LIGO-T880076-00-R

# 35

List of 3/1/89

# SEISMIC NOISE SURVEYS OF A CHOSEN LIGO SITE

**WRITTEN BY: Yekta Gürsel** **December 14, 1988**

## I. Introduction

Once a site for a receiver of the Laser Interferometric Gravitational Wave Observatory is chosen, detailed seismic surveys of the site needs to be conducted in order to determine the amount of seismic isolation that is necessary to attain the desired sensitivity within the limited bandwidth of the instrument. As the bandwidth of the receiver extends into lower and lower frequencies, the amplitudes of the expected gravitational waves grow larger increasing the chance of detection. Such a bandwidth is also necessary in extracting detailed information from the waveform about the generation process. Although there are other competing noise sources, like mechanical resonances in the receiver at low frequencies, the seismic noise may be the eventual limiting factor as other noise sources are eliminated by careful design. In this memorandum, I will outline procedures to record and to analyze the seismic disturbances at a receiver site that may affect the operation of the interferometer. The phrase "seismic disturbances" is used in its most general sense as "all processes which cause the crust of the earth to move locally."

## II. What to record?

Naturally, one would record motions of the ground in three orthogonal directions. The waveforms and the timing of the events that are recorded will give some indication of what their source might be. However, a complete determination of the source can not be inferred solely from the waveforms in general. For this reason, it is essential to record as much objective information about the local environment as possible. The subjective observations of the people performing the measurements are also a valuable aid, but they may be inaccurate and infrequent as the data collection will take too long a time for any one person to be present all along. The presence of people is likely to disturb the instruments as well. Separate measurements with people present should be performed to determine the effects of everyday activity on the seismic noise levels.

I propose that the following signals to be recorded at several chosen locations on a receiver site: The local motion of the earth's crust in three perpendicular directions (two horizontal and one vertical), time and date, the local temperature of the ground and of the air, the barometric pressure, the local wind speed and direction, the local humidity, the local rainfall (or snowfall), the local cloud cover (sunny, partly cloudy, cloudy, foggy, etc...), the signals from two microphones: one buried in the ground and one in the air. Once these signals are recorded, it may be possible to identify remote sources of disturbances like waves on the ocean since almost all local causes can be distinguished.

## III. The Duration of the Measurements

Measurements taken for short periods of time scattered throughout the day may give an indication of the average conditions at the site during that day. A much better way is to record data continuously for a week at a time and repeat the measurements about four times a year in order to take seasonal variations and extremes into account. As it will be shown in the following sections, it is possible to take data continuously for about 12 hours with no operator intervention. This means that data can be taken for a week with just two short interruptions per day. By carefully timing the interruptions one can arrange that for any given time in a day there will be data taken at that time in several different days.

If these measurements are repeated each year as the receiver gets built it will be possible to quantify the changes in the seismic disturbances brought by the developing components of the receiver complex. These data can then be used to circumvent any potential problems that might arise by making minor adjustments in the design.

## IV. Instrumentation

### IV.a. Sensors

The sensors used in detecting the motions of the ground are seismometers and geophones. The seismometers are devices which are sensitive to the velocity of the ground motion in the frequency band from 0.5 Hz to about 30 Hz. Above 30 Hz their internal resonances start to show up and their sensitivity goes down. There are seismometers that are sensitive to motion only in one direction. If these seismometers are used, three of them will be needed at each location. There are also combined seismometers which give signals for three perpendicular directions.

I propose that four individual seismometers (two horizontal and two vertical) should be used in making the measurements outlined above. The reason for this choice is that one can perform many more experiments with four seismometers: An interesting experiment that should be performed is to place the two seismometers at the same horizontal location, but at different depths to examine the dependence of the seismic disturbances on the depth of the soil. Another such experiment is to use two seismometers placed at different distances from a potential source of seismic disturbance to determine its contribution to the local seismic noise. Note that with this arrangement one can record simultaneous data from the devices which makes it easier to identify any correlations.

The other sensor which covers the frequency band from 5 Hz to 500 Hz is the geophone and these are also velocity sensitive, usually three axis devices. I propose that in addition to the four seismometers, two three-axis (or four single axis) geophones should be used. The experiments which are mentioned above should be carried with geophones as well at the same time.

The sensors for the other environmental variables can be a portable weather station and two ordinary microphones with associated amplifiers. An example of such a weather station is shown in figure 1.

## IV.b. Recording Instruments

The data from the sensors mentioned above can be recorded several different ways: All data can be recorded on magnetic tape on an analog FM instrumentation recorder, but this usually is a waste of the recording capacity. All slowly varying environmental variables are already digitized by the portable weather station, and these digitized data can be collected every five minutes by a portable lap-top computer with a battery backed-up CMOS memory which records them on magnetic media once in every 12 hours or more. The output of the microphones can be recorded on an ordinary long playing cassette recorder which can record 14 hours of sound on C180 tape. Figure 2 shows a 12 hour version of such a recorder. Two of the illustrated recorders will cover an unattended period of 12 hours.

The signals which should be recorded with care are the outputs of the seismometers and the geophones. The recording device should have enough dynamic range to cover the expected variations in the signal levels. By using seismometers and geophones, the requirement on the dynamic ranges of the recording instruments are somewhat relaxed since the frequency bands of the sensors are significantly different and the signal levels are not expected to vary more than 60 db for any reasonable seismic disturbance short of earthquakes.

The outputs of the four seismometers can be recorded on an analog FM instrumentation recorder for about a week on a spool of 2400 ft magnetic tape and it is possible to get an instrumentation recorder with about 60 db of dynamic range. The problem will be the output of the geophones because of their higher frequency response. If their output is band-limited from 5 Hz to 100 Hz, then it will be possible to record them continuously on an instrumentation recorder for about 12 hours.

The digital storage of data is only possible for short periods of time due to the storage-capacity available in the field with battery powered equipment. The data can also be taken by spectrum analyzers but this method is not preferred since it does not give a continuous time domain data which is essential in identifying transients and correlations.

## IV.c. Power Sources and Other Support Devices

All sensors, associated amplifiers and the recording equipment must be battery powered initially. As the receiver location is developed, continuous power will be brought to the site which will relax the power consumption requirements on the seismic survey equipment. For the initial phase I propose that the equipment should be powered with two high capacity banks of car batteries. One of the banks will power the equipment on the site for 12 hours while the other bank is removed from the site and charged at a remote location. The banks will be switched when the equipment is serviced every 12 hours.

The recording equipment will have to be protected from the elements by a suitable tent with enough ventilation to remove the equipment generated or the environmental heat. In winter, the equipment may need to be heated to keep them functional especially on the east coast. These will put additional demands on the power requirements.

## V. Calibration

### V.a. Laboratory Calibration

Just before and just after a measurement session all sensors and their associated amplifiers should be calibrated. In the laboratory the seismometers and the geophones should be calibrated by placing them on an seismic isolation stack and by actively shaking the stack while comparing the sensor outputs with another calibrated motion sensitive device.

The motion sensitive device can either be an accelerometer or the motion of the base of the seismometers can be measured by a suitable optical arrangement as shown in figure 3. The light beam from a stationary laser hits a suitably oriented prism and reflects back into a quadrant-diode which gives a read-out of the position of the laser beam. The prism is oriented in such a way that small tilts will have no effect on the position of the beam to first order. This arrangement gives a direct read-out of the displacement of the base of the seismometer. This calibration procedure should be repeated at several different frequencies within the usable band-width of the instrument.

Extreme care should be taken to stop the acoustic noise from contaminating the calibration procedure. The seismometers and the geophones are extremely sensitive to acoustic pick-up. They will have to be isolated acoustically during the calibration procedure. Ideally one would like to perform these measurements in vacuum, however almost none of these devices are likely to be vacuum compatible.

Another important quantity which should be measured is the noise level in the sensors and the amplifiers. Again, during these measurements the seismometers and the geophones should be seismically and acoustically isolated and a recording of the noise level should be made using the same settings of the amplifiers that were used at the site. A separate measurement of the amplifier noise should also be made by terminating their inputs with the appropriate resistors. If the seismometers have a moving mass that can be locked, the noise level should also be recorded while the mass is locked and the seismometer is seismically and acoustically isolated.

### V.b. Field Calibration

Since a data taking session is expected to last a week, the sensors and the amplifiers can alter their characteristics due to a variety of reasons. Because of this it is essential that a field calibration is performed once every 24 hours. It is not possible to shake the seismometers and the geophones in a calibrated manner in the field. However the seismometers usually have a calibration coil built into them.

I propose that a signal with harmonics evenly distributed across the usable bandwidth of the seismometer should be applied to the calibration coil of the instrument and the output signal should be recorded for about a minute for several different amplitudes of the calibration signal. The amplitudes should be chosen so that there are several steps within the dynamic range of the recording instrument. Such a calibrator is known as a "comb calibrator". If the geophones have a similar arrangement a similar calibrator can be used with them as well.

The noise level of the amplifiers should also be recorded for similar periods of time by terminating their inputs with appropriate resistors. The weather station does not need to be calibrated during the measurement session. Its accuracy can be checked after the session has ended.

## VI. Sensor Placement in the Field

The seismometers and the geophones should be placed in three feet deep wells and the wells should be completely filled with soil. The horizontal and the vertical seismometers should be at the same depth unless a measurement of the depth dependence of the seismic disturbances is conducted.

This particular choice of depth is based on my experiences of the seismic survey of the JPL Test Facility in the Edwards Air Force Base. I took data both above and below ground in the service tunnels of the rocket engine test stands. These tunnels were typically covered with about 3 feet of soil and this cover was providing enough acoustic isolation from jet aircraft noise. It is also relatively easy to dig a three-feet-deep well that can accommodate the horizontal seismometers since they usually have a larger horizontal extent than the vertical ones.

## VII. General

An accurate field log-book of the measurements should be kept. Photographs of the measurement location containing some identifiable references should be taken. The sensor placement should also be pictured before and after the well is filled. A polaroid camera should be used in order to make sure that the exposures are adequately made. All power supplies, batteries and the recording devices should be checked for proper operation after they are set up in the field.

A test signal should be recorded on the recording devices and read back on a portable oscilloscope to assure the proper operation of the recorders. The amplifier settings should be checked to make sure that the signal is above the instrument noise by a comfortable margin and its level is within the dynamic range of the recorders with enough headroom. If a spectrum analyzer that can be carried to the field is available it will make these checks much easier. These devices consume a lot of power however.

## VIII. Analysis

The detailed analysis of the collected data will depend on what is encountered in the data. In this section I will outline some general procedures that will carry the data analysis down to the individual events that will have to be understood. The analysis of such events will have to rely on the information which is extracted from the data by the procedures above and on other bits of information that is collected about the site.

First of all a crude review of the signals will be needed in order to decide which sections of the recorded data may have to be discarded or which sections may need a closer look. This can be accomplished in several ways. I propose the following two methods: The signals after being suitably filtered can be played into a multi-channel chart recorder.

This recording on paper will indicate which sections of the data were exceeding the dynamic range of the recording instruments and which sections were exceptionally quiet or noisy.

It will also be possible to see some correlations between the different recorded signals. The field calibration procedures will be easily identifiable by their timing and signature. Interesting transients will be immediately visible. The chart speed of the multi-channel recorder can be changed to compress the data to examine trends.

The disadvantage of this method is that the signals may vary too much causing the chart recorder traces to become too crowded to distinguish any trends. One way to overcome this is to look at the root-mean-square of the signals integrated for relatively short time periods within a given bandwidth. Both of these methods have been used in analyzing the data from the previous site surveys.

It may also be useful to have some chart recorders running while the data collection is taking place. They will certainly indicate the troubled areas of the signal, and the settings of the instruments can be altered during the next service period to cover those times in a better way.

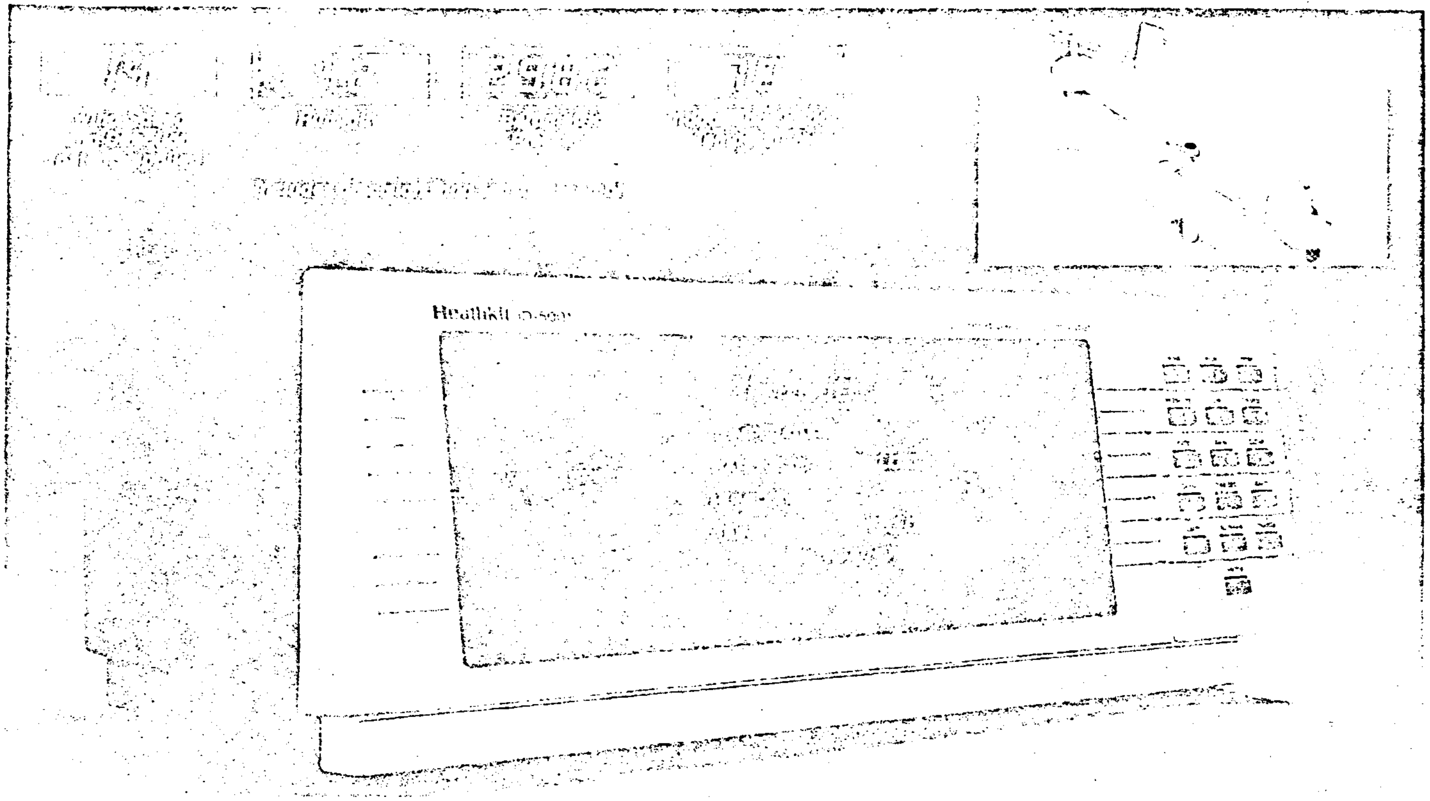
Once the "typical" sections of the data are identified in a several chosen times during the period of a day, these sections can be analyzed with a spectrum analyzer to determine the frequency distribution of the "typical" ambient seismic noise level. A comparison of these spectra corresponding to different times will show the hourly and daily variations in the seismic noise. Such spectra can then be averaged to get a "weekly" spectrum which can be compared with other weekly spectra to determine other large-time-scale variations in the seismic noise levels.

The "typical" spectrum of the site may show a different distribution of energy in the frequency bands than spectra taken in another site. The importance of such differences depends very much on the amplitude of the seismic noise and the frequency band of the region which exhibits these. If they are significant, in the sense that the design of the instrument needs to be altered because of them, then it may be worth while to determine the causes of such differences. The data collected about the environment and other existing data about the site may be instrumental in resolving these issues.

The causes of transient signals may have to be determined if they are of significant amplitude and if they are frequent enough to make a major impact on the design of the ligo receivers. The transients can easily be identified from the chart recorder signals and they can be individually spectrum analyzed to determine their causes. Again the data recorded about the environment will be an invaluable tool in this analysis.

An interesting variety of the transients may involve atmospheric phenomena coupling to the ground through the irregularities of the surface at the site and through the vegetation that surrounds the site. The data recorded with separated seismometers and the weather station will be able to answer this question.

The transient signals which are caused by the "cultural activity" in and around the site should be carefully tracked to determine their impact on the instrument design. Even if they are identified, it may not be possible to eliminate them completely.



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can easily be modified
for battery operation.

Figure 1(a)

Figure 1(b)

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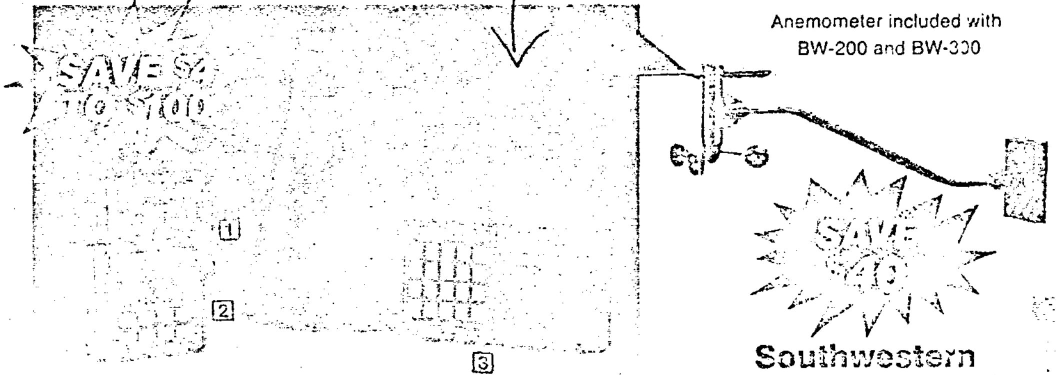

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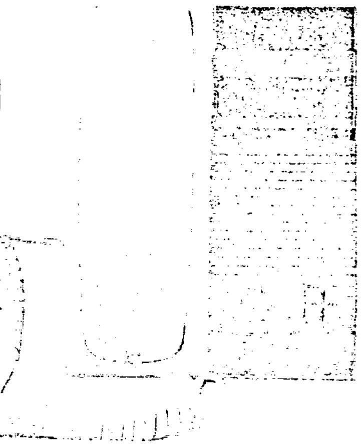

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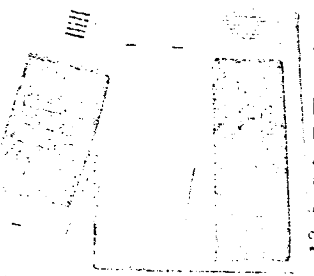

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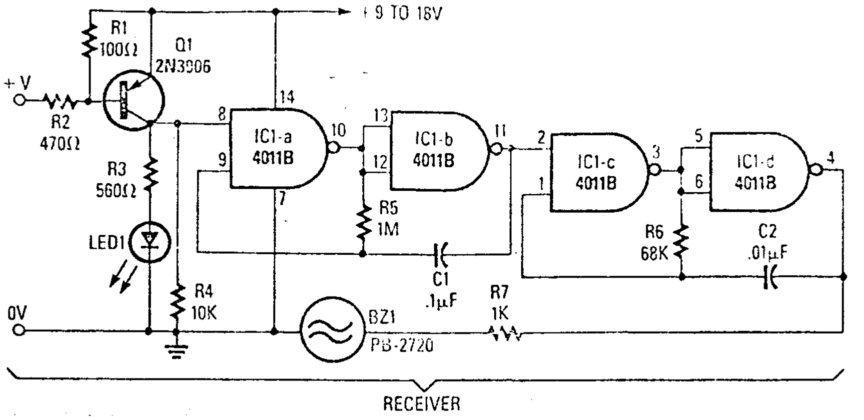


**FIG. 18—AN AUDIO-VISUAL output indicator that turns on an LED and sounds a buzzer can be connected directly to any one of the circuits in Figs. 15 to 18.**

switches high turning Q1 on. At that point, the circuit draws enough current to activate D2, which pulls the 3140's supply voltage down to 4.7 volts. The supply current then rises to between 8 and 25 mA (depending on Q2's supply-voltage value), and the resulting drop across R1 turns Q2 on, which activates the output indicator. It can now be seen how the positive supply line of the 2-wire system also carries the "state" information. Note that, in order for the circuit to operate properly, the minimum supply voltage must be at least 2 volts greater than $V_{REF}$.

In most applications for the type of circuit in Fig. 15, a half-supply reference voltage is applied to one input of the comparator, and a variable voltage is applied to the other input. That variable input is usually obtained from a Wheatstone-bridge network in which one of the elements is a resistive transducer that is sensitive to light, heat, pressure, etc. Because the variable input is bridge-derived, the "trigger point" of the circuit is independent of the supply-voltage value and is determined only by the resistance ratio of the input bridge.

In figures 16 and 17, only the transmitter portion of the circuit is shown. That is because all of the circuits can use the receiver in Fig. 15.

Figure 16 is a light-sensitive transmitter circuit in which a cadmium-sulphide photocell or *L*ight-*S*ensitive *R*esistor (LSR) is used as the sensing element. The potentiometer (R3) and the LSR (R4) should have nominal values of at least 10K. In Fig. 16, the LSR is wired above R3. Consequently, the voltage at pin 3 rises as the light intensity increases and the LSR's resistance falls; that circuit can be referred to as a light-sensitive transmitter. If the LSR were to be wired below R3, the voltage at pin 3 would rise as the light intensity decreases and the LSR's resistance would increase; the circuit would then be referred to as a dark-sensitive transmitter. In both configurations, the light level at which the circuits become active can be preset via R3.

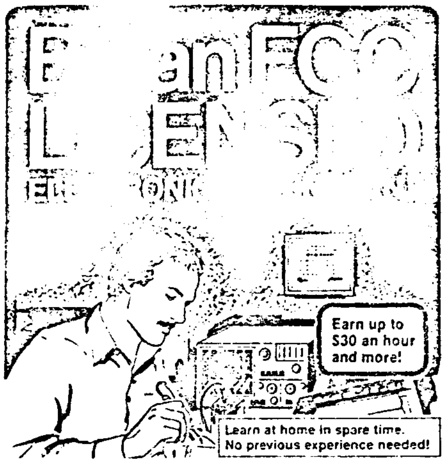
The circuit in Figure 16 can easily be modified to be sensitive to temperature rather than light. By replacing the light-sensitive resistor with a *N*egative-*T*emperature-*C*oefficient (NTC) thermistor (nominal value 10K), the first configuration would become an over-temperature transmitter, and the second configuration would become an under-temperature transmitter. Of course, the temperature at which the circuits would become active could be preset via R3.

Figure 17 shows a circuit that has a high output when the level of a liquid exceeds a pre-set level. When the liquid level is below the probe's tip, pin 2 of the op-amp is pulled above pin 3, and the op-amp's output is low. When the liquid reaches the probe, the liquid's resistance pulls pin 2 below pin 3 and the op-amp's output switches high. With R3's value as shown, the liquid's resistance between the probe and the container must be less than 3.3 megohms for correct operation.

Finally, Fig. 18 is an audio-visual output indicator that can be used with any of the circuits that are in Figs. 15–17. When a high output is detected from the transmitter, transistor Q1 turns on and its collector is pulled high, simultaneously driving LED1 on via R3 and activating IC1, which produces a pulsed tone in the buzzer BZ1.

R-E

Figure 2 →



# Seismometer Calibrator

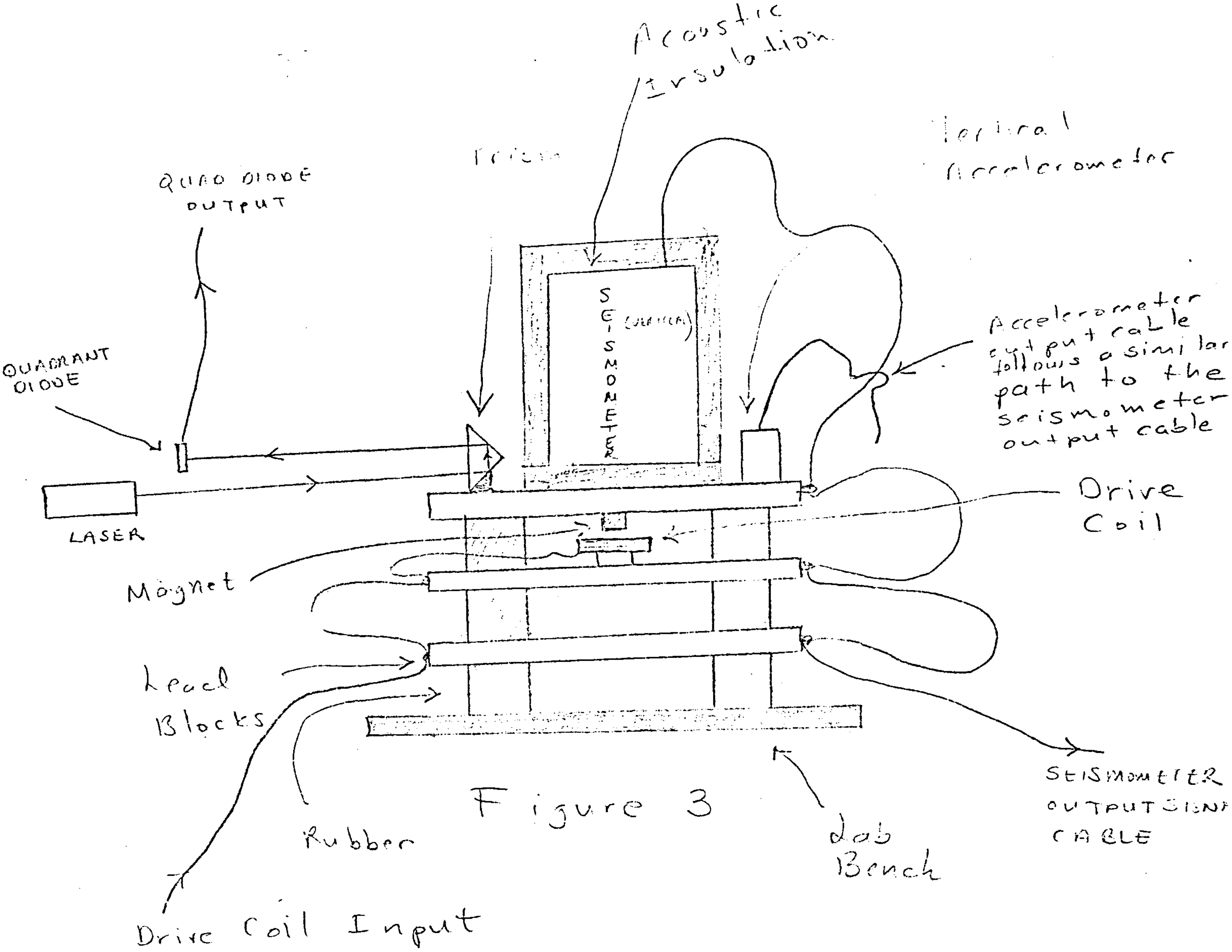


Figure 3

The number of stacks should be chosen to reduce the ambient seismic noise at top of the stack below the instrument noise.