# Developing a Low Noise Seismometer in the Frequency Range of 0.3-20Hz

**Gregory E. Vansuch, University of Colorado at Boulder**
**Jan Harms, Ph.D., California Institute of Technology**
**Riccardo DeSalvo, Ph.D., California Institute of Technology**
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*Abstract*

*When measuring for gravitational waves, detectors pick up gravitational disturbances from local sources (Newtonian noise). This causes a problem. Measurements are polluted with this Newtonian noise, making it necessary to subtract it in order to view data accurately. To study this noise for formulating methods of its subtraction, seismic stations have been set up at the former Homestake mine in Lead, South Dakota. While there are currently no problems with the seismometers set up at these stations, it has been predicted that in the future seismometers with higher sensitivity in the Range of 10-30Hz will be required. In order to obtain a seismometer with this sensitivity, the SS-1 Ranger has been reverse engineered. Looking at its parts and modeling the seismometer on AutoCAD, it is being determined what parts of seismometers that are of similar design to the Ranger may be modified to obtain less mechanical and electronic noise, which will lead to higher sensitivity.*

## I. Introduction

Current generations of gravitational wave detectors are not limited by gravity gradient noise (Newtonian noise) since these are concerned with measurements at frequencies of 40Hz and above, where NN is not a limiting factor. This will not be the case come future generations of GWD's which, upon having sensitivity increased to 10Hz, noise models indicate detectors will have major limitations from NN from a little below 10Hz through 20Hz (Figure 1).

This Newtonian noise that will be a limitation of these detectors is a direct product of seismic noise [1,5], so, to understand Newtonian noise, seismic noise must be understood. Seismic noise may be characterized as one of very low frequency with origins from a variety of sources, such as a pencil falling, a car starting, a small earthquake, etc. These sources create fields of waves that cause perturbations along the ground, resulting in the ground displacing ever so slightly along the horizontal and vertical axes. Due to this, the density around a test mass changes, resulting in an induced force upon the mass which then displaces it ever so slightly along the horizontal [1]. This horizontal displacement is what is classified as gravity gradient noise (Newtonian noise).

While this may sound simple, in actuality the noise is very complicated with the density changes that induce a force on the test mass coming from many directions [1]. Since it is so complicated, little is known about the noise [1,7], which is problematic since it needs to be subtracted from gravitational wave data compiled from future detectors. Learning what we can about this noise is thus imperative and has already begun at the former Homestake mine in Lead, South Dakota. This location was chosen due to its tendency to decrease seismic noise at locations deep underground [5][1] and several seismic stations have already been set up here: 1 at 3000ft, 3 at 2000ft, and 3 at 4000ft. Problems, however, have arisen. One is that only one station is still operable since humidity has destroyed the computers at the other stations (see Appendix A for information on solving this issue) [1]. Another problem, more important than the humidity destroying the computer, is that the seismometers used at the stations are not built to study Newtonian noise in the range of 10-20Hz since electronic and mechanical noise mix in with the seismic data at frequencies in which Newtonian noise is relevant in future detectors, hindering advances in understanding it [1]. The proposed solution is to build a new seismometer.

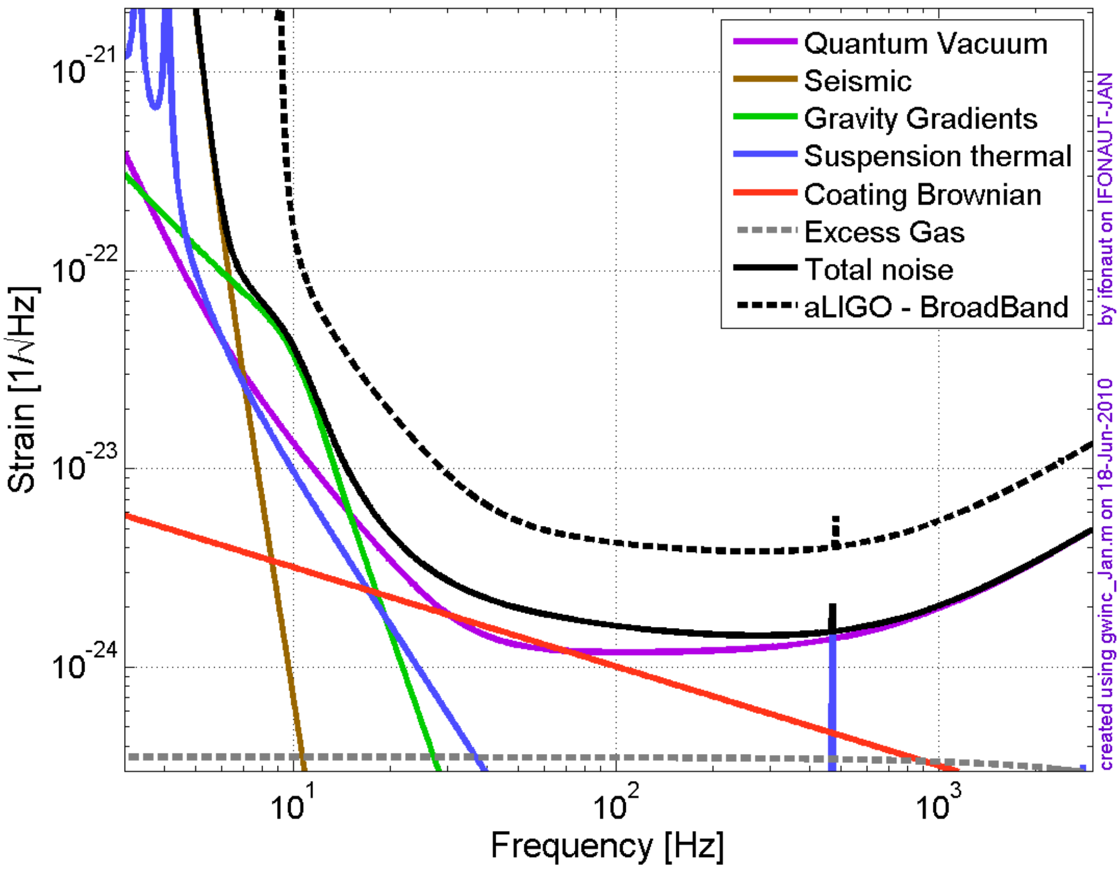

**Figure 1: Noise curve of Advanced LIGO. Note how gravity gradient noise is the main limitation from around 10 to 20Hz where the total noise curve is "hugged" by the gravity gradient noise contribution.**

To do so, a SS-1 Ranger (Figure 2) was dissected to construct a seismometer modeled off of it [1]. While dissecting it, it was noted how surprisingly simple its design is. In short, there is a test mass of cylindrical shape at its core with a circular magnetic strip around it, a rod attached on top of it, and a spring passing through its center. From its design, more of which is discussed in Section IV, a titled mirror is placed in a spot where the rod passes if the mass moves. The

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[1] Due to this low noise level, if it is shown subtracting noise is easier underground than above ground, a location of similar style to the Homestake mine would be ideal for a future detector [2,4,7].

Figure 2: The SS-1 Ranger.

mirror, along with a readout coil at the top of the mass and a calibration coil below it, determine how far the mass has been displaced form equilibrium. Using a seismometer with the sensitivity range in which Newtonian noise is a limiting factor in gravitational wave measurements, this displacement would be sent as an electrical signal to a readout system, amplified, and then recorded. Using this electrical signal, Newtonian noise may then be modeled from this recorded seismic data [1].

With the goal of a seismometer to function like this in mind, drawings and measurements of the Ranger have been made and AutoCAD is being used to model its components. Using these models, it will be determined where modifications would be necessary on the Ranger to achieve better sensitivity and applied to build a seismometer capable of studying Newtonian noise.

## II. The Limitations of Current Seismometers

Seismometers are limited by a variety of noises, some noises limiting particular design types more than others. As mentioned earlier, the seismometer that is to be constructed will be modeled off of the SS-1 Ranger's build. The Ranger itself, however, is not a good seismometer, and basing improvements of the new seismometer off of it would not be useful. Instead, the new seismometer's noise will be compared to that of the GS-13, a seismometer of similar design to the SS-1 Ranger, but of superior performance as well [1].

The noises most relevant in the limitations of the GS-13 at frequencies in which NN is concerned are amplifier voltage noise, amplifier current noise, Johnson Nyquist noise, and thermal suspension noise. To model these for determining just how much each is a limiting factor in the Ranger, a transfer function was formulated to calculate the noises at various frequencies. To design this transfer function, it was taken into account that the GS-13 behaves somewhat like a pendulum [1] in that there is the frequency of the spring in it, a loss angle of the spring, and a frequency of the signal the seismometer is generating. With this in mind, the following transfer function was yielded:

$$|H(f)|^2 = \frac{f^4}{\left(f_o{}^2 - f^2\right)^2 + \varphi^2 f_o{}^4}$$

$$\varphi = loss\ angle\ of\ spring$$
$$f = signal\ frequency$$
$$f_o = resonant\ frequency\ of\ spring$$

[1].

Using data from the GS-13 manufacturer, a noise model of the seismometer was produced.

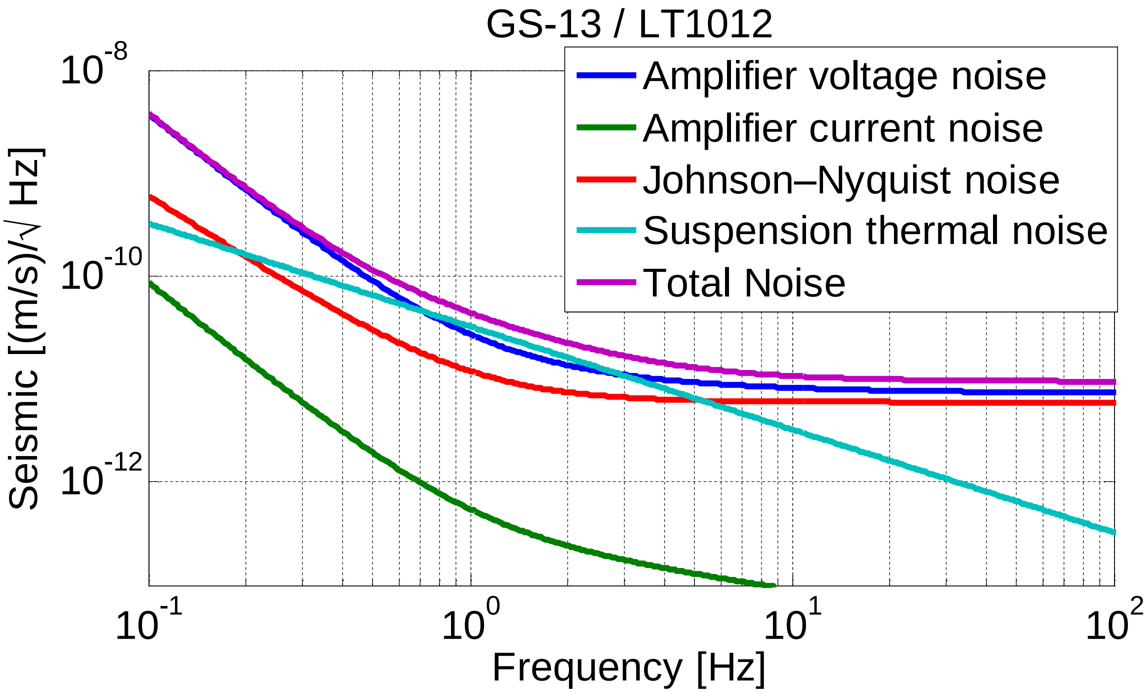


Figure 3: Noise curve of the GS-13 when used with the LT1012 amplifier.

The noise sources and how each comes about are as follows.

The amplifier voltage noise and amplifier current noise are due to the amplifier. The amplifier's voltage and current generate noise and this is simply minimized by acquiring a better amplifier [1].

Johnson Nyquist noise is a result of the thermal resistance in the readout coil [1]. A readout coil contains much resistance and when an electrical signal on how far the test mass has been displaced from equilibrium is sent to it, current flows, causing the resistance to produce thermoelectric noise [1]. As will be discussed later, it has been determined this readout coil can be, at least right now, supplemented (in the future it will be ideal to remove it completely) with a capacitor sensor of much less noise, allowing for this thermoelectric noise to be disposed of and the Johnson Nyquist noise to become much less significant [1].

The three noises just discussed have relatively trivial ways to be dealt with. Unfortunately, suspension thermal noise and other mechanical noises not shown on the graph are less trivial to minimize.

A source that is considered very plausible for these noises is spring damping [1]. When the test mass moves, the spring that is attached to it and passes through the mass's center moves, causing particles within the spring that have damping to move and produce noise. A second possible source of this suspension thermal noise and other mechanical noises are eddy currents [1]. The seismometer, as will be discussed later, is made of many metal and magnetic components that move amongst each other, inducing currents that may cause significant noise. To reduce this noise, acquiring a better spring, if one is to be used, is necessary. A better solution would be to design a seismometer that does not use a spring. Along with this, if it is determined experimentally eddy currents are a major contributor to thermal noise, reducing the number of magnetic and metal components by using materials that will have very small to no eddy currents as a result of the materials' motion will be used in the design of the new seismometer in place of the magnetic and metal components.

## III. Improving Sensitivity

Since current seismometers are not sensitive enough for studying Newtonian noise in the frequency range where it must be understood, the task of refitting seismometers to get the sensitivity required is underway. At the moment, ideas for limiting the more trivial noise sources (amplifier voltage and current noise, Johnson-Nyquist noise) are in development. As mentioned earlier, the readout coil causes much noise due to its resistance. Removing this coil and utilizing an instrument of much less noise that is able to perform the same functions is ideal. This can be done with the capacitor readout system [1] that is shown in Figure 4.

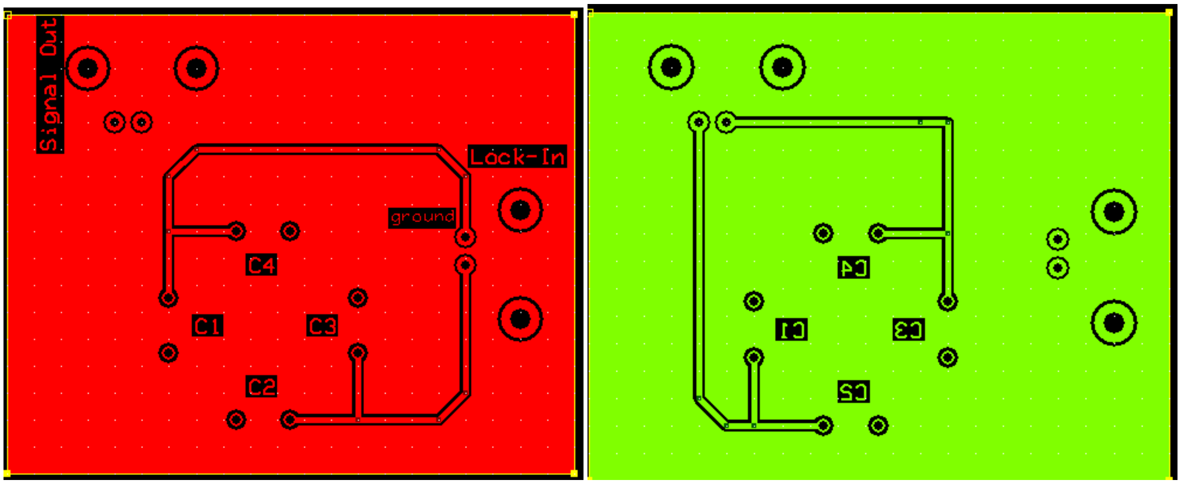


**Figure 4: The readout system was designed on ExpressPCB [3]. There are four capacitors in it. Each is in series with one of the other capacitors and in parallel with the other two [1]. On the top portion of the board one of the sets of capacitors in series are connected to the ground at one end of each of the capacitors, and the other set is connected to the input signal the same way. On the bottom of the PCB board the other ends of the capacitors are connected to the readout system where an amplifier will be located. The input/ground and the output are both made of two BNC connectors. A low noise pre-amplifier will be used to limit electronic noise in the system [1]. This readout system will then amplify the electrical signal given by the seismometer.**

Two capacitors (C1 and C2 in Figure 4; the other two capacitors will be explained in Section IV) will be put in place of the readout coil. One will be located on the test mass; the other will be located just above it.

Low noise amplifiers will be used for this readout system as well so the amplifier voltage and amplifier current noise are lowered.

Taking this capacitor into account and other values that will be used for the improved seismometer (the type of amplifier that will be used, the capacitors, etc have been chosen. The only value that is not certain is the loss angle phi, as it may be higher or lower), the transfer function from Section I:

$$|H(f)|^2 = \frac{f^4}{\left(f_o{}^2 - f^2\right)^2 + \varphi^2 f_o{}^4}$$

may be used to graph the noise curve of the seismometer that will be constructed for studying Newtonian noise. Naming the seismometer that will be built for this the VH-1; its noise curve is seen in the following graph:

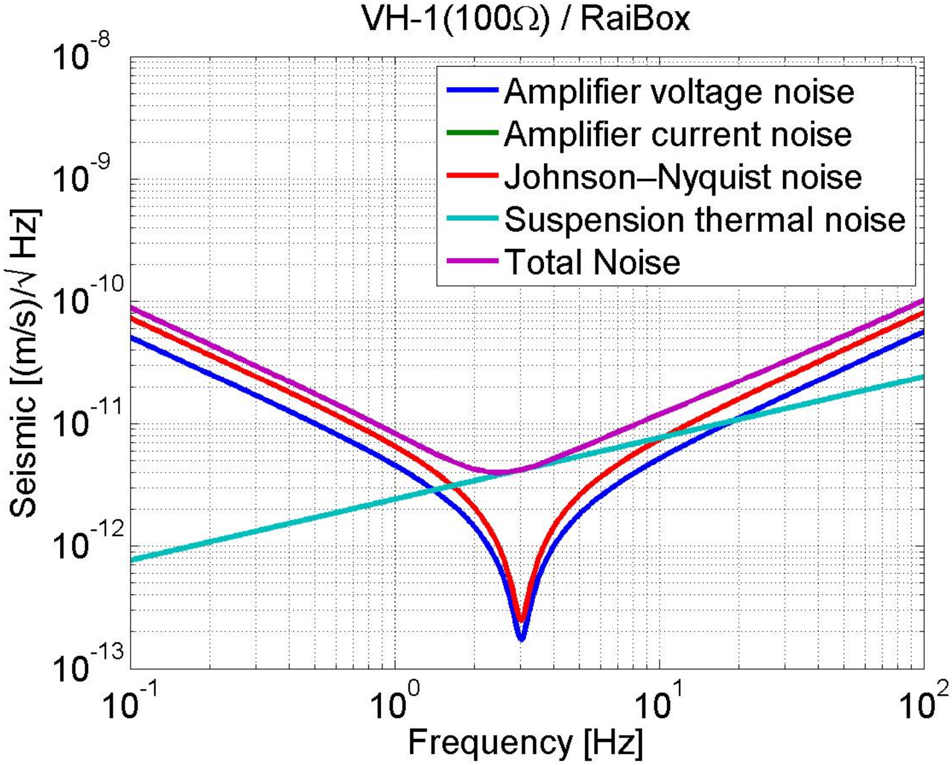


Figure 5: Noise curve of the VH-1 prototype with the low noise RaiBox amplifier.

Compared to the GS-13, the VH-1 has around a magnitude less of noise from .1-10Hz, which is excellent, as this is where Newtonian noise is relevant.

It is now time to look at the VH-1 and compare it to what is already out there. Figure 6 shows a graph of the GS-13's total noise compared to the desired noise level of a seismometer and the total noise of LIGO 2.5.

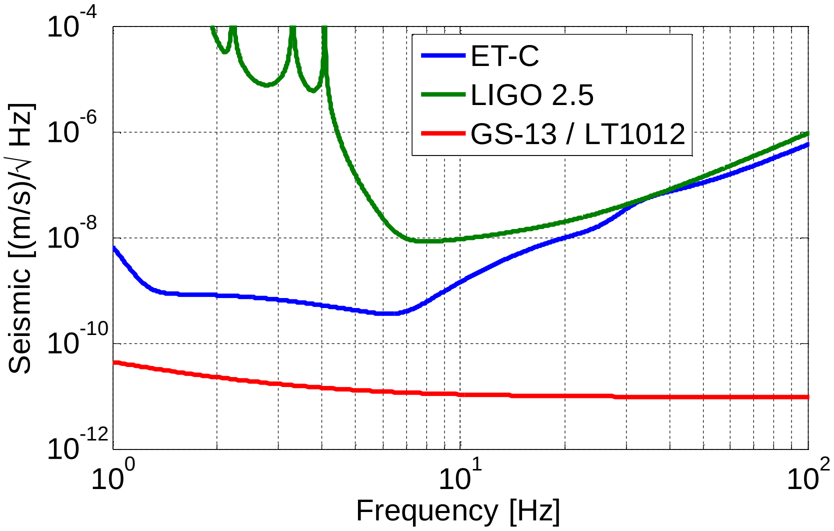


**Figure 6: This graph shows three different total noise curves. The ETC-C curve is that target curve for the third generation of gravitational wave detectors [1], representing the maximum amount of noise that a seismometer studying NN for this generation may contain. The LIGO 2.5 curve represents what the noise level of upgrades during the runs of Advanced LIGO may bring its noise curve to. The GS-13 curve, naturally, shows the total noise curve of the GS-13 seismometer. Its noise curve is a bit below the target curve, but even less noise is desired.**

The noise curve of the VH-1 compared to LIGO 2.5 and the target curve is seen in Figure 7.

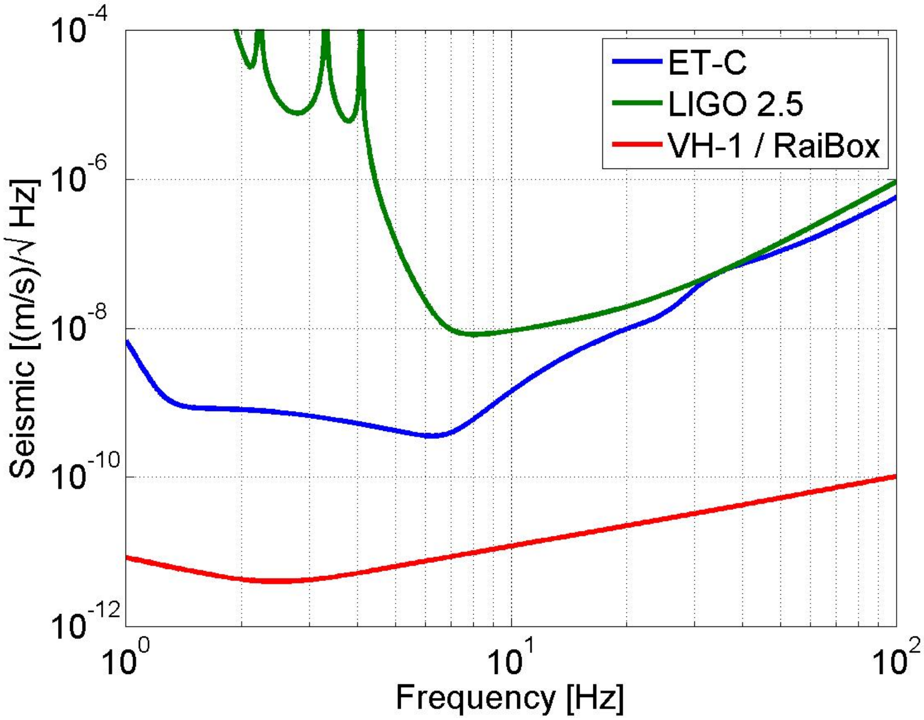


**Figure 7: The VH-1 prototype's total noise compared to LIGO 2.5 and the target curve. The noise of the VH-1 is a magnitude less than the GS-13 was in the previous graph.**

Looking at these noise graphs, it is seen that the total noise of the VH-1 is a bit less than the GS-13 in the frequency range of .1-30Hz, showing that the small modifications that are currently planned for a new seismometer are already leading to less noise. More improvements will be made in the future for an even better seismometer with much less electronic and mechanical noise that will allow for excellent NN studies. How the planned changes will be implemented and ideas for future changes are discussed in the final section.

## IV. AutoCAD Design and Analysis

Using a couple of screwdrivers, the SS-1 Ranger was dismantled. Following this, a standard caliber was used to measure the majority of its parts and the main components have been modeled in 3D on AutoCAD. Shown below is a picture of the actual seismometer and its transformation into a 3D model.

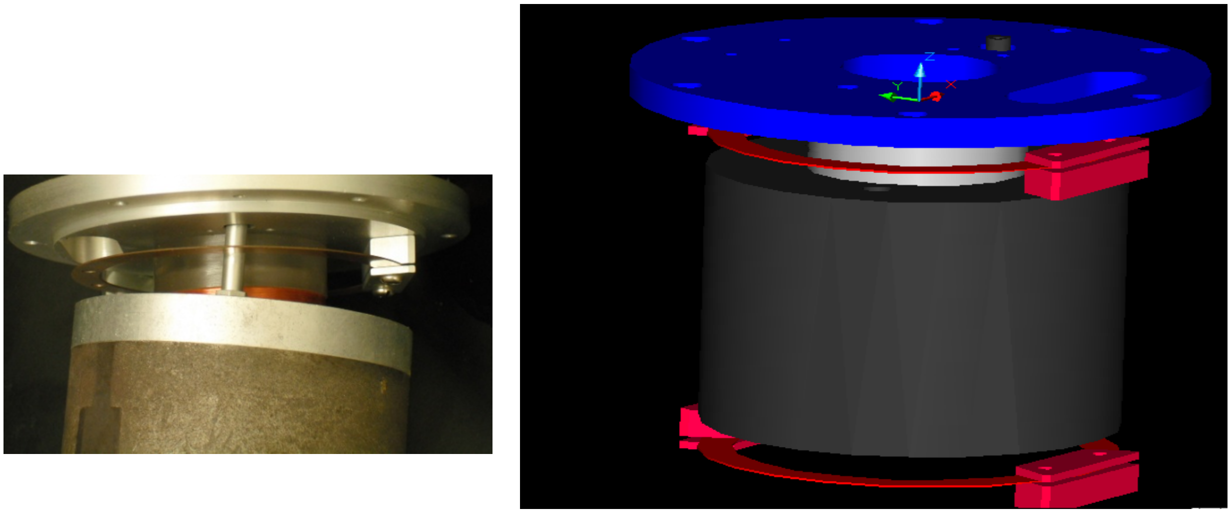


Figure 8: The photograph on the left is a picture of the seismometer's test mass and readout coil above it. On the right is the same picture with the test mass (black) and readout coil (grey), and two flexure rings (red) keep which the components of the test mass and pieces connected to it aligned.

The test mass actually looks different in a model on its own, where it has black and grey coloring, but for purposes of putting the pieces together the test mass was made on color (black). Figure 9 shows the test mass in a model by itself:

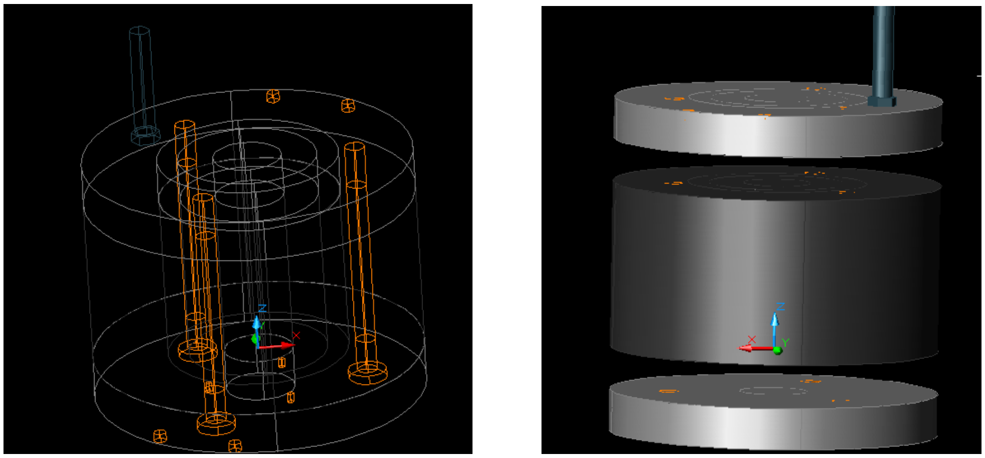


Figure 9: AutoCAD 3-D design of the test mass. The center of the test mass was placed at 0,0,0, which is the bottom and center of the black looking strip in the right hand figure. Each of the gray pieces that sandwich this is 9.5mm high and everything is placed based on Cartesian and Polar coordinates from there. Screws and the rod were mostly placed with Polar coordinates, and the other cylinders, as seen in the left figure, were placed with Cartesian coordinates. The tall, orange colored screws seen on the left figure were done in three parts, one for each segment (the 9.5mm gray pieces, and the gray piece that is not visible but right behind the black piece. This is because to make layers, as are done on this particular model, and to have successful subtraction afterwards where parts of the layers do not disappear for some reason, each component of the screw had to be attached to a particular layer. The hexagon that holds the rod was done by creating two trapezoids with subtraction of squares from squares and then adding the two hexagons together.

To view the seismometer in more detail to determine points where modifications are possible within the constraints of space, cross sections were made [1]:

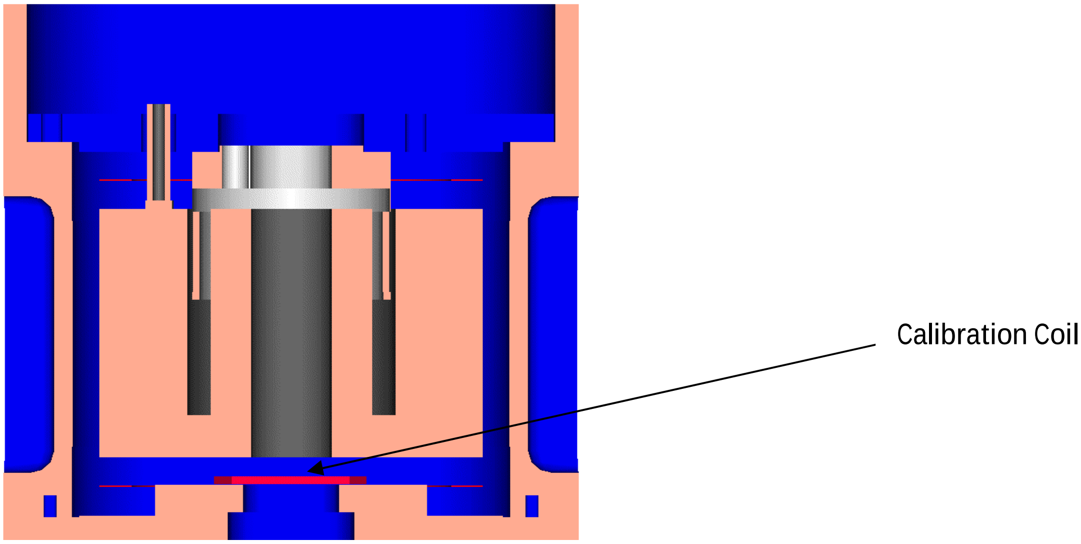
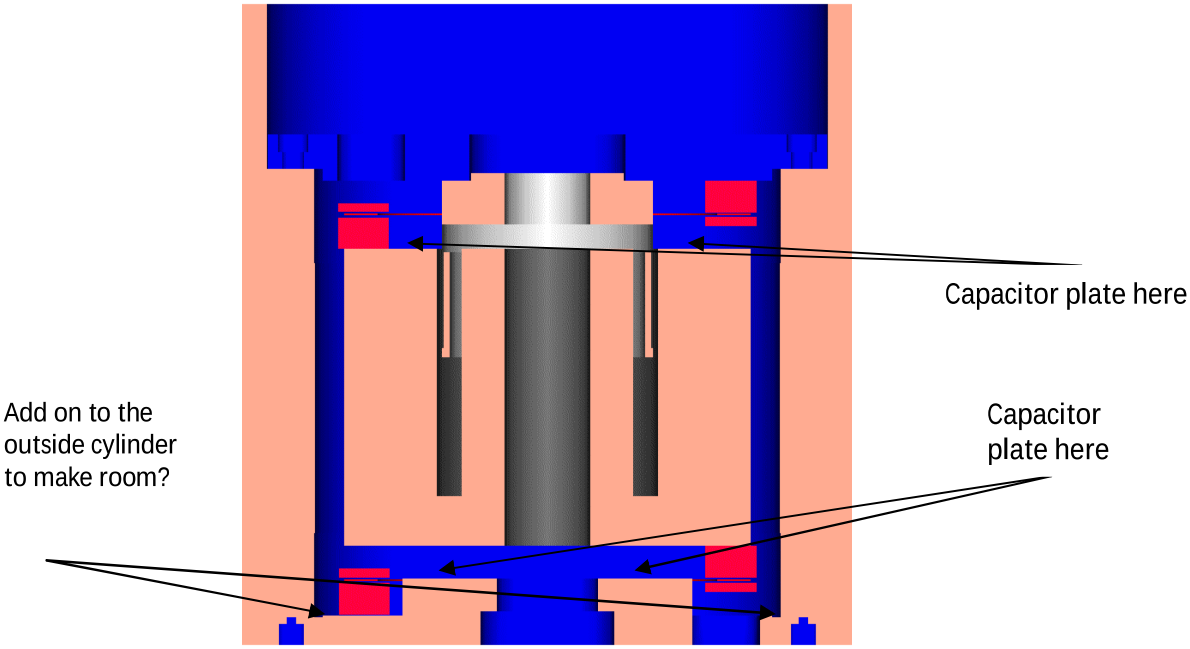

Calibration Coil

Figure 10: Cross section of what is mostly composed of Figure 8. The outside blue parts are the cylindrical shell that goes around the test mass.

Due to the calibration coil, there may or may not be room for the capacitor plates that will be added below the test mass (it will be seen if there is room once the capacitors are acquired physically. It has been suggested that, if this is the case, the cylindrical shell around the test mass be made a little bigger to allow room for the capacitors [6]). This can visually be seen in another cross section of the seismometer.


Capacitor plate here

Add on to the
outside cylinder
to make room?

Capacitor
plate here

The capacitor plates will, no matter what, be added on to the seismometer. One will be on the bottom of the test mass, one on top, and the other two will be located a small distance from each of these.

## V. Conclusions and Future Work

This report discussed limitations of seismometers and solutions to create one sensitive enough at frequencies where Newtonian noise must be understood. The first step to doing so was to understand how seismometers are built. Then, looking at noise models of very well built seismometers, the noises that needed to be lowered for sensitivity in the range of .1-30Hz (the frequency range in which Newtonian noise will limit future GWD's, plus a little) were observed and ways to lower these noises in a new seismometer speculated.

At the moment, the most prominent change that has been determined is adding a low noise capacitor readout system to being to use in place of the high noise readout coil. The Ranger, which is still "unassembled" into all its parts, will need to put back together with this readout system. When this is completed, comparisons of seismometers that are just not good enough for studying Newtonian noise will make noise measurements side by side with this improved Ranger and it will be determined what still needs modification to make the new seismometer even better. The lower its internal noise, the better we will understand Newtonian noise which will allow for studying it to proceed more quickly and methods of its subtraction formulated and put in place for gravitational wave detectors of the future.

**Sources:**

[1] Hans, Jan. notes from personal conversations. June 9-July1, 2010.

[2] Harms, Jan, et al. Characterization of the seismic environment at the Sanford Underground Laboratory, South Dakota. *LIGO Document*, DRAFT, 2010.

[3] Harms, Jan, Vansuch, Greg. Seismometers and the Insulation Box. *LIGO document*, M1000204-v1, 2010.

[4] Harms, Jan; Vansuch, Greg. Subtraction of Newtonian Noise. *LIGO document*, M1000203-v1, 2010.

[5] Harms, J., Sajeva, A., Trancynger, T., DeSalvo, R., Mandic, V. Seismic studies at the Homestake mine in Lead, South Dakota. *LIGO document*, page T0900112-v1-H, 2010.

[6] Heptonstall, Alastair. personal conversation. July 26, 2010.

[7] Mandic, Vuk. Status of the Seismic Noise Study at the Homestake Mine (DUSEL).*LIGO document*, page G080491-00-Z, 2008.

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## Appendix A (an excerpt from *Seismometers and the Insulation Box*)

The first task of the summer was building the box that contained the proposed cooling system to let a computer survive in it while at Homestake. The ultimate goal was to bring the temperature inside the box down a decent amount from an early design that brought the computer's temperature to 30 degrees Celsius.

**Materials:**

- 12x24 inch .036in aluminum, black (4)
- 24x24 inch .036in aluminum, black (2)
- 2.5x23 inch .0655in aluminum (20)
  - Bend into L's so that the 2.5 inch is bent into 1.5 and .75inch segments
- 1x22inch .13in aluminum (4)
  - Bend into L's so the 1inch is bent into two .5inch segments
- 1x10inh .13in aluminum (8)
  - Bend into L's so the 1inch is bent into two .5inch segments
- Ruler (standard 12 inches)
- Drill that can hold a drill bit to drill the size hole the rivets fit
- 2 clamps
- Permanent marker
- Aluminum Water Proof Tape

**From McMaster-Carr:**

Loctite Hysol Adhesive Cartridge, E-60NC Electrical Potting Epoxy, 1.69 oz (50ml), 6430A27. Quantity: 6

Dispensing Gun for 1:1, 2:1 50mL Cartridge, 74695A71. Quantity: 2

Bayonet Mixer Nozzle, 5.9'' L with 1/4'' Taper Tip, 74695A12

Did not come with the order and was not used, but is needed for building the box properly

Pop Blind Rivets: Poppack 100

- AD44BSLF203
- Aluminum
- Recommended grip range : .188-.250in
- Recommended hole size: .129-.133in
- Rivet: aluminum
- Mandrel: coated steel
- Lot no. 409417
- 97517A320. Quantity: 4

Comfort Grip Blind Rivet Tool with 4 Nosepieces (3/32'', 1/8'', 5/32'', 3/16''), 6862A21. Quantity: 1

### Building the Box

The dimensions of the box were to be 12’’x24’’x24’’. To begin building it, two 24’’x24’’ and four 12’’x24’’ black aluminum (.036in) pieces were ordered. When these arrived the 12’’x24’’ were placed on a table where the 24’’ were on the horizontal and the 12’’ on the vertical. Using a ruler .5’’ was measured from each corner horizontally and this .5’’ line from the horizontal drawn up vertically for future reference (measure in on the x axis .5’’ and then draw where the .5’’ mark is, aka x=.5 in a graphical sense). Following a mark every 2’’ on the vertical was made up through the 10’’ mark and drawn across horizontally (lines y=2,4,6,8,10 in a graphical sense). Both of these steps were applied to both sides of the two 12’’x24’’ pieces.


Figure 11: The holes were marked on both the L's and the black aluminum so when more drilling and riveting occurred the holes would be in the right places.

These lines would help place the cooling system which would consist of twenty 2.5’’x23’’ aluminum pieces bent into L’s with segments of .75’’ and 1.5’’ (It should be noted these L’s were bent by hand with a machine. It was attempted to have all the segments at .75’’ and 1.5’’, though none came out perfect). When laid down on the black aluminum pieces the L’s were placed where the .75’’ segment was on the aluminum and the 1.5’’ segment was in the air.

The next step was to take 10 of the .13 aluminum pieces (5 for each side of both 12’’x24’’ black aluminum pieces) and to measure 40cm inward on each end of the pieces along the x axis and 10 cm from the bottom (part that faces away from the bend) on the x axis and make the mark of an X where the 40cm and 10cm point met (intersection of y=40 and x=10 in a graphical sense). There will thus be 2 X marks on each of these 10 pieces. This is where drill holes were to be put. To drill these L’s a drill piece was found that would fit the rivets eventually used to rivet one L, the black aluminum, and an L below that, together. The size of the hole these rivets make are .129 .133 inches. The drill bit used with this box was in fact a bit bigger due to supply limitations (the bits within the proper range were too dull to use). A hole was then drilled through at each X mark and labeled, which would be handy later (see Figure 1).

The following was then done.

With a clamp, one of the L pieces previously drilled through was lined up on the black aluminum board at the 2’’ mark and .5’’ from the edge of the board as horizontally as possible. This was done by using a ruler to draw a straight, horizontal line across the board at y=2 (and was done for the other points as well). Then, with a clamp, one of the L’s with no holes drilled through it was lined up on the other side of the piece at the 2’’ mark and lined up with the other L as well as possible and then clamped to it. Each L was made sure to be as straight as possible by making small adjustments with removing the clamp and realigning as needed.

Then the drill was placed in one of the holes that had been drilled earlier on and the black aluminum and other L were then drilled through. The resulting holes were labeled (for example, if three holes were in the same set, (a hole in one L faced a hole through the black aluminum which faced a hole in the other L below it, one could mark these holes as 1A top, 1A, 1A bottom). This process was done for all the 2'' marks on both 12''x24'' pieces.

When this drilling was complete it was time for gluing and riveting the L's onto the black aluminum. To do this sets of L's (one on one face of the aluminum, one on the other) were glued down, and right after riveted together.

Problems that occurred in this step are noted here. At first only the L's for the top black aluminum piece were glued out of misunderstanding of directions. It was decided, due to this misunderstanding, to wait until the next day to glue the bottom pieces, and once all the glue was dried the pieces would be riveted together. It was fortunate this mistake was caught right away. If waiting to glue the bottom and then doing the riveting had taken place, the box would not have turned out so well, as the pieces would have shifted while drying so the holes would have not been in place, so riveting would have been very, very difficult.

Also, the glue being used needed a mixer to work properly, and no mixer was sent. This was not realized until much gluing had taken place, so the glue had to be mixed by hand, the result quite a mess as seen in Figure 2. Proper gluing would have required this mixer for the glue gun.

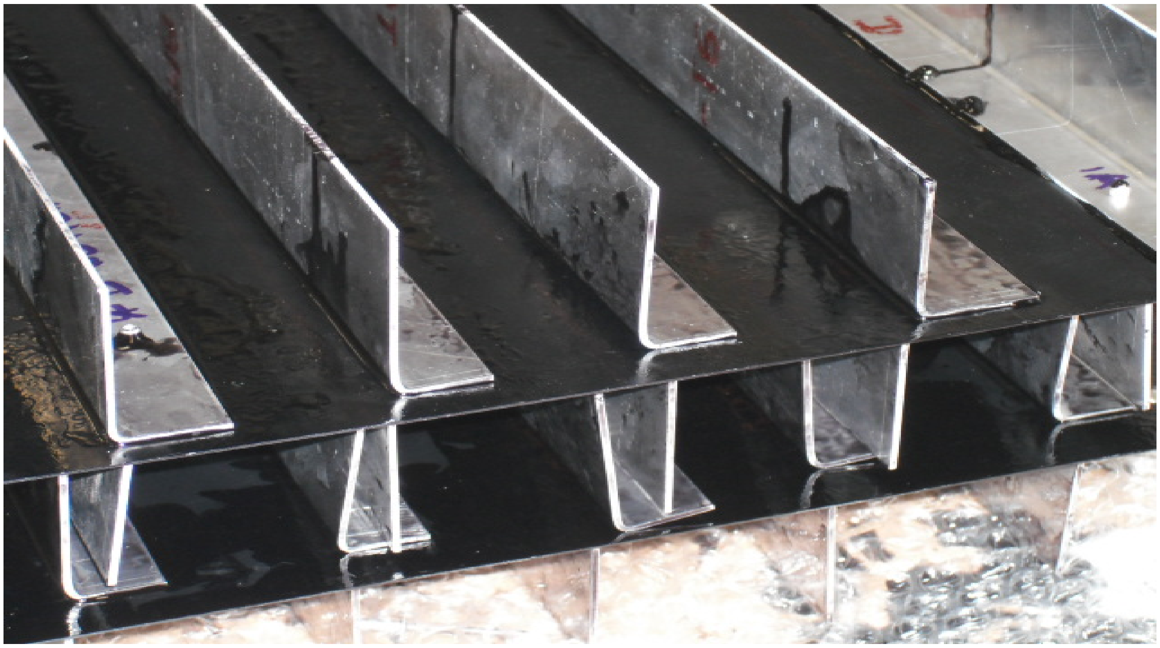


Figure 12: The result looked like this. It did not matter which direction the L's were glued, but here, except for one mess up, the top of the black pieces had the L's facing to the right, the bottom L's facing to the left.

When the glue had dried, which was much later than expected (it should have been 24 hours, but this was about five days later, and the glue was still a bit wet) it was time to make the box. On each piece of the box it was decided which side would face outward and inward (the outward parts would contain the smooth side of the rivet to place tape with more ease around the edges of the box as soon described). A 1'' mark from each edge on the inward portion of the box pieces was made. These would be where the four 1''x22'' and eight 1''x10'' .13in aluminum pieces, bent into segments of .5'', would be placed. Each of the black aluminum pieces were to contain two of the L's on its side, riveted to it and its partner black aluminum piece as the box was put together (see Figure 3). The .13in aluminum pieces were lined up at the 1'' marks in each corner and positioned in a way such that it lined up with the edge of the black aluminum perfectly. Clamps were used to keep these in place, and 3 holes were drilled through each of the 1’’x10’’ pieces, 4 holes for the 1’’x22’’ pieces. The top piece of the box was not riveted to the rest of the box since the top needs to be removed easily to put in and take out items from the box. To seal off gaps aluminum water proof tape was put around the edges and holes in the box (each of black pieces had 4 holes near the corners. This was not intentional; the manufacturers delivered the pieces this way).

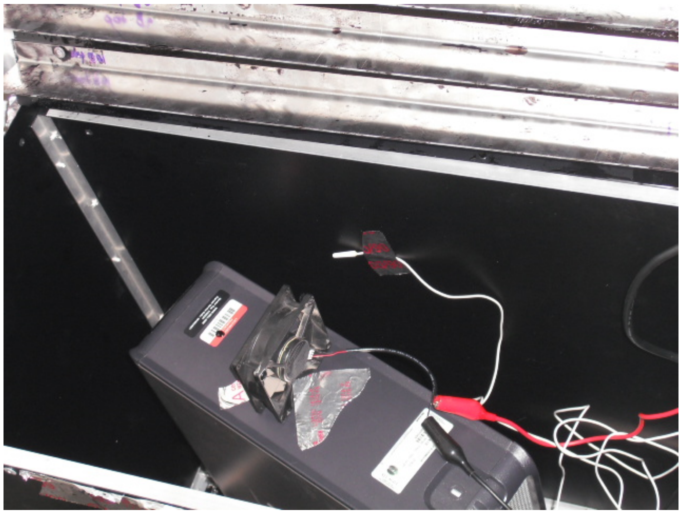
The box was now equipped with scientific instruments. The computer was placed on the cooling system at the bottom of the box. This computer was then connected to a monitor located outside the box. A small fan was taped on top of the computer with its wire attached to the black end of a BNC connector. A temperature sensor was attached to the side of the box and its wire connected to the end of a red BNC connector. This way the fan could be turned on and off and the temperature read out with the box closed as the other end of the black BNC was connected to the switch that turns the fan off and on and the readout screen of the temperature sensor sat on a table outside the box. For better visualization inside the box see Figure 4.

Figure 13: How to rivet and position the .13 aluminum.

With everything inside and the computer running the top of the box was put in its place. It would not go down all the way as there were wires connecting devices in the box to outside the box. To seal it as best as possible the aluminum tape was used in the same way as on the other sides. It was now time to determine if this box improved the inside the box as compared to the modification from before.

Ideal results placed the aim for temperature significantly under 30 degrees Celsius. At 10:00 am the measurements began. At first the inside fan was turned on, then the outside. The temperature started out in the 40’s and by 11:30, when it was a reasonable time to see what temperature the cooling system would allow the box to be, it was 28.7 degrees Celsius. The goal for under 30 degrees was attained, but only by an absolute value of 1.3, not enough to make a difference.

Figure 14: The box with the computer, fan, and heat and temperature sensor inside.



A good portion of the box design/cooling system will remain. The box design itself will not change, as the .13in aluminum L’s and tape were found to make the box much more sturdy and the black .036in aluminum will keep heat absorbed within the walls and not flowing around in the box as much. Since the cooling system did not make much of an improvement, only the 10 L’s making up the bottom portion of the box’s cooling system will remain. The idea behind this is the computer will not sit directly on the bottom of the box allowing for air to move more freely and the box itself not touching the ground directly allowing for air to move under. Both of these key points could keep heat from building up under the computer/box and avoid unnecessary temperature increase.

Small modifications will also be made to the 10 cooling system L’s as well. When glued onto the black aluminum pieces, some were closer than .5’’ to the edge of the black pieces resulting in modifications to the .13in aluminum L’s (the pieces that were riveted at the sides of the box in Figure 3) being necessary to fit them next to the cooling system along the 12’’ axis. It was decided where the .13in pieces needed to be shorter to fit onto the black pieces just right and then a filer was used to cut the pieces accordingly. To avoid this in the future the cooling system will have L’s that are 2.5’’x21’’ bent into .5’’ and 1.5’’ segments.

Seven to eight more boxes will be made in the near future for use at Homestake.