Sensor noise of L-22D and L-4C Geophones

Technical Note

For the Albert Einstein Institute / Max Planck Institute Hannover

Authors: Robin Kirchhoff (AEI/MPG Hannover), Sam Cooper (University of Birmingham), Conor Mow-Lowry (University of Birmingham)

1 Abstract

At the AEI-10 m-Prototype in Hannover, Germany the sensor noise of several L-22D and L-4C geophones (from Sercel) was measured in a huddle test. New amplifier electronics were employed in order to drastically reduce electronic noise below 1 Hz. With some minor modifications to our new front-end electronics, we were able to achieve sensor noise limited only by Johnson-noise of the sensing coil and the (white) input voltage noise of the first-stage amplifier, an OPA188. Each of these noise sources contributes approximately equally. The sensitivity improvement from L-22Ds with our initial electronics to L-4Cs with new and refined electronics was more than a factor of 10 at 1 Hz and more than a factor of 100 at 0.1 Hz and below.

2 Theory

The first step was to calculate the theoretical noise performance of the L-22D geophones that are currently installed in the prototype. The calculation is based on [AB98]. The noise is calculated as a "displacement equivalent noise" (DEN) which is defined as a fictional displacement of the ground that would cause a signal equal to the sensor noise. This way the sensor noise can be compared to the amplitude spectral density of seismic motion.
The calculated total sensor noise consists of 4 components: the suspension thermal noise of the geophone oscillator; the Johnson noise of the geophone coil; the voltage noise of the operational amplifier being used in the first gain stage of the amplifier electronics; and the current noise of this amplifier. The total noise is calculated as:

$$DEN_{total}(\omega)^2 = DEN_{susp}(\omega)^2 + DEN_{Johnson}(\omega)^2 + DEN_{volt}(\omega)^2 + DEN_{curr}(\omega)^2 \tag{1}$$

Where the components are calculated (in $m/\sqrt{Hz}$) by the following equations:

$$\begin{aligned} DEN_{pend}(\omega) &= \sqrt{\frac{4k_bT\omega_0}{mQ}} \cdot \frac{1}{f^2} \\ DEN_{Johnson}(\omega) &= \sqrt{4k_bTR} \cdot Resp \\ DEN_{volt}(\omega) &= \frac{N_V \cdot Resp}{S} \\ DEN_{curr}(\omega) &= \frac{N_A R \cdot Resp}{S} \end{aligned} \tag{2}$$

- k_b: Boltzmann-constant
- T: temperature
- ω_0: resonant frequency of the geophone
- m: suspended mass of the geophone
- Q: quality factor of the geophone oscillator
- R: resistance of the geophone coil
- $Resp$: inverse response of the geophone and the amplifier electronics
- N_V: input-referred voltage noise of the operational amplifier
- S: sensitivity of the geophone
- N_A: input-referred current noise of the operational amplifier

The characteristics of the L-22D geophone and their amplifier electronics are listed in table 1. The resulting sensor noise is shown in figure 1. By exchanging the L-22Ds by L-4Cs, we expect improved broadband noise performance, as the L-4C is inherently more sensitive. The characteristics of the L-4C geophones are also listed in table 1. Additional improvement below approximately 1 Hz can be achieved by the implementation of new amplifier electronics. The dominating factors in this frequency range are the voltage and current noise of the operational amplifier, INA128. Improving the low frequency sensitivity is the main aim of this work, and designing new amplifier electronics is a crucial part of that.

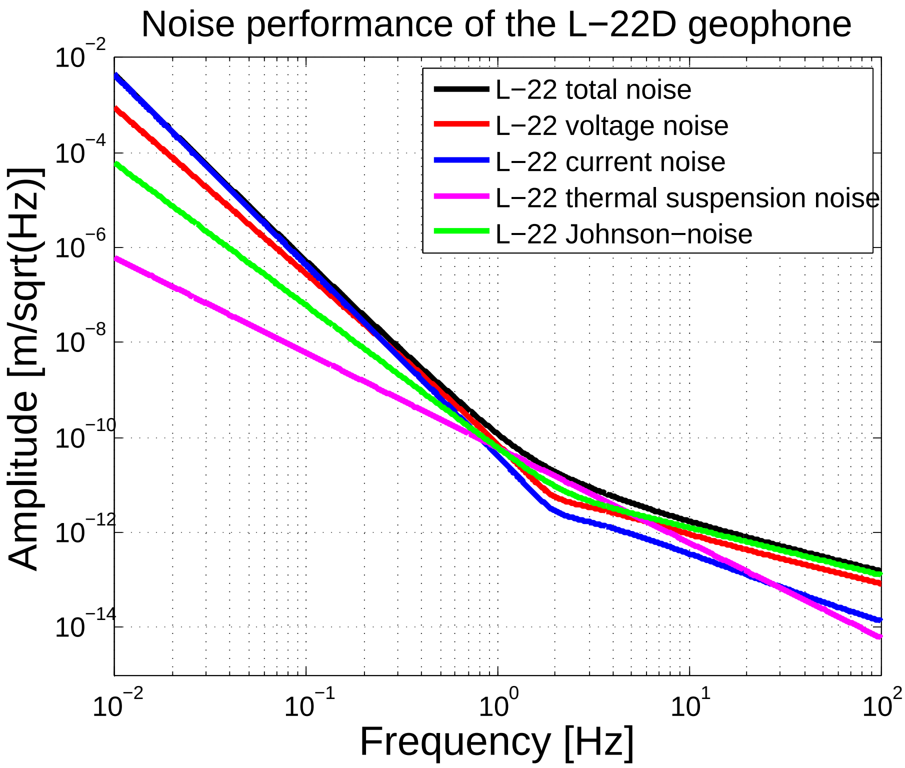

Figure 1: The "DEN" of the L-22D geophone with an INA128 first-stage amplifier.

New amplifier electronics were designed based on low-frequency noise tests of several op-amps LIGO-T1600206. The operational amplifier OPA188 was chosen, and is used in every stage, as this amplifier has low noise at low frequencies. There are three stages in total, a differential input stage for common-mode rejection and with a gain of 101, an additional gain stage with a gain of 52, and a differential output stage with a gain of 2. Due to problems with damage to this amplifier when connecting geophones, the input stage has safety diodes. Low-pass filters to ground with a corner frequency of 615.7 Hz are installed to reduce high-frequency pick-up. The signal-chain schematic is shown in figure 5.

The noise calculation of the L-4C with OPA188 amplifiers is shown in diagram 2. The voltage noise and Johnson noise are nearly equal, and dominate the total noise over the whole frequency range. The current noise is assumed to be small enough to be negligible, despite difficulties measuring the actual current noise during op-amp testing. As the Johnson-noise is a characteristic of the L-4C geophone, further significant improvements in the total noise of a L-4C are not possible. The improvement of the noise at high frequencies is about a factor of 2.5. At low frequencies the improvement is significantly higher. At 0.1 Hz for example, we expect the L-4C with OPA188 to be more than a factor 60 quieter than the old L-22Ds.

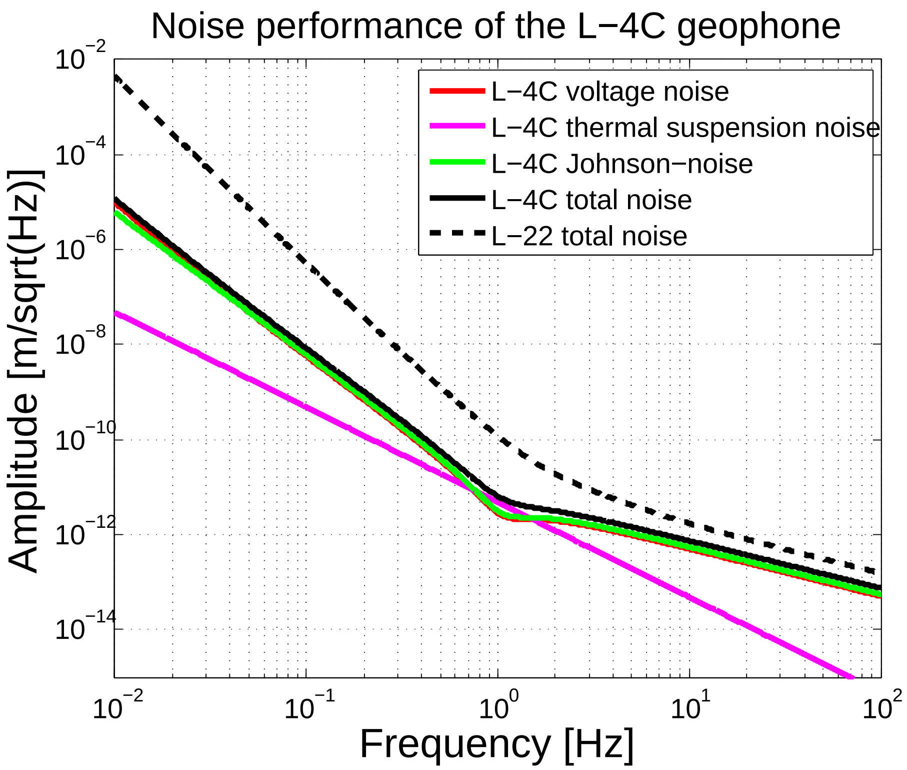

Figure 2: The "DEN" of the L-4C geophone with an OPA188 first-stage amplifier. The "DEN" of the L-22D with INA128 is shown for comparison.

Parameter	**L-22D**	**L-4C**
T	300 K	
ω_0	2 Hz	1 Hz
m	0,0728 Kg	0,96 Kg
Q	0,5	3
R	2200 Ω	5500 Ω
$Resp$	figure 3	
N_V	figure 4	
S	75,7 Vs/m	277 Vs/m
N_A	figure 4	negligible

Table 1: The characteristics of the L-22D geophones with the old electronics and the L-4C geophones with the new electronics. The values were either measured or taken from the data sheets.

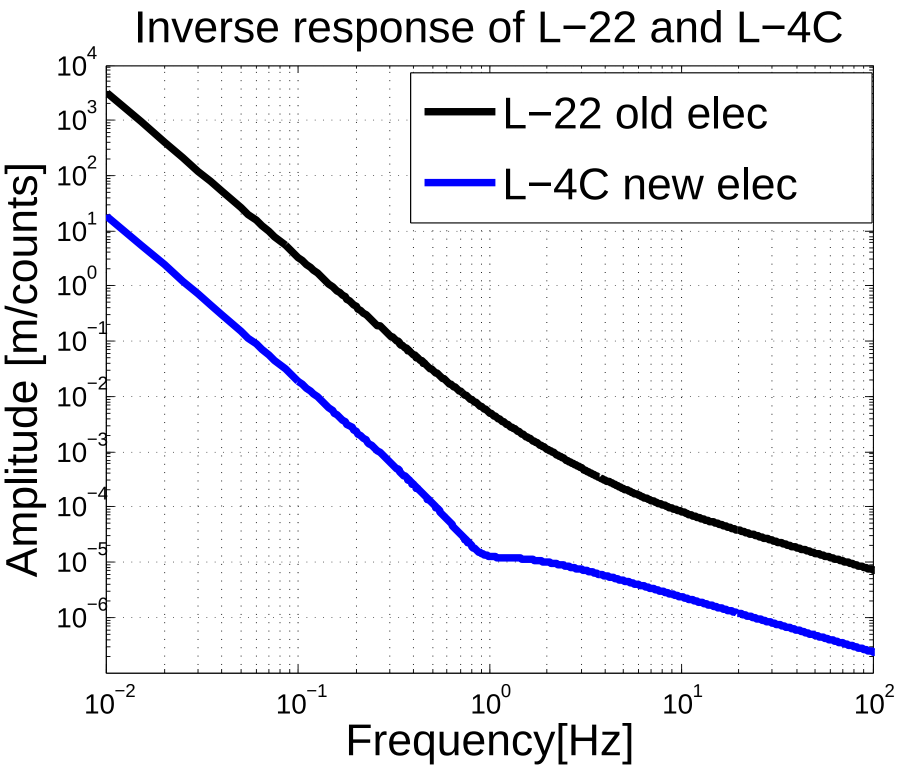

Figure 3: The inverse response, *Resp*, of the L-22D and L-4C geophones with the old and new amplifier electronics respectively.

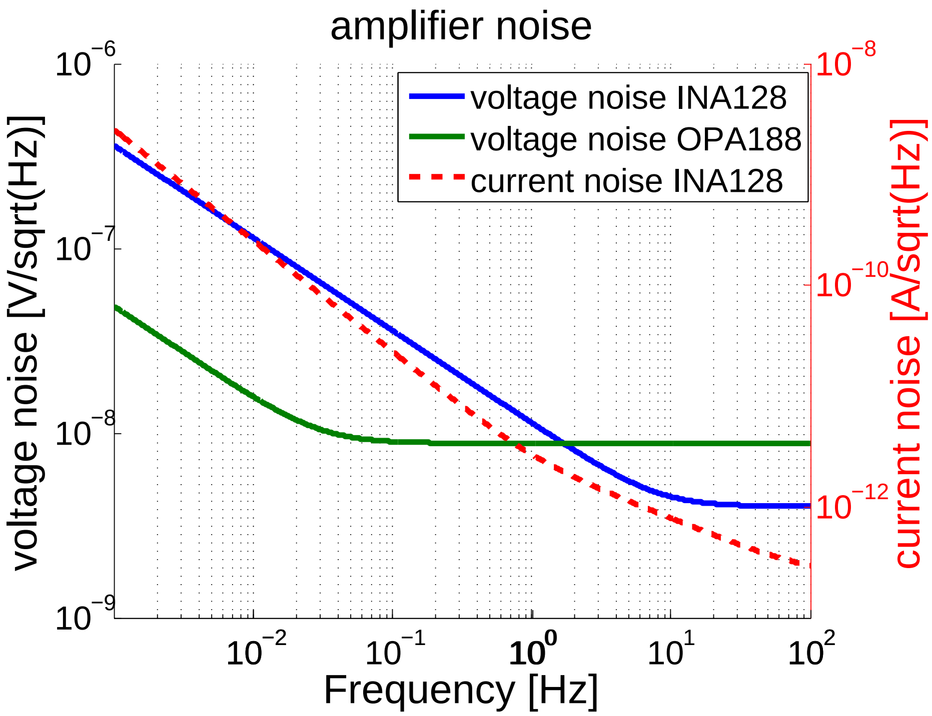

Figure 4: The input-referred noise of the INA128 and OPA188 operational amplifiers. The current noise of the OPA188, while unmeasured, is low enough to be negligible at all frequencies.

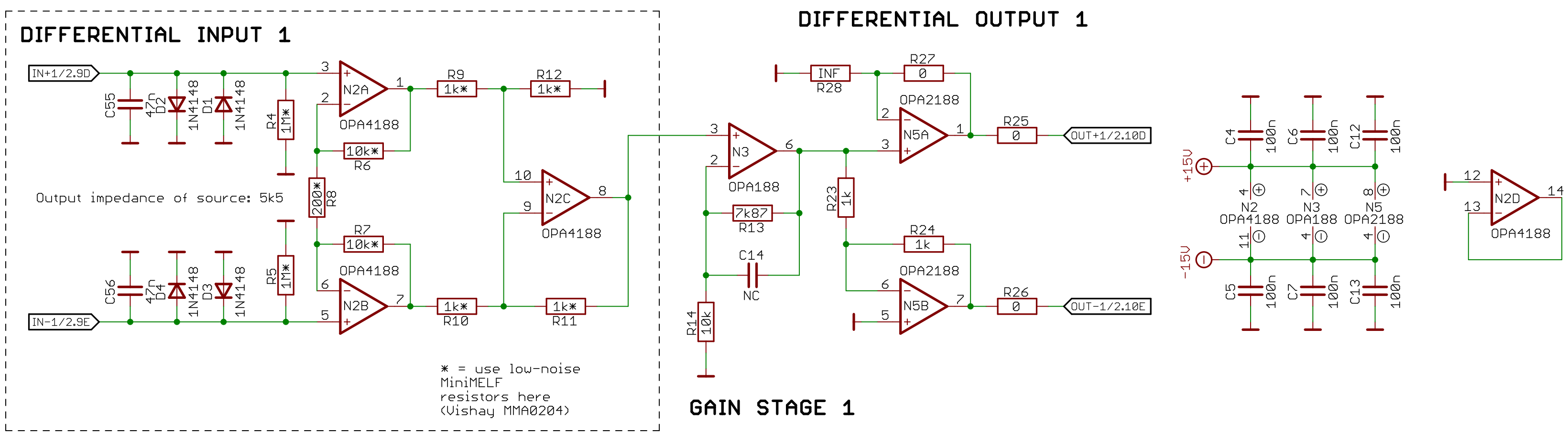

Figure 5: The schematics of the new amplifier electronics used for the L-4C geophones.

3 Testing Procedure

To verify that the sensitivity of these geophones matches our predictions a 'huddle test' was performed. Ground motion is far larger than the sensor noise of these geophones across a range of frequencies. To remove ground noise and expose the sensor noise, multiple devices are placed close together such that they measure the same input motion. The highly-correlated input motion can be subtracted leaving just the uncorrelated individual noise of the geophone. This should be performed with at least three devices in a line to subtract the effect of tilt.

At the AEI there are six previously installed L-22D geophones that measure the motion of two suspended platforms ('Central' and 'South'). Data from these geophones is recorded (and stored) continuously via an Advanced-LIGO CDS (control and data system). An STS2 force-feedback seismometer, with superior low-frequency performance, continuously records the floor motion.

Three separate huddle-test results are reported here: L-22Ds with old electronics, L-4Cs with new electronics, and L-4Cs with increased gain to overcome CDS input noise. For each test approximately 3000 seconds of data was used to measure sensor noise. Prior to each test a few hundred seconds of data were examined to ensure the devices were operating correctly. For all tests the table was unclamped such that its resonant frequency of approximately 0.2 Hz provided passive isolation against higher frequency motion. For the final tests, damping was engaged using displacement sensors to reduce input motion near resonance.

For the first test an additional pair of L-22Ds were clamped side-by-side on the South table. They were placed directly over the top of one of the existing L-22D geophones, such that the three were approximately in-line. Next, three L-4C geophones mounted in-line were fastened to the table, and the table was rebalanced. The result of this test showed that the L-4Cs were limited by CDS input noise, and as such the amplifier gain was increased for the third test.

The results of the huddle-test get closer to sensor noise when more coherent input motion is subtracted, and our best results were achieved using all relevant sensors: the 3 installed L-22Ds, all the additional geophones (L-4Cs or L-22Ds), and the STS2.

To produce the sensor noise measurements, time-series data from all available sensors was passed to a multi-channel coherent-subtraction script, `mccs2.m`. This script was developed by Brian Lantz and Wensheng Hua[1]. It takes a single time series channel as a 'target' and subtracts all coherent information found in a number of 'reference' channels. It outputs the ASD of the target with its corresponding frequency vector, and the residual ASD of the target once all the coherent information from each reference time series has been subtracted.

If there are sufficient reference channels with sensitivity comparable to the target, the residual should only contain uncorrelated sensor noise.

4 Results

The following graphs all show displacement equivalent noise, and as such the plotted curves are directly comparable to a real seismic signal affecting the geophone.

[1] This script and many other useful tools can be found at:
https://svn.ligo.caltech.edu/svn/seismic/Common/MatlabTools.

The plots in figure 6 show the results of the L-22D huddle test. The upper plot shows the amplitude spectral density, the residual output from `mccs2.m`, and the theoretical noise. The lower plot shows the corresponding coherence between two geophones installed on the table. It is clear that the noise of the geophones becomes dominant below 0.15 Hz as this is the region where the signals become incoherent. The theoretically calculated noise is lower than the measured noise, presumably due to differences between the noise performance of the INA128 and the noise quoted in its datasheet. Significant differences between channels using INA128s from different batches had already been observed.

In this measurement a slightly higher noise floor at low frequencies dominated the ASD of the two additional L-22D geophones that were installed on the optical table. This noise was only observed in these two geophones and they had a coherence of ≈ 1 down to at least 0.01 Hz. No coherence was observed between these two geophones and any other sensor, and thus seismic motion, or electrical/magnetic couplings to the surroundings, was discounted. Since this feature was not seen in any other devices (and was not reproducible), one of the previously installed L-22D geophones was used as the target signal.

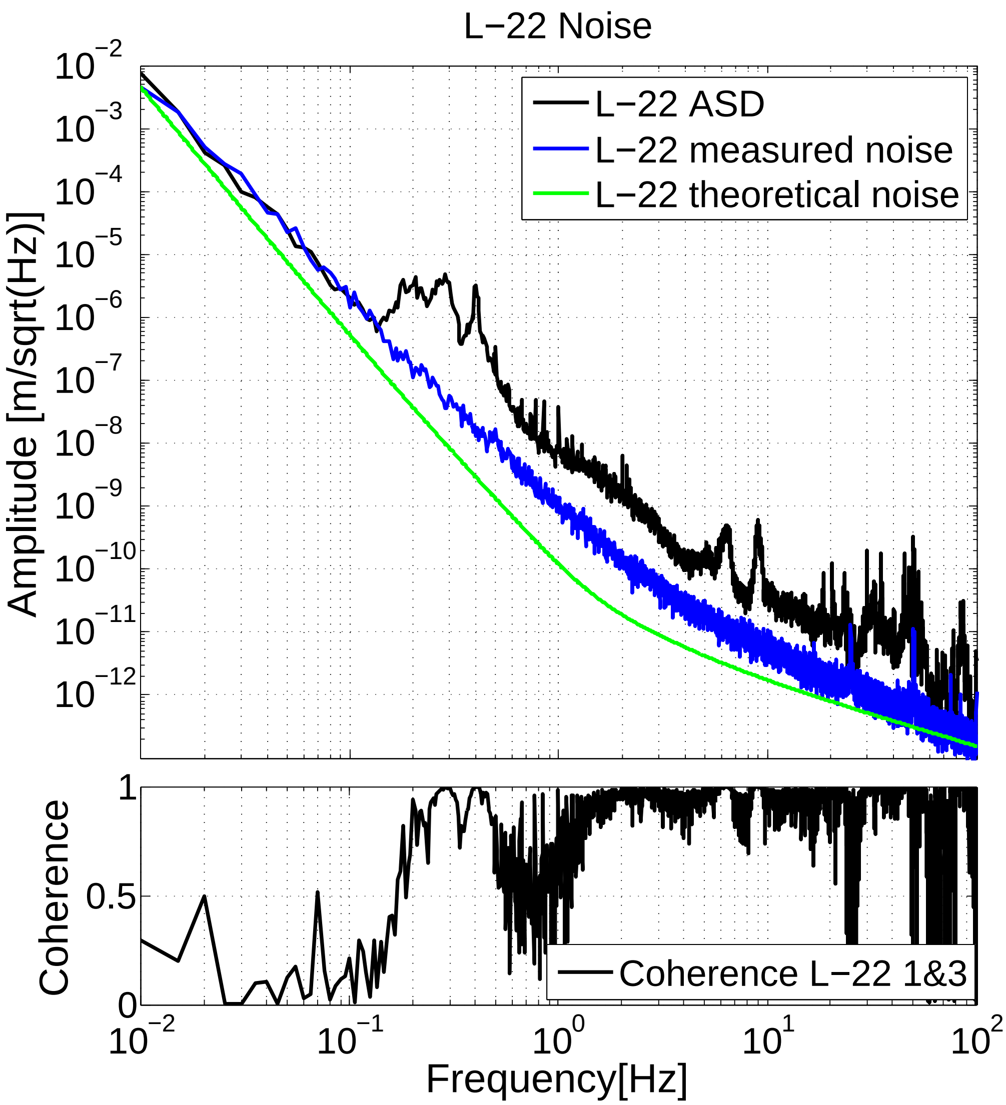

Figure 6: The results of the huddle test for L-22D geophones. The ASD is dominated by sensor noise at low frequencies which causes a loss of coherence. The measured noise is higher than predicted, possibly due to incorrect assumptions about the first-stage amplifier.

Figure 7 shows the first results for the L-4C geophones. The upper plot contains the input ASD, the incoherent residual, and the theoretical noise. Additionally, CDS input noise was plotted. The lower plot shows the coherences between the target L-4C and the reference L-4Cs installed next to it. The input spectrum is dominated by noise below 0.1 Hz, confirmed by the loss of coherence. The measured noise fits the theory down to about 0.7 Hz. Below this frequency the measured noise is higher than expected. A measurement of CDS input noise confirmed that this is the cause of the low frequency noise. By raising the gain of the amplifier electronics the signal of the geophone is amplified whereas the CDS noise stays the same, and we should be able to find the true noise floor of the L-4C.

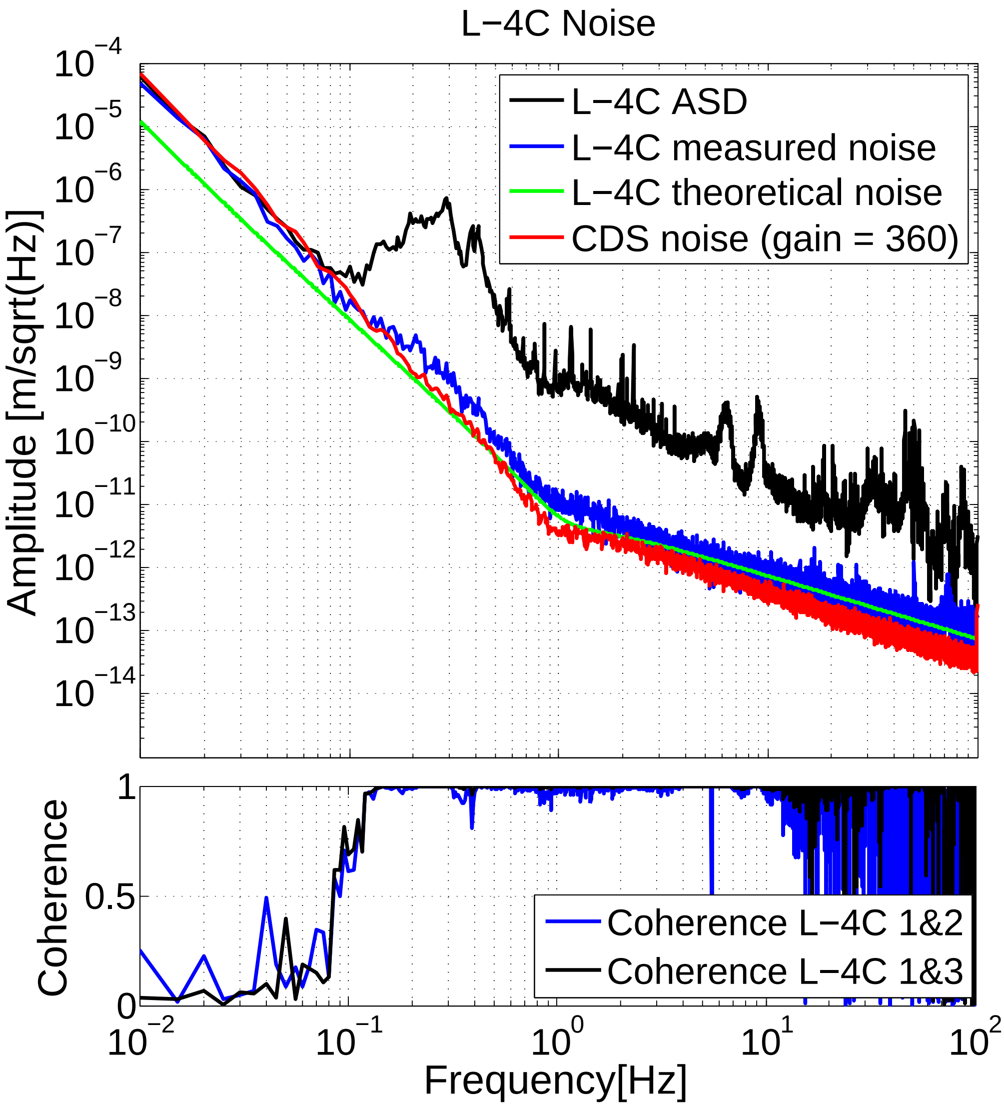

Figure 7: The results of the first L-4C huddle test. Noise dominates the ASD below 0.1 Hz and the coherence drops at the same frequency. The measured noise is dominated by the CDS noise below 0.7 Hz which can be avoided by increasing the gain of the electronics.

The measurements with the L-4Cs were repeated with a increased gain, from 364 to 10420, in the amplifier electronics. Figure 8 shows the results. The DEN of the CDS noise has been reduced substantially and is no longer the limiting factor in the residual. The resulting agreement between theory and measurement is very good, in contrast to the L-22D test.

The discrepancy around 0.3 Hz is attributed to residual differential motion between the three L-4Cs. At these frequencies the L-22Ds are completely incoherent (due to their higher noise). Additionally there is strong cross-coupling from ground horizontal-motion to table tilt-motion at these frequencies, making the STS2 also incoherent.

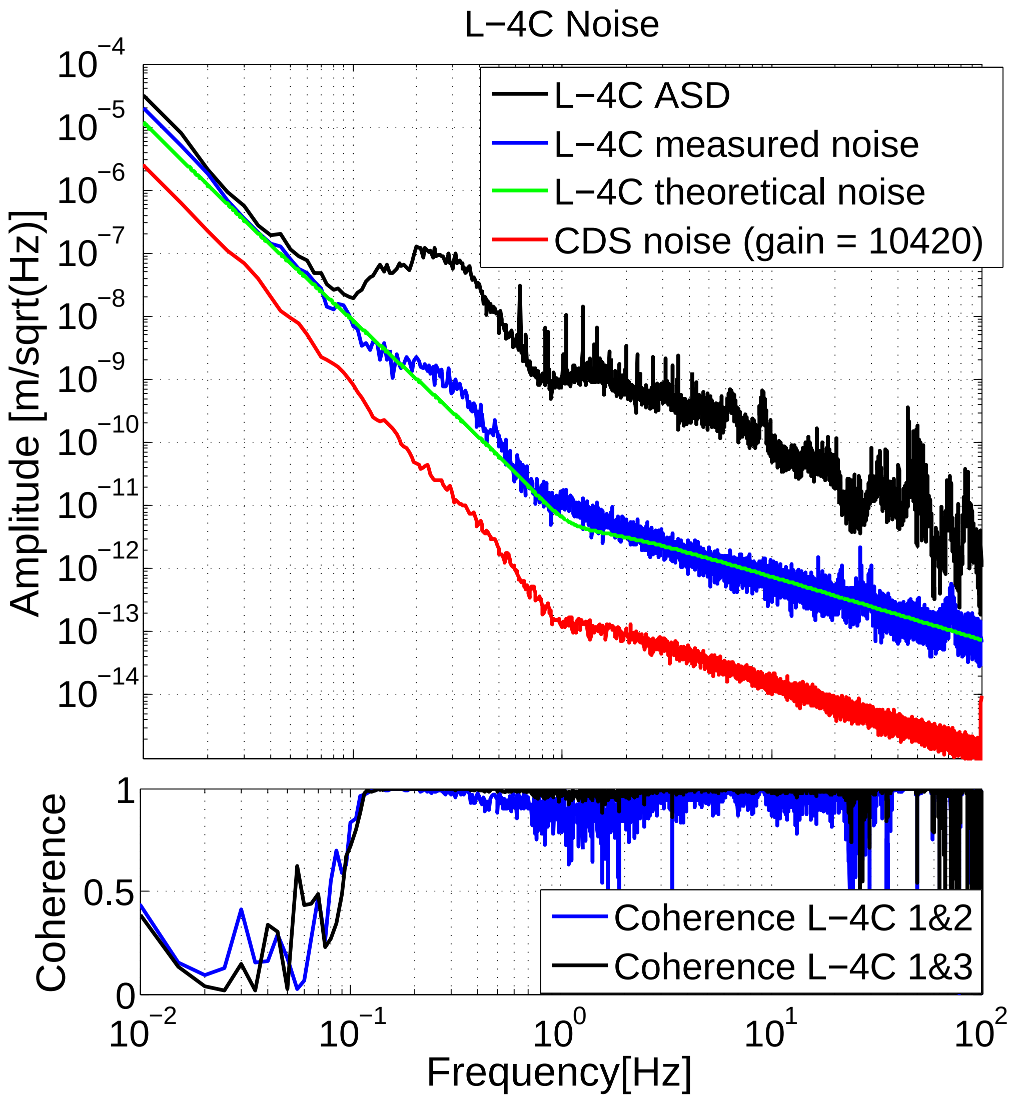

Figure 8: This plot shows the results of the second huddle test for the L-4Cs. The CDS noise is now negligible. Ignoring the discrepancy at ≈ 0.3 Hz, there is now excellent agreement between measurement and prediction from 100 Hz to 10 mHz.

Figure 9 shows a comparison between the sensor noise of the L-22Ds with old electronics and the L-4Cs with the new electronics. The L-4Cs with OPA188 amplifiers have a factor of 100 lower noise at 0.1 Hz than the L-22Ds with INA128s. A simple model has been fitted by-eye to the L-4C measurement with three poles at DC, two real zeroes at 1Hz, and a level of 10^{-11} m/$\sqrt{\text{Hz}}$ at 1 Hz. The noise model for LIGO's L-4Cs, taken from `SEI_sensor_noise.m`, is plotted for comparison.

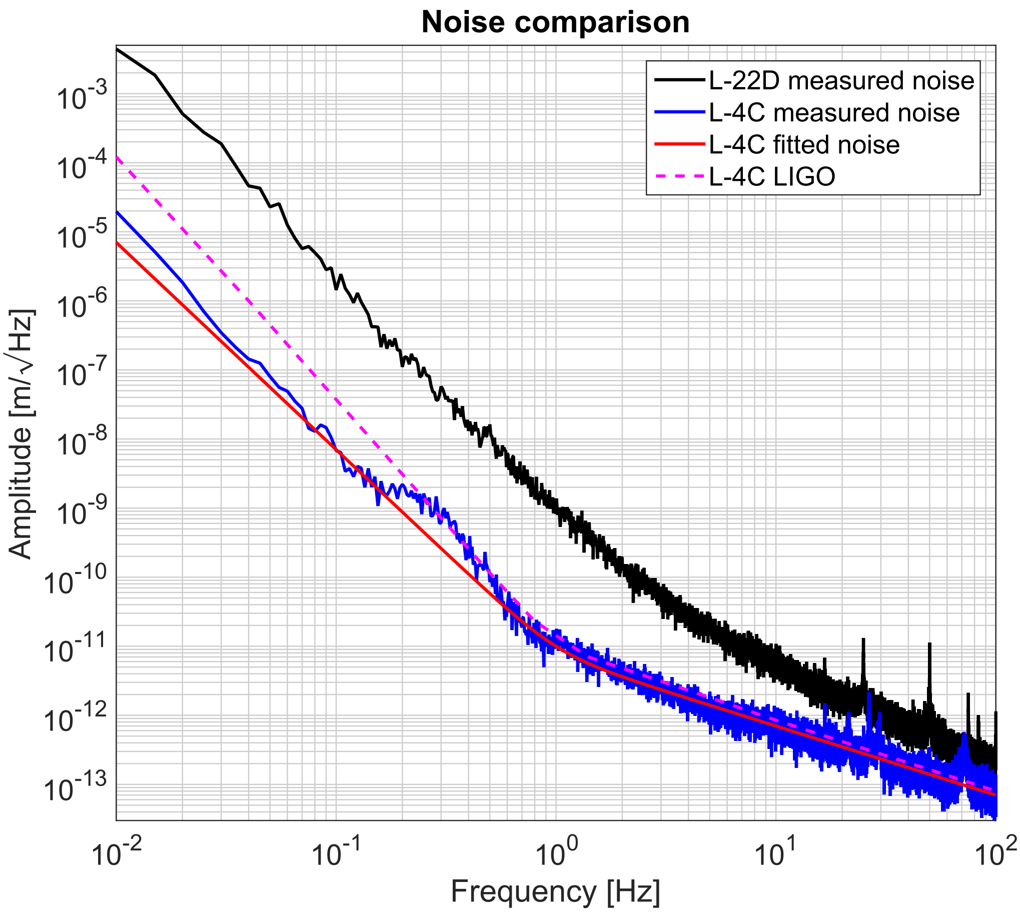

Figure 9: A noise comparison between an L-22D with an INA128 amplifier and an L-4C with an OPA188.

The noise components resulting in the total noise of the L-4Cs are shown in figure 10. The voltage noise of the OPA188 amplifier and the Johnson noise of the geophone coil are approximately equal, and they limit the total noise over nearly the whole frequency range. The suspension thermal noise effects the total noise only in a small area around 1 Hz and CDS input noise is negligible. As the Johnson noise is a characteristic of the geophone itself, a significantly better noise performance with an L-4C cannot be achieved.

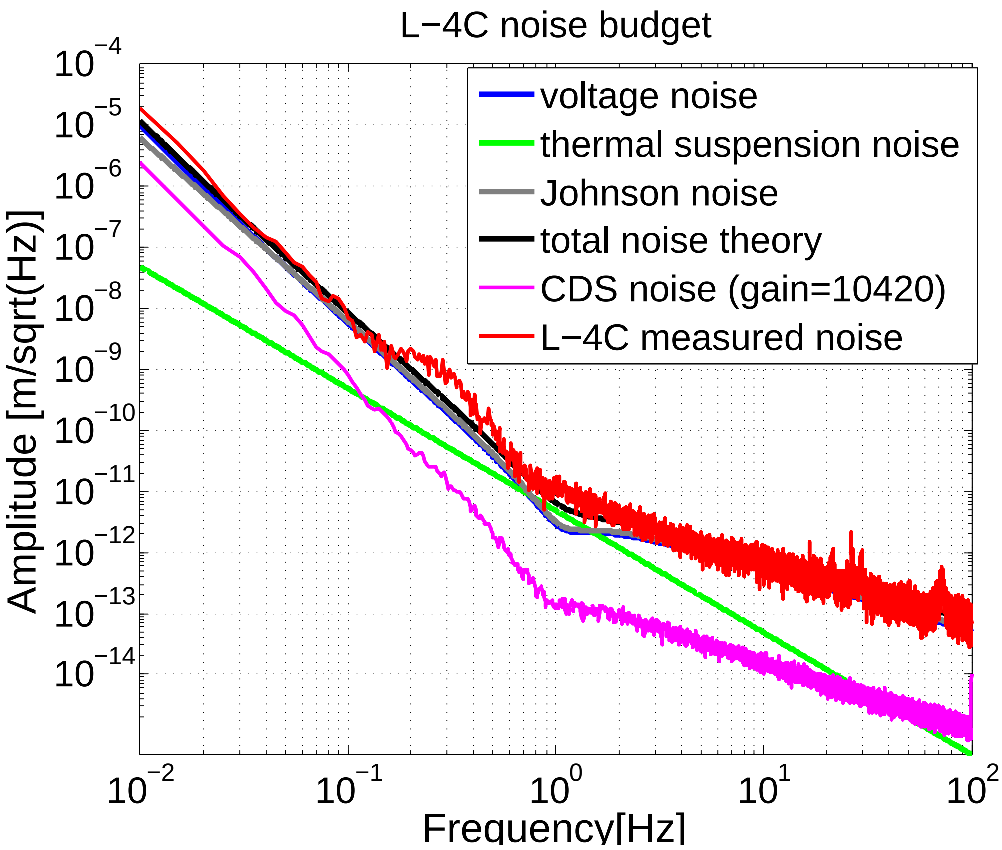

Figure 10: A noise budget for the L-4Cs. The Johnson noise and the voltage noise dominate the total noise over the whole frequency range.

References

[AB98]A. Barzilai et al., *Technique for measurement of the noise of a sensor in the presence of large background signals*, Rev. Sci. Instrum **69**, 2767 (1998).