS binary inspiral The inspiral range of LCGT-LF is 196 Mpc, which is still high enough to contribute to the observation with other detectors. However, as was discussed in Ref. [1], the accuracy to estimate the arrival time and some other source parameters will decrease.

NS-NS binary merger and ringdown The high end of the inspiral frequency band for the NS-NS binary is 1.57 kHz. The merger of the binary causes gravitational waves that range from a few kHz to the ringdown frequency, $7 \sim 8$ kHz. The sensitivity of LCGT-LF is 60 times worse than that of bLCGT in this frequency band at around a few kHz. Choosing the LCGT-LF, we will have to give up the information of the merger, unless we find a way somehow to switch to the BRSE operation within ~ 30 second when the gravitational-wave frequency shifts from 20 Hz to 1.57 kHz (only ~ 1 second from 40 Hz to 1.57 kHz).

BH-BH binary inspiral The merger frequency of a 50-50 solar-mass black-hole binary is 44 Hz. While the ring-down can be, the inspiral signals of such a heavy system cannot be obtained with bLCGT. Some of the information can be obtained only from the inspiral signals; for example, the mass ratio, which would tell us the accretion mechanism. The inspiral range of LCGT-LF for the 50-50 solar-mass BH binary is better than that of aLIGO but only by 20 %.

Pulsars Vela pulsar generates a gravitational-wave signal at 22 Hz, which is the most sensitive frequency for LCGT-LF. This would be clearly one of the main targets for the low-frequency measurement. However, there are many other pulsars that would be missed by the narrow-band operation.

LMXB Most of the LMXBs are still one order or so below the bLCGT sensitivity, but Sco X-1, which is estimated to produce a continuous gravitational wave around 600 Hz, is one of the probable targets of bLCGT while it is hopeless to see it with LCGT-LF.

Supernovae A supernova may be the most popular candidate for a gravitational wave source according to the history of its observation in our galaxy as a luminous glow in the sky. From the scientific point of view, supernovae are expected for the source candidate since we can count on counterpart observations with high energy phenomena from supernovae and its remnant; neutrino, gamma, charged particles, radio-pulsar, etc. For these reasons, our detector must be capable of measuring gravitational waves from supernovae in the vicinity of our galaxy even if the observation range is shorter than and the event rate is not as certain as the inspirals.

Various scenarios of gravitational-wave emission according to its physical processes of supernovae are predicted. In stellar-core collapse process, a bounce of the rotating core will emit burst gravitational waves for 1-10 msec, which in the power spectrum appears at 100-1 kHz [3]. Proto-neutron star's g-mode instability may emit gravitational waves, the energy of which is larger than the core-bounce in a narrow frequency band around 900-930 Hz [4]. Convection and standing accretion shock instability[5] will generate gravitational waves, which widely spread over several ten Hz to a kilo Hz. A neutrino emission will cause gravitational waves at lower frequencies ($\lesssim$ 50 Hz). Detection of these gravitational waves will provide the information of the inside of supernovae.

Cosmic gravitational-wave background The target source of stochastic background of gravitational waves in the advanced detector era is cosmic strings and inflation, of which strength $h_0^2\Omega_{gw}$ are 10^{-8} and 10^{-14} over their observation bands, respectively. Since the sensitivity of bLCGT or aLIGO can reach 10^{-9}, we may detect the cosmic strings. Search for Stochastic background of gravitational waves is performed by cross-correlation analysis of a pair of detectors. Considering the overlap reduction functions, the optimal configuration of the pair is with a same sensitivity and a same orientation. So the advantage of LCGT-LF in low frequency band becomes disadvantage in turn.

3.3 Technical feasibility

3.3.1 Absorption of Sapphire

The required levels of the substrate and coating absorptions for bLCGT are 20 ppm/cm and 0.5 ppm, respectively, with a safety factor of 2. These are very challenging; no one has achieved the substrate absorption level ever, and no one has achieved the coating absorption level in the cryogenic temperature. This has been one of the largest risks for the success of LCGT.

Changing the configuration to LCGT-LF is one way to ease the requirement. The required levels for the narrow-band operation are 160 ppm/cm and 4.0 ppm, respectively.

3.3.2 Seismic-motion-related noise

The seismic-noise level in the bLCGT noise budget is a few orders magnitude lower than the sensitivity above 20 Hz. In the case of TAMA, however, seismic motion induced alignment noise that couples to the longitudinal degrees of freedom to limit the sensitivity at low frequencies. It should be noted that seismic-motion-related noise can easily surpass the requirement by small imperfections.

On the other hand, the seismic motion at Kamioka is 2×10^{-9} m/$\sqrt{\mathrm{Hz}}$ at 1 Hz, which is about 100 times lower than that at the TAMA site. The rms motion of the ground is accordingly much smaller than TAMA. The low rms motion in the underground helps reducing most of the seismic-motion-related noise, such as alignment noise, control loop noise, up-conversion noise, etc.

3.3.3 Other noise

There could be technical noise sources at low frequencies other than seismic-motion-related noise. Electric noise or laser noise is an example. The requirements to these kinds of technical noise are set not to deteriorate the bLCGT sensitivity. If we shift the target to the low frequency, most of the requirements will be changed for the more challenging.

3.3.4 Schedule

Tightness of the schedule is one of the biggest concerns of LCGT. It would be attractive if LCGT-LF could be complete faster than bLCGT, but it will not be the case. Its cryogenic operation, with less risk for the heat absorption, makes the schedule tight anyhow.

4 LCGT-LF(2)

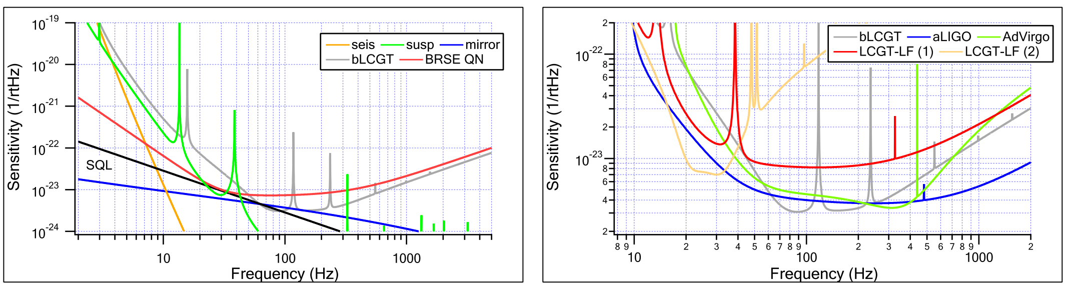

Figure 3: LCGT-LF(2) noise budget (*left panel*) and comparison of the sensitivity with aLIGO and AdVirgo (*right panel*).

An alternative way to go low frequencies is simply to decrease the power with the broadband configuration. Figure 3 shows the spectrum of this LCGT-LF(2). The suspension fiber thickness is 0.6 mm and the mirror temperature has to be as high as 32 K. Substrate thermoelastic noise has increased so that there is almost no room to improve the inspiral range by detuning. The inspiral range for NS-NS binaries is 159 Mpc.

The laser power is set 1/5 of bLCGT. The safety factor for the cooling capability of bLCGT is about 2, so that if we could somehow keep the factor and put another factor of 2.5 on top of it, the sensitivity curve of bLCGT without the peaks around 100 Hz would be realized. If not, we will replace the suspension fibers to the 1.6 mm ones so that the bLCGT configuration can be recovered.

In fact, this shall be regarded as an optional choice of the roadmap; both the heat absorption and the suspension peaks are one of the biggest issues so that we could choose to avoid one of them and to cope with the other.

5 Summary

LCGT-LF would be no better than bLCGT for the following reasons:

- There are some attractive gravitational-wave sources at low frequencies but we will lose too many at high frequencies and also lose some important information by the narrow-band operation.
- Xylophone concept (see Ref. [2]) does not perfectly work with LCGT and other second generation detectors for the different locations.
- LCGT-LF can be technically more reasonable than bLCGT for its low seismic motion and the risk of cooling Sapphire, but the roadmap will not be shortened anyhow as far as we are to cool the mirrors.

It should be also noted that the benefit of the cryogenic operation is not only to reduce thermal noise but also to avoid such a heat problem as thermal lensing. Even if our target frequency band is around 100 Hz, the low seismic motion in the underground will help us realizing the high-sensitivity detector. We have no doubt in our strategy to operate our cryogenic detector in the semi-broadband configuration with slightly deep spectrum for the optimal sensitivity.

References

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