

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

### LOW-NOISE BOREHOLE TRIAXIAL SEISMOMETER

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#### **ABSTRACT**

This report describes the preliminary design of a Low Noise Borehole Triaxial Seismometer for use in networks of seismic stations for monitoring underground nuclear explosions. The design assumes the use of the latest technology of broadband seismic instrumentation. Each parameter of the seismometer is defined in terms of the known physical limits of the parameter. These limits are defined by the commercially available components, and the physical size constraints. A theoretical design is proposed, and a solid model of the proposed instrument is included to verify the ability to meet the size constraints.

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### **OBJECTIVES**

The goal of this Small Business Innovation Research (SBIR) award is to design a Low Noise Borehole Triaxial Seismometer for use in networks of seismic stations for monitoring underground nuclear explosions. The design assumes the use of the latest technology of broadband seismic instrumentation. Each parameter of the seismometer is defined in terms of the known physical limits of the parameter. These limits are defined by the commercially available components, and the physical size constraints. A theoretical design is proposed, and a computer assisted design (CAD) model of the proposed instrument is included to verify the ability to meet the size constraints.

The design goals set out for the SBIR are for a triaxial seismometer that can be deployed in 7-inch boreholes at a depth of 100 meters. The instrument must operate over a bandwidth of 0.2 to 16 Hz with a response flat to velocity or acceleration. Two instruments may be used to meet the requirements. The self-noise of the instrument(s) must be 6 dB below the United States Geological Survey (USGS) low-noise model over the full bandwidth and have a dynamic range of 120 dB. Self-calibration within 5 percent of amplitude and within five degrees for phase over the bandwidth is a requirement. The instrument must have low power requirements and a high reliability when operated unattended in harsh environments.

### **RESEARCH ACCOMPLISHED**

For Phase I, seven parameters of a broadband instrument were analyzed to define the requirements needed to meet the design goals for response, low-noise, and dynamic range and the requirement to fit into a 7-inch diameter or less borehole. Phase I looked at the suspension, the minimum mass requirements, and maximizing the sensitivity of the suspension to acceleration. Detecting the mass motion of the sensor relative to the reference frame, the mass motion transducer, and the control loop requirements are described. A noise analysis of the control loop was done, and a CAD feasibility model was made to verify a fit into the borehole.

In the analysis, comparison is made to the characteristics of existing and historical seismometers such as the KS36000, KS54000, and KS2000 instruments in order to verify the validity of some of the calculations and characteristics of the proposed design.

A pendulous suspension was chosen for the response analysis and a natural frequency of approximately 10 Hz was used. This natural frequency will allow a simple seismometer design that does not require a mass lock. It is assumed that the suspension is not in a vacuum to further simplify the design. The mass size is set according to the well-known MPQ criteria.

The ratio of the distances from the pivot point to the center of mass ( $\bar{r}$ ) and to the center of percussion ( $q$ ) is set to maximize the angular sensitivity of the suspension within the constraints of the borehole diameter requirements. Figure 1 shows this relationship and the historical characteristics of existing designs. The maximum sensitivity occurs at a ratio  $q/\bar{r}$  of 2.

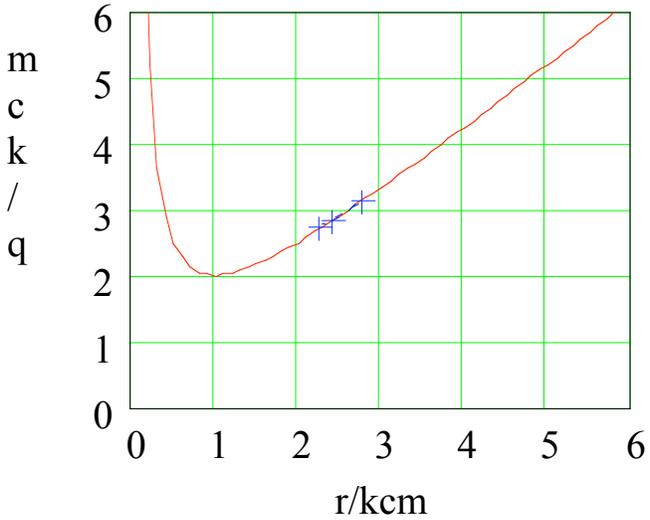


Figure 1. Relationship of  $q$ ,  $\bar{r}$ , and  $\kappa_{cm}$  for maximizing angular sensitivity of the suspension. Blue '+' symbols show ratios (from left to right) of the KS2000, KS54000 (vertical) and KS54000 (horizontal).

Figure 2 shows the relationship if the goal is to maximize power delivered by the suspension, and the historical data of previous designs.

There must a compromise between these to extremes. When the minimum mass is computed from the MPQ thermal noise criteria, it is found that maximizing angular sensitivity requires that the mass be twice the size that is required for maximizing power. But, maximizing power requires the mass to be located as far as possible from the suspension pivot point. The design must fit into the borehole and doubling the mass to increase sensitivity is not desirable, but the borehole diameter places a limit on  $\bar{r}$ . Basically it is the size of the mass and the configuration of the mass that is important.

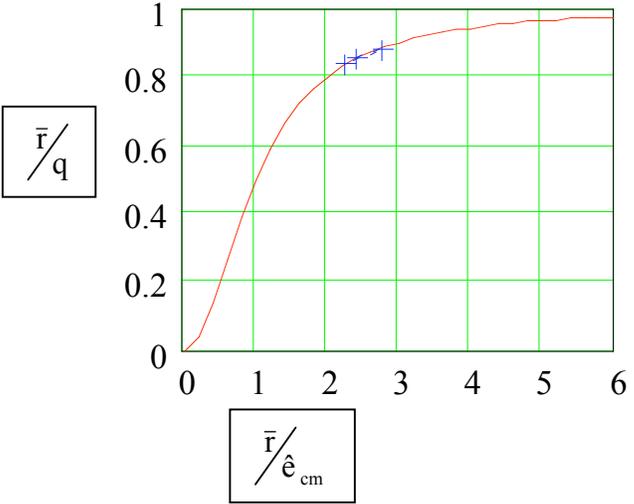


Figure 2. Relationship of  $q$ ,  $\bar{r}$ , and  $\kappa_{cm}$  for maximizing power sensitivity of the suspension.

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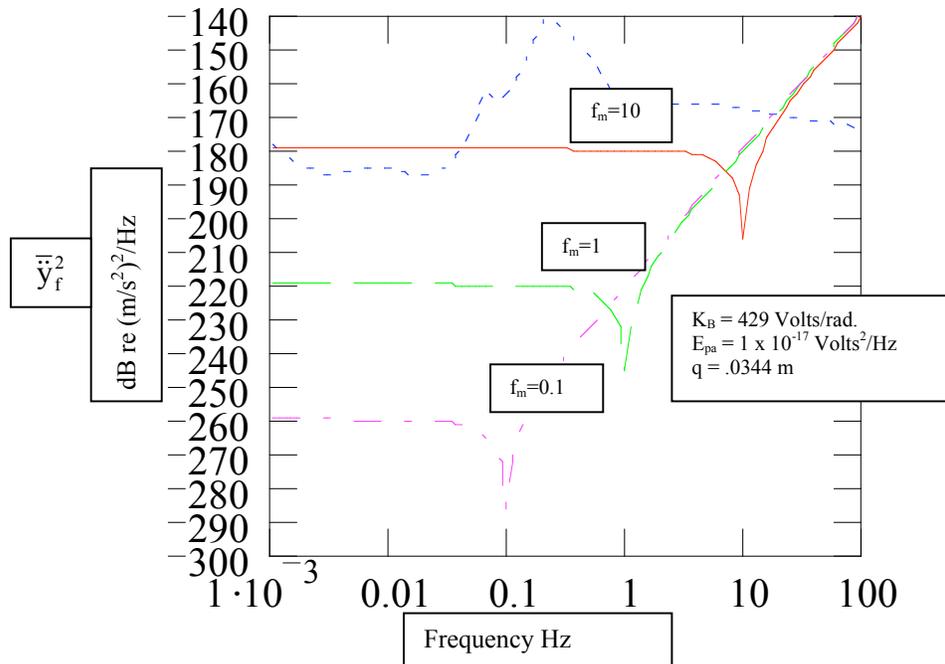
Once the suspension has been designed to have a threshold signal greater than the thermal noise, the next step is to convert the angular output of the suspension into a useable electrical or digital signal.

For an analog design assume the amplifier at the output of the detector has a noise spectra referred to its input of  $E_{pa}$  volts<sup>2</sup>/Hz, and that the noise is white noise without 1/f noise. Also assume the detector has a sensitivity of  $K_B$  and that the suspension has a natural frequency of  $f_m$ . Figure 3 shows the affect on noise threshold referred to the input of the suspension when  $f_m$  is varied and  $K_B$  is held constant. Figure 4 shows the variation when  $K_B$  is varied and  $f_m$  is held constant.

It should be restated that Figure 3 and Figure 4 assume the ideal theoretical situation of no 1/f noise and possibly  $K_B$  values that may not be realistic.

Figure 5 shows the theoretical  $E_{pa}$  noise thresholds of the KS54000 and KS2000 suspensions. Other noise sources in the system will generally keep the design from seeing these thresholds. In particular, the thermal noise threshold of the KS54000 is -200 dB worst case, and typically it is -204 dB. The typical thermal noise threshold of the KS2000 is -195 dB. It is obvious that the KS54000 suspension has much more sensitivity at the low frequencies than is required, and that the KS2000 suspension has far better potential at the higher frequencies.

Also shown in Figure 5 is a theoretical model of a suspension plus detector that could have a noise level 15 dB below the Albuquerque Low Noise Model (ALNM) over the frequency from dc to 16 Hz. Again the assumption of no additional noise added by other elements of the system applies. The design goal is to be 6 dB below the ALNM, so there is considerable margin for other noise sources.



**Figure 3.  $E_{pa}$  noise threshold versus  $f_m$ .**

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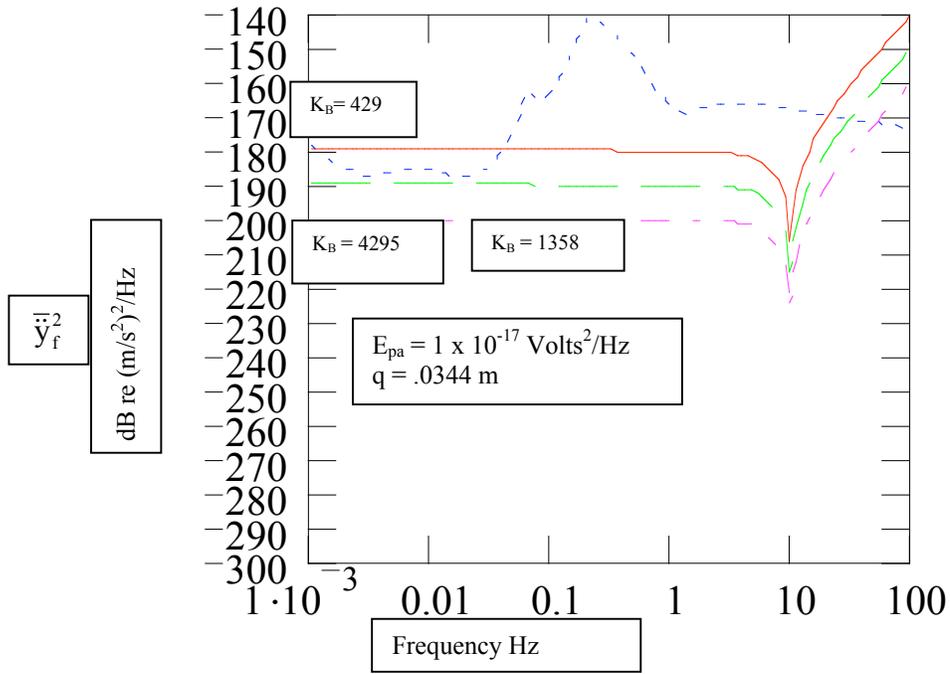


Figure 4. Epa noise threshold vs.  $K_B$ .

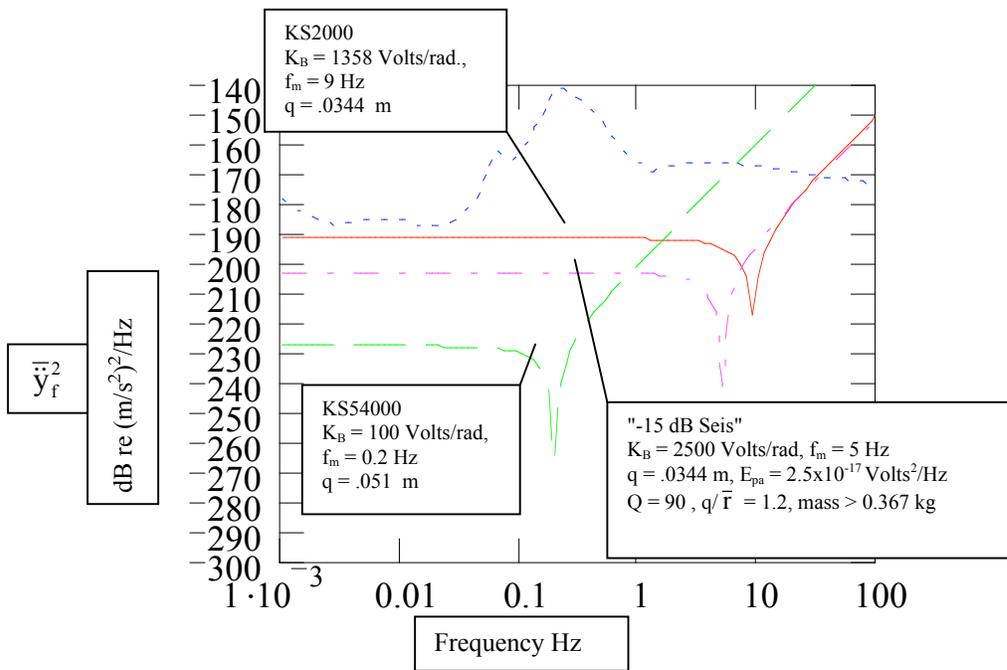


Figure 5. Theoretical  $E_{pa}$  noise threshold of KS54000 and KS2000 suspensions.

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Based on the equations underlying the above figures, a CAD feasibility model indicates that the instrument can be housed in a 4-inch diameter housing that is approximately 48-inches long. This concept is shown in Figure 6.

One of the requirements may be to install this new seismometer into existing KS54000 boreholes. The larger diameter accessories that are shown at either end will allow installation in larger boreholes. Without these accessories the seismometer will fit into a 6-inch casing or possibly a 5 3/4 inch casing.



**Figure 6. Model for estimating size and configuration.**

### **CONCLUSIONS AND RECOMMENDATIONS**

One of the questions to be considered in this preliminary study was to determine if it was feasible to achieve a seismometer self noise level at least 6 dB below the USGS low noise model over the frequency range of 0.2 to 16 Hz. A second question was could it be done with one instrument or would two instruments be required. Based on this preliminary theoretical study, only one instrument will be required. The requirements for the electronics, suspension, and basic sensors can be achieved with current technology based on the experience with and the history of the KS36000, KS54000 and similar designs.

It is recommended that Phase II of the SBIR proceed with the development and testing of prototypes.