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# Self-Noise Spectra for 34 Common Electromagnetic Seismometer/Preamplifier Pairs


## Peter W. Rodgers



## Abstract

Because of a lack of such information, computed self-noise spectra are presented for a total of 34 frequently used electromagnetic-seismometer / preamplifier combinations. For convenience, most of these data are given in three sets of units. Peterson's Low Noise Model is included on each plot for comparison. The self-noises of nine frequently employed electromagnetic (EM) seismometers properly matched to their operational amplifier (op-amp) preamplifiers are plotted. In terms of amplitude density spectra in (m / s**2) / Hz**0.5, the values of the self-noise spectra at resonance range from a low of $3 \times 10^{-10}$ for the GS-13, to a high of $1.3 \times 10^{-8}$ for the HS-1. Between these two seismometers, in order of increasing noise at resonance, are the SV-1, SL-210V, S-13, SS-1, L-4C, S-6000CD, and the L-22D.

In order to show which seismometers exhibit the lowest noise with which operational amplifier preamplifiers, the self-noises of the HS-1, L-22D, L-4C, GS-13, SV-1, and SL-210V are plotted each paired with four commomly used op-amps: the LT1028, OP-227, OP-77, and the LT1012. For the GS-13, the LT1012 was the quietest. For the rest, the OP-227 was the best. For a given seismometer, the differences in self-noise between op-amps were frequently a factor of 2 or 3, and as large as 10 in one case. The use of these op-amps in the analog front ends of five current digital seismic recorders is discussed.


## Introduction

The dynamic range for an electromagnetic (E-M) seismometer in combination with its necessary electronic preamplifier is set at the high level by electrical, or sometimes mechanical, saturation (clipping), and at the lowest level by the self-noise (or noise-floor) of the seismometer/

preamplifier combination . So in order to determine the dynamic range, both of these quantities must be known. The upper, electrical saturation level can be obtained from the parameters in the preamplifier circuit; and the mechanical saturation level can be calculated from the manufacturers' data on the maximum displacement for the E-M seismometer. However, despite its importance, very little data is available on the lower level, self-noise of popular E-M seismometer / preamplifier combinations. This short note attempts to alleviate this situation by providing calculated generalized self-noise data for nine frequently used E-M seismometers coupled with representative preamplifiers. Another use for this self-noise data is to ascertain whether a particular seismometer / preamplifier is suitable for resolving pre-event noise or low-level signals at a particular seismic site. In addition, the self-noises resulting from the use of each of six seismometers with four operational amplifiers (op-amps) commonly used in seismic recorders are compared.

## Self-Noise Model for an E-M Seismometer / Single-Ended Preamplifier Pair

A generalized model for the Signal-to-Noise Ratio (SNR) referred to the input for an E-M seismometer operating into a single-ended preamplifier is given by Rodgers (1992, Part 1), and Rodgers (1993). This model is repeated in equation (1) below in slightly different form by the substitutions $\omega = 2\pi f$ and $\Omega = 2\pi f_o$ :

$$\mathrm{SNR} = \frac{\left(\frac{r_d}{r_c + r_d} G\right)^2 \frac{4\pi^2 f^2}{(16\pi^4)(f_o^2 - f^2)^2 + 64\pi^4 \zeta^2 f_o^2 f^2} P_{aa}}{E_{nn} + \left(\left[\frac{r_d}{r_c + r_d} G\right]^2 \frac{4\pi^2 f^2}{[16\pi^4][f_o^2 - f^2]^2 + 64\pi^4 \zeta^2 f_o^2 f^2}\right) S_{nn}} \quad . \tag{1}$$

$P_{aa}$ is the acceleration power density spectra (acceleration pds) of the input acceleration, $E_{nn}$ is the generalized pds of the total electronic noise associated with the seismometer and preamplifier, and $S_{nn}$ is the pds of the suspension noise from the seismometer. The derivation and exact form for $E_{nn}$ and the form for $S_{nn}$ are given in the two papers referenced previously. The other terms in equation (1) are defined as follows:

$f$ = Frequency in Hz

$r_d$ = Damping resistor in ohms

$r_c$ = Coil resistance in ohms

G = Generator constant (open circuit) in V/m/sec

$f_o$ = Resonant frequency of the spring-mass system

$\zeta$ = Damping ratio

The expression for the SNR given in equation (1) is based on having the damping resistor in parallel with the seismometer together with a preamplifier employing an operational amplifier in the non-inverting configuration. This configuration is used because it results in a larger SNR than the other possible configurations, (Rodgers, 1993).

The self-noise referred to the input of the seismometer, $P_{nn.i}$, can be found from equation (1) as follows. Set the magnitude squared transfer function term of the seismometer equal to $|H(f)|^2$ :

$$|H(f)|^2 = \left[\frac{r_d}{r_c + r_d} G\right]^2 \frac{4\pi^2 f^2}{[16\pi^4][f_o^2 - f^2]^2 + 64\pi^4 \zeta^2 f_o^2 f^2} \quad \frac{V^2 / Hz}{(m/s^2)^2 / Hz} . \tag{2}$$

Then equation (1) becomes:

$$SNR = \frac{|H(f)|^2 P_{aa}}{E_{nn} + |H(f)|^2 S_{nn}} \tag{3}$$

The SNR referred to the input of the seismometer is obtained by dividing numerator and denominator by $|H(f)|^2$ .

$$SNR_{input} = \frac{P_{aa}}{\frac{E_{nn}}{|H(f)|^2} + S_{nn}} . \tag{4}$$

But since

$$SNR_{input} = \frac{P_{ss.i}}{P_{nn.i}} , \tag{5}$$

it is clear that the signal referred to the input, $P_{ss.i}$, is given by the numerator of equation (4) and equals $P_{aa}$. Similarly, the noise referred to the input, $P_{nn.i}$, is given by the denominator of equation (4) :

$$P_{nn.i} = \frac{E_{nn}}{|H(f)|^2} + S_{nn} \qquad (m/s^2)^2 / Hz . \tag{6}$$

The units of all the quantities referred to the input are $(m/s^2)^2/Hz$.

Finally, substituting equation (2) into equation (6), the self-noise referred to the input is found to be:

$$P_{nn.i} = \frac{\left[4\pi^2\left(f_o^2 - f^2\right)\right]^2 + \left[8\pi\zeta f_o f\right]^2}{(2\pi)^2\left[\frac{r_d}{r_c + r_d}G\right]^2 \cdot f^2} \cdot E_{nn} + S_{nn} \qquad (m/s^2)^2/Hz \ . \tag{7}$$

The suspension noise, $S_{nn}$, is given by:

$$S_{nn} = 16\pi\frac{kT\zeta f_o}{M} \qquad (m/s^2)^2/Hz \ , \tag{8}$$

where k is Boltzmann's constant and T is the room temperature in degrees Kelvin.

The generalized total electronic noise, $E_{nn}$, is:

$$E_{nn} = V_{oo}\left(\frac{f_{cv}}{f} + 1\right) + I_{oo}\left(\frac{f_{ci}}{f} + 1\right)r_p^2 + 4kTr_p \qquad V^2/Hz \ . \tag{9}$$

In equation (9), $r_p$ is the parallel combination of $r_c$ and $r_d$. The two resistances which set the gain of the operational amplifier based preamplifier are assumed to be of low values compared to $r_p$ and thus do not appear in $E_{nn}$. This is the proper strategy to follow to achieve minimum electronic noise. It may be difficult to achieve with a low-resistance seismometer but it serves well as a limiting case here permitting a generalized form for $E_{nn}$. $V_{oo}$ and $I_{oo}$ are the high-frequency levels of the op-amp voltage and current noise pds's respectively. The corner frequencies for the voltage and current noise pds's are $f_{cv}$ and $f_{ci}$, respectively. As mentioned earlier, complete details regarding $S_{nn}$ and $E_{nn}$, and the SNR's for various seismometer and circuit configurations are given in the two previously cited papers.

## Seismometer and Amplifier Parameters

The instrumental parameters for the nine common E-M seismometers being considered are given in Table 1, ordered in terms of resonant frequency. They range from the Oyo-Geospace HS-1 geophone to the long-period Teledyne-Geotech SL-210V and SL-220H. Four out of the nine seismometers treated have 1-Hz resonant frequencies.

Two different operational amplifiers are used in these calculations, the high Noise Resistance Linear Technology LT1012 for the high coil resistance GS-13, and the lower Noise Resistance Precision Monolithics OP-27 for the remaining lower coil resistance seismometers. Noise Resistance, $R_n$, is defined as the ratio of the voltage noise pds, $V_{nn}$, to the current noise pds, $I_{nn}$. The noise data on the LT1012 and the OP-27 operational amplifiers are given in Table 2. They are a good but not exact match to the seismometers. It is shown in Rodgers (1993) how to exactly match the operational amplifier and seismometer to achieve the maximum SNR over the entire passband, which requires a FET-based or FET-like op-amp. Despite the fact that the bipolar LT1012 and OP-27 cannot do this, they are used for these computations because they represent the common current practice, and so are felt to make the self-noise data more useful.

## Plots of Self-Noise Spectra

Using equation (7) together with equations (8) and (9), the self-noise spectra referred to the input are computed for the nine seismometers listed in Table 1. The nine self-noise spectra are shown in Figures (1) and (2). In Figure (1), the spectra are given as spectral densities (per Hz). In order to increase the utility of the data, the same curves are given in three different sets of units: amplitude density spectra in (m / s**2) / Hz**0.5, power density spectra in (m / s**2)**2 / Hz, and in decibels re 1 (m / s**2) / Hz**0.5 for the amplitude density spectra and re (m / s**2)**2 / Hz for the power density spectra (pds). Because of the definition of decibels, this results in the same numerical dB value for both sets of units. The dB values are given on the right-hand scale of Figure 1. Peterson's Low Model, labeled LNM (Peterson, 1982; Peterson and Hutt, 1982; Peterson and Tilgner, 1985; Peterson and Hutt, 1989), is included for comparison purposes. All of the self-noise curves have a vee shape with a minimum at the resonant frequency, $f_o$, of the seismometer. The reason for this can be seen in equation (6), which shows that the shape of $P_{nn,i}$ results from dividing the relatively constant noise term, $E_{nn}$, by the magnitude squared transfer function term, $|H(f)|^2$ , which has the shape of an inverted vee with a maximum at $f_o$.

Because Figures 1 and 2 contain so many curves , self-noise data on some of the horizontal components were omitted because they were nearly identical to those of the vertical components. The omitted horizontal components are the Kinemetrics SH-1 and the Teledyne-Geotech SL-220H. In addition, the self-noises of the Kinemetrics SS-1 and the Mark Products L-4C were very similar and are shown as one curve. Actually, the SS-1 is about 20% less noisy than the L-4C. The levels of the nine self-noise curves are as expected, with the weak motion seismometers being the quietest and the noise levels rising as the curves progress toward the higher frequency, lower generator constant geophones.

In order to give the self-noise data in real (non spectral density) units, the data in Figure 1 is presented again in Figure 2 in rms meters in a one-half octave bandwidth. This conversion uses the relationship (Aki and Richards, 1980):

$$\text{rms} = \sqrt{2 \cdot BW(f) \cdot P_{nn.i}} \quad , \qquad (10)$$

where the expression for the bandwidth, BW(f), is given by equation (11) with n = 2, as

$$BW(f) = \left(2^{1/2n} - 2^{-1/2n}\right) \cdot f \; . \qquad (11)$$

Equation (11) corrects equation (2) in Rodgers (1992, Part 1).

The self-noise curves in Figure 2 are similar to those in Figure 1 but are rotated counter-clockwise by half a unit of slope due to the multiplication by the square root of f, which occurs when equation (11) is substituted into equation (10). The data from Figure (2) can be used to calculate the dynamic range of a particular seismometer / preamplifier pair as described at of the beginning of the paper. Because the upper clipping or saturation level is a zero-to-peak value, to determine the dynamic range, the self noise must also be put in the same units of zero-to-peak values. This can be done using equation (12) of Taylor (1981):

$$\text{zero-to-peak} = 3 \times \text{rms} \qquad (12)$$

## Self-Noise Model for an E-M Seismometer / Differential Preamplifier Pair

Seismic data recorders all use differential (double-ended) analog input stages in order to reject common mode signals. The self-noise model for an E-M seismometer differential preamplifier configuration is nearly the same as that for a single-ended configuration with only the total electronic noise being different. The total electronic noise, $E_{nn}$, for the differential preamplifier configuration is nearly twice that of the single-ended configuration (Rodgers, 1993). This can be seen from equation (9) where, for the differential configuration, $V_{oo}$ and $I_{oo}$ are doubled but $4kTr_p$ remains the same. However, in an actual circuit, the noise in the differential preamplifier is also reduced by its ability to reject common mode noise such as that picked up by connecting cables. The self-noises for six E-M seismometers operating into differential input stage preamplifiers using four different differential op-amps are computed using equation (9), in which the terms $V_{oo}$ and $I_{oo}$ in equation (7) are doubled.

Of the nine seismometers treated in the previous section, only six are considered here: the HS-1, L-22D, L-4C, GS-13, SV-1, and the SL-210V. The SS-1 is similar to the L-4C, and the S-13 is nearly the same as the GS-13 but with an amplitude density spectra self-noise level almost exactly twice that of the GS-13. The op-amps used in the computations are the Linear Technology LT1028 and LT1012 and the Precision Monolithics, Inc., (PMI) OP-227 and OP-77, both of which are differential op-amp pairs mounted on a single chip. Their noise parameters are given in Table 2. The PMI OP-227 is used in the analog input stage of the Refraction Technology REF TEK 72A-07. The PMI OP-77 is used in the input stages of the Teledyne-Geotech PDAS-100 and the USGS GEOS-I. The REF TEK Low Noise preamplifier module used with the REF TEK 72A-02 uses two LT1012's in a differential configuration (Menke *et al.*, 1992). The QPREAMP used for connecting E-M seismometers to the Quanterra, Inc., Quantagrator Q680 uses two OP-27's also in a differential configuration. Several recorders, such as the REF TEK 72A-02 and -06 and the Kinemetrics SSR-1, use the PMI AMP-01 differential op-amp in their input stage. The manufacturer, PMI, does not publish the current noise spectrum for this component, so the AMP-01 could not be included in these computations.

## Self-Noise Spectra for Six Seismometers with Four Op-Amps

Self-noise spectra for the HS-1, L-22D, and the L-4C paired with the LT1028, OP-227, OP-27, and the LT1012 op-amps are given in Figures 3(a), 3(b), and 3(c). The file names are given in the lower right-hand corner of the plots and are listed with the quietest on the bottom and the noisiest on top. The units are amplitude density spectra in (m / s**2) / Hz**0.5. Amplitude density spectra (ads) rather than power density spectra are used because ads relates directly to data amplitude. As in Figures (1) and (2), Peterson's Low Noise Model (labeled LNM) is included as a reference.

As shown in Figure 3(a), the HS-1 is quietest when paired with the OP-227 and noisiest with the LT1012. The reason for this is that the Noise Resistance of the LT1012 is much too high at all frequencies to match the 7.5 K-Ohm coil resistance of the HS-1. A detailed development and discussion of matching a seismometer and preamplifier to the achieve the maximum signal-to-noise ratio (SNR), and the lowest self-noise is given in Rodgers (1993). The L-22D and L-4C shown in Figures 3(b) and 3(c), respectively are also both quietest with the OP-227 but are noisiest with the very low Noise Resistance LT1028. The reason for this is that the mismatch with the very low Noise Resistance LT1028 is worse than the mismatch with the very high Noise Resistance LT1012. Both the L-22D and the L-4C are about 20% more noisy with the OP-77 than the OP-227.

A different situation is shown in Figure 4(a) for the very high coil resistance and generator constant GS-13. It has its lowest self-noise with the high Noise Resistance LT1012, although it is almost as quiet, with the OP-227 and OP-77. The self-noise spectra for the SV-1 are shown in Figure 4(b), in which it is seen that the comparative results are similar to those for the L-22D and L-4C, although the absolute self-noise levels are much lower.

Finally, the spectra in Figure 4(c) for the long period, low coil resistance SL-210V show that it is very much more quiet (by a factor of 3) with the OP-227 than the LT1012. Furthermore, the SL-210V is twice as quiet with the OP-227 as with either the LT1028 or the OP-77.

The conclusion to be drawn from Figures 3(a, b ,c) and 4(a, b, c) is that when connecting an E-M seismometer to a seismic recorder, for minimum noise it is important to consider the op-amp used in the analog front end of the recorder. The PMI OP-27 or OP-227 appear to be good general choices, except when using the GS-13.

## Acknowledgments

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## CAPTIONS

**Figure 1.** Calculated self-noise spectral densities, referred to the input, of nine electromagnetic seismometers are shown in three sets of units: amplitude density spectra in (m / s**2) / Hz**0.5, power density spectra in (m / s**2)**2 / Hz, and in decibels re one unit of each of the above two quantities. Peterson's LNM is included for comparison. The GS-13 is operating into the LT1012 op-amp. The remaining eight seismometers are operating into the PMI OP-27 op-amp. The op-amps are assumed to be in the non-inverting configuration with the damping resistors in parallel with the seismometer coil terminals.

**Figure 2.** Calculated self-noise spectra, referred to the input, for nine electromagnetic seismometers are given in rms meters in a one-half octave bandwidth. The curves are similar to those of Figure 1, but are rotated counter-clockwise by 1/2 a unit of slope because of the one-half octave bandwidth assumption. Peterson's LNM is included as in Figure 1. The GS-13 is operating into the LT1012 op-amp. The remaining eight seismometers are operating into the PMI OP-27 op-amp. The op-amps are assumed to be in the non-inverting configuration with the damping resistors in parallel with the seismometer coil terminals.

**Figure 3.** Calculated self-noise spectra for the HS-1, L-22D, and L-4C seismometers paired with the LT1028, OP-227, OP-77, and LT1012 operational amplifiers. The units are amplitude density spectra in (m / s**2) / Hz**0.5. The file names are ordered in terms of self-noise with the noisiest on the top. .Peterson's Low Noise Model (LNM) is included for comparison.

**Figure 4.** Calculated self-noise spectra for the GS-13, SV-1, and SL-210V seismometers paired with the LT1028, OP-227, OP-77, and LT1012 operational amplifiers. The units are amplitude density spectra in (m / s**2) / Hz**0.5. The file names are ordered in terms of self-noise with the noisiest on the top. Peterson's Low Noise Model (LNM) is included for comparison.

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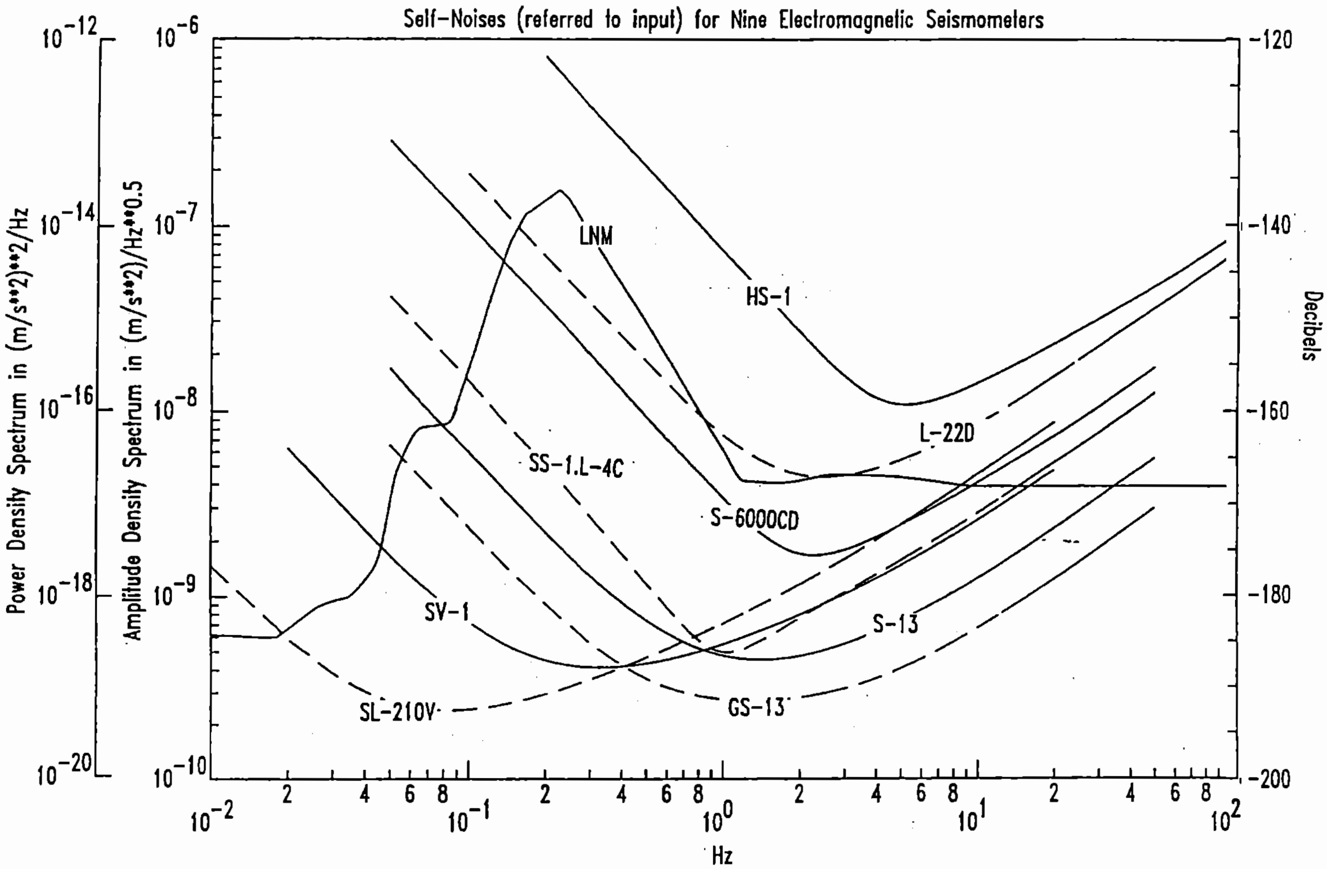
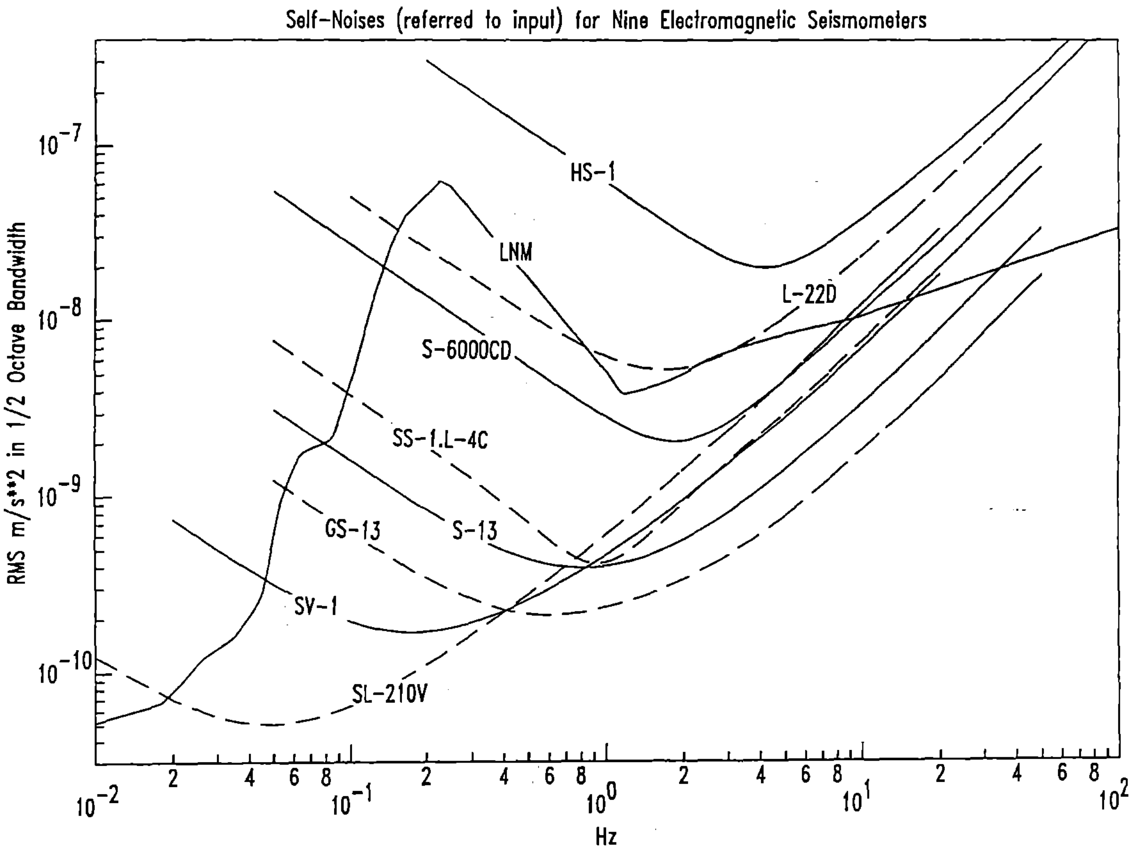


Self-Noises (referred to input) for Nine Electromagnetic Seismometers
Power Density Spectrum in (m/s**2)**2/Hz
Amplitude Density Spectrum in (m/s**2)/Hz**0.5
Decibels
Hz
LNM
HS-1
L-22D
SS-1,L-4C
S-6000CD
SV-1
S-13
GS-13
SL-210V


**Figure 1.**



Self-Noises (referred to input) for Nine Electromagnetic Seismometers
RMS m/s**2 in 1/2 Octave Bandwidth
Hz
HS-1
LNM
L-22D
S-6000CD
SS-1,L-4C
GS-13
S-13
SV-1
SL-210V


**Figure 2.**

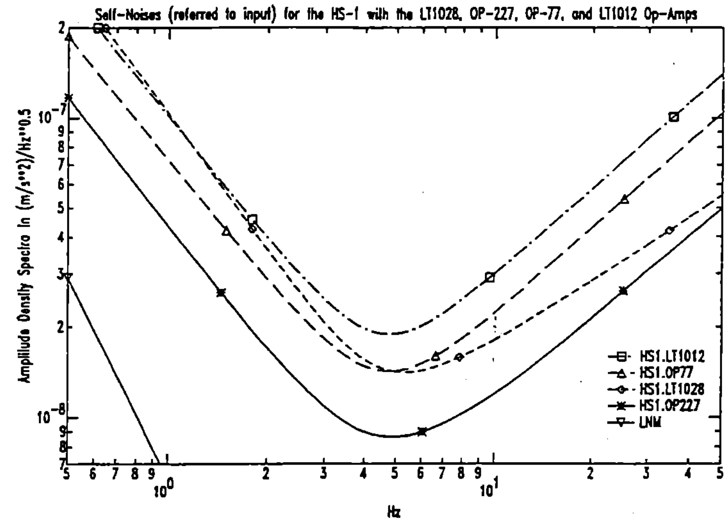



Figure 3(a)

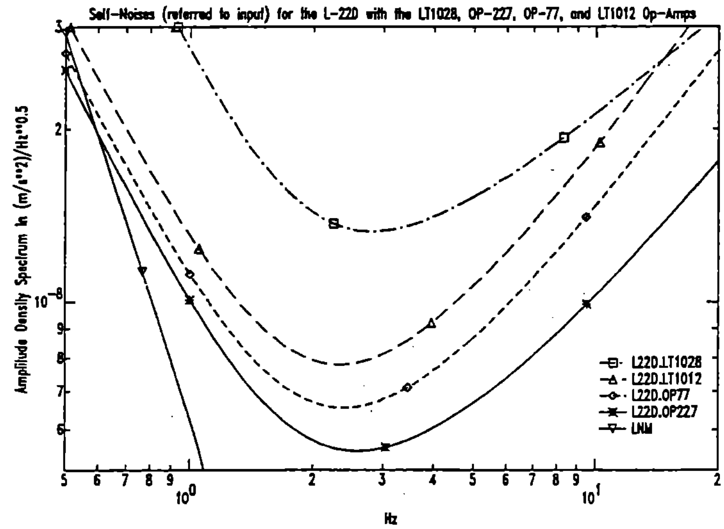



Figure 3(b)

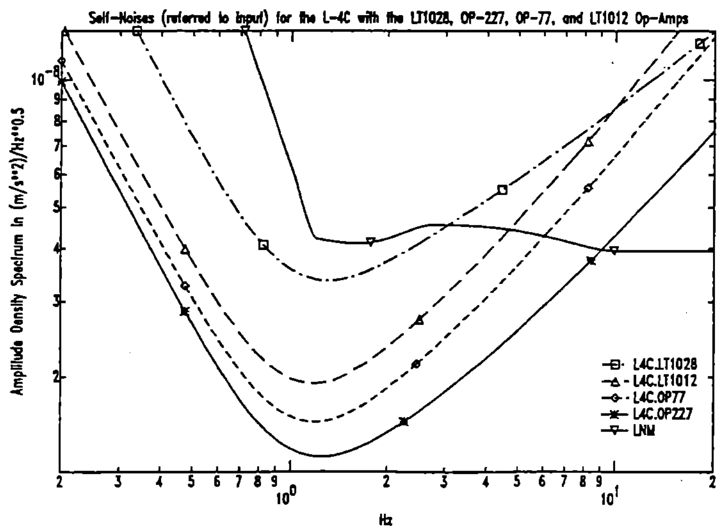



Figure 3(c)

**Figure 3.**

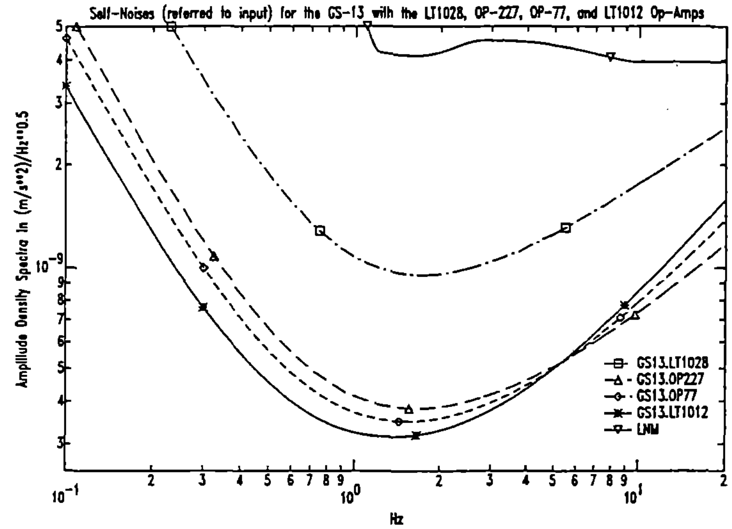



Figure 4(a)

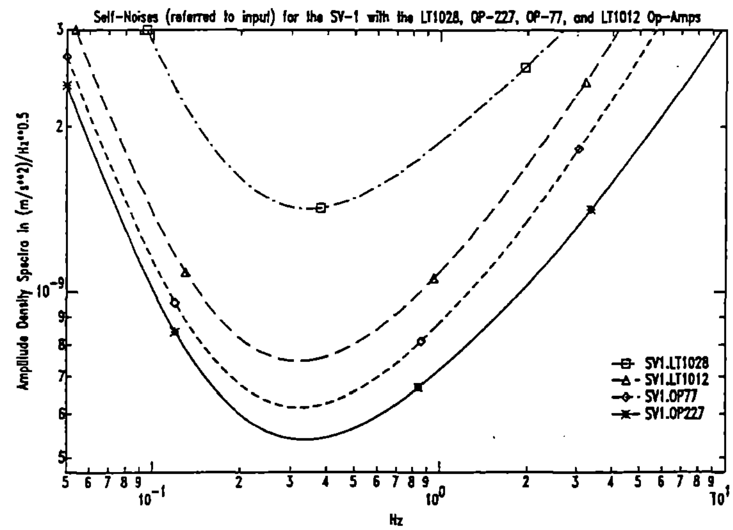



Figure 4(b)

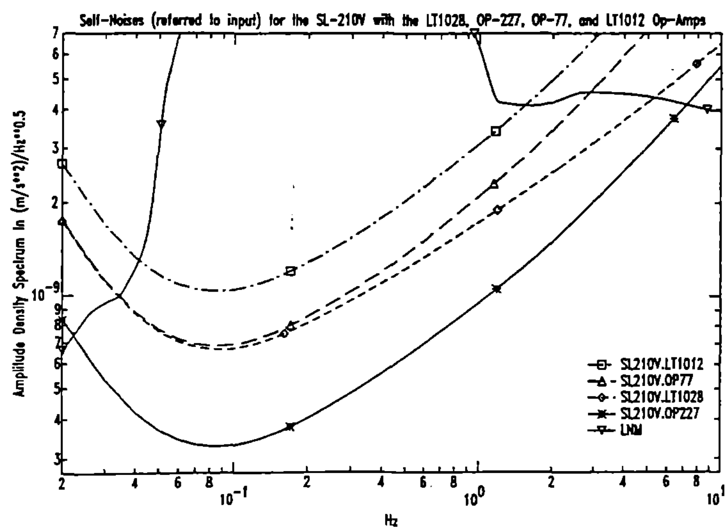



Figure 4(c)

**Figure 4.**