



Proceedings of the Guidelines for Seismometer Testing Workshop, Albuquerque, New Mexico, 9–10 May 2005 ("GST2")



Open-File Report 2009–1055

**U.S. Department of the Interior
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Suggested citation:

Hutt, C.R., Nigbor, R.L., and Evans, J.R., eds., 2009, Proceedings of the guidelines for seismometer testing workshop, Albuquerque, New Mexico, 9–10 May 2005 ("GST2");

U.S. Geological Survey Open-File Report, 2009–1055, 48 p.

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Cover photograph: Workshop attendees.

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Proceedings of the Guidelines for Seismometer Testing Workshop, Albuquerque, New Mexico, 9–10 May 2005 (“GST2”)

By Charles R. Hutt, Robert L. Nigbor, and John R. Evans, Editors

1 Preface

Testing and specification of seismic and earthquake-engineering sensors and recorders has been marked by significant variations in procedures and selected parameters. These variations cause difficulty in comparing such specifications and test results.

In July 1989, and again in May 2005, the U.S. Geological Survey hosted international public/private workshops with the goal of defining widely accepted guidelines for the testing of seismological inertial sensors, seismometers, and accelerometers. This document reports the *Proceedings* of the 2005 workshop and includes as Appendix 6 the report of the 1989 workshop.

In a future document, we will attempt to collate and rationalize a single set of formal guidelines for testing and specifying seismic sensors, supplementing Advanced National Seismic System (ANSS) guidelines on instrumentation likely used by ANSS as its standard for verification, acceptance, and intermittent testing, as well as for responses to ANSS instrument requisitions.

We thank Sandia National Laboratories and to the Incorporated Research Institutions for Seismology for providing funding and support, which made this workshop possible.

2 Workshop Purpose and Objectives

2.1 Purpose

The goal of the “GST2” workshop of May 2005, was to elicit a comprehensive set of guidelines for the testing and specification of seismological and earthquake-engineering inertial sensors. The USGS and ANSS plan to use these guidelines for purposes of requisitioning such sensors and monitoring their long-term viability.

2.2 Objectives

The objective of the first *Standards for Seismometer Testing* workshop in 1989 (“GST1”) is equally applicable to the 2005 workshop (“GST2”) so long as the word “Standards” is changed to “Guidelines”, to wit, “*to develop a set of recommended testing and reporting [guidelines] that may be used by seismometer manufacturers and instrumentation users.*” The present issue is how to achieve this objective. The GST2 workshop was convened with the intent of making

1. Using the GST1 standards draft created over 19–20 July 1989 as a starting point, the current workshop should review the conclusions of this earlier group and revise them as deemed necessary by technological developments during the intervening 15 years.

The current group should address and expand the items that the original group failed to resolve. These should include:

- A. Instrument noise — coherence based *versus* direct measurement. Discuss and form a study group, as suggested by GST1.
- B. Transfer Function — calibration coil, frame input, model fitting. Form a study group as suggested by GST1.
- C. Cross-Axis Coupling — Propose practical methods for testing.
- D. Orientation and component orthogonality (the latter is a new topic) — Propose practical methods for testing.
- E. Absolute mid-band sensitivity — compare shake table, stepping table, comparison to reference instruments and propose practical methods for measuring.
- F. Environmental sensitivity — sensitivity of instrument parameters to its environment (pressure changes, temperature changes, magnetic field variations, etc.).
- G. Stability — do the instrument's parameters change with time?
- H. Distortion and linearity — how to measure.

(For all items, a draft of the report to be due in one year from the workshop and shall include any research performed, the recommended test procedure(s), and the recommended reporting metrics, units, and possibly formats.)

Devote a day and a half (plus possibly an evening session) to this first portion of the meeting.

2. The final afternoon will be spent organizing future activities, including:
 - A. Create an e-mail list to keep attendees informed of standards activities. Study groups are asked to provide brief, monthly e-mail reports on the status of their project.
 - B. Form a two or three member group to write a GST2 meeting summary report detailing conclusions reached and ongoing activities and plans.
 - C. Form a two or three member group to manage and facilitate subsequent activities. This group may well be identical with the group mentioned under item 2(B).
 - D. Form a three to five member group to integrate the GST2 summary report plus the results from study groups into a final report (due 14 months after May 2005 = one year of study plus two months for writing). This group would then circulate this report within the sensor testing community for comment (two months) and finally publish it in the Bulletin of the Seismological Society of America (BSSA) or some other suitable journal or publication (two years after May 2005 = May 2007).

3 Working Group Reports

Four working groups were formed from the workshop participants. The following are the groups and their topics for discussion. The reports from these Working Groups are included in Appendixes C–F.

3.1 *Working Group I*

Jon **Berger**, Eric **Canuteson** (Chair), John **Evans**, Jim **Kerr**, Dick **Kromer**, Shane **Ingate**, Nathan **Pearce**, Reinoud **Sleeman**, Yuri **Starovoit**, and Rick **Schult**

- Self-noise measurement (coherence, direct calculation, etc.)
- Definition of bandwidth
- Distortion and linearity
- Clip level, dynamic range, bandwidth
- Analysis and reporting

3.2 *Working Group II*

Noel **Barstow**, Stephane **Cacho**, John **Collins**, Robin **Hayman**, Fred **Followill**, Elu **Martin**, Paul **Passmore**, and Erhard **Wielandt** (Chair)

- Transfer Function Measurement
- Absolute sensitivity measurement
- Analysis and reporting

3.3 *Working Group III*

Jim **Fowler** (Chair), Gary **Holcomb**, David **McClung**, Bruce **Pauly**, and Leo **Sandoval**

- Cross-axis coupling
- Orientation
- Orthogonality
- Analysis and reporting

3.4 *Working Group IV*

Igor **Abramovich**, Kent **Anderson**, Yang **Dake**, Jeanine **Gagnepain-Beyneix**, Takashi **Kunugi**, Peter **Melichar**, David **Mimoun**, Bob **Nigbor** (Chair), Selwyn **Sacks**, Al **Smith**, Michael **Thursby**, and Tom **VanZandt**

- Environmental sensitivity
- Sensitivity to power supply
- Stability — how often to calibrate?
- Reliability
- Analysis and reporting

4 Summary

The second Guidelines for Seismometer Testing Workshop (GST2) met in Albuquerque in May 2005, to elicit a comprehensive set of guidelines for the testing and specification of seismological and earthquake-engineering inertial sensors. The USGS and ANSS plan to use these guidelines for purposes of testing and characterizing such sensors, both in procuring them and monitoring their long-term viability.

The objective of GST2 was effectively the same as that of the first *Standards for Seismometer Testing* workshop in 1989 (GST1) so long as the word “standards” is changed to “guidelines”, to wit, “*to develop a set of recommended testing and reporting [guidelines] that may be used by seismometer manufacturers and instrumentation users.*”

GST2 was successful in attracting the participation of 42 interested seismic instrumentation specialists, including users from research, government, and treaty monitoring organizations, as well as 13 representatives from eight seismological-equipment manufacturers. Participants are listed in Appendix B. After presentations and general discussion, the participants formed four Working Groups that concentrated on specific aspects of seismometer testing and reporting guidelines. The Working Group reports (Appendixes C–F) provide a starting point upon which to base our final document, *Guidelines for Seismometer Testing*.

5 Recommendations

We recommend that a much smaller group, perhaps three to five individuals, be formed to draft these formal *Guidelines for Seismometer Testing*, based on the GST2 working group reports, ANSS instrumentation guidelines, and the earlier work of GST1. The editors will select from participants a list of group members to be *Guidelines* authors. We recommend that the *Guidelines* authors be chosen from among those GST2 participants for their range of skills and the willingness to commit to producing a draft document by March 2008.

6 Appendix A: Workshop Agenda

Guidelines for Seismometer Testing Workshop

9–10 May 2005

Albuquerque, New Mexico

Monday May 9 — Morning

- | | |
|-------------|---|
| 8:00–8:15 | Welcome and Introduction |
| 8:15–8:30 | C. R. Hutt — Review of 1989 Standards for Seismometer Testing |
| 8:30–9:00 | Presentation: L. Gary Holcomb (USGS/ASL)
“Direct Calculation of Seismometer Noise via Side-by-Side Comparison” |
| 9:00–9:30 | Presentation: Reinoud Sleeman (KNMI – Royal Netherlands Meteorological Institute)
“MCCA — Multi-Channel Coherency Analysis — A direct method to reliably estimate instrument noise and transfer function ratios” |
| 9:30–10:00 | Topical Discussion: Coherence based <i>vs.</i> direct calculation of instrument noise |
| 10:00–10:15 | Break |
| 10:15–10:45 | Presentation: Erhard Wielandt (Univ. of Stuttgart, retired)
"Absolute Calibration of Seismometers Using a Step Displacement Table" |
| 10:45–11:15 | Presentation: Bob Nigbor (UCLA) and John Evans (USGS)
"Testing, Calibration, and Qualification of Strong-Motion Seismometers: Why, What, When, How" |
| 11:15–11:45 | Presentation: Peter Melichar (ZAMG Austria)
"The Conrad Observatory: A New Geophysical Observatory in Austria" |
| 11:45–12:00 | Set agenda for technical discussions |

Monday May 9 — Afternoon

- | | |
|------------|---|
| 12:00–1:00 | Lunch (Restaurant in hotel) |
| 1:00–3:00 | Topical Discussions: <ul style="list-style-type: none">• Transfer Function — calibration coil, frame input, model fitting• Absolute mid-band sensitivity: Shake table, stepping table, comparison to reference instruments |
| 3:00–3:15 | Break |
| 3:15–5:00 | Topical Discussions: <ul style="list-style-type: none">• Cross-Axis Coupling — propose practical methods for testing• Orientation and component orthogonality |
| 5:00–7:00 | Dinner (Restaurant in hotel) |
| 7:00–8:30 | Evening Session: Continue topical discussions, ad hoc presentations (manufacturers, etc.) |

Tuesday May 10 — Morning

8:00–10:00 Topical Discussions:

- Environmental sensitivity: Sensitivity of instrument parameters to environment (pressure changes, temperature changes, magnetic field variations, etc.)
- Stability: Do the instrument's parameters change with time and exposure?
- Distortion and linearity
- Clip level, dynamic range, bandwidth

10:00–10:15 Break

10:15–12:00 Topical Discussions:

- For all parameters: How to measure? How to report?
- Test Categories:
 - Manufacturer
 - Laboratory
 - Field

Tuesday May 10 — Afternoon

12:00–1:00 Lunch (Restaurant in hotel)

1:00–3:00 Organize future activities

- Form study groups to work on focus topics.
- Create an e-mail list to keep attendees informed on standards activities.
- Form a small group to write a GST2 meeting summary report detailing conclusions reached and ongoing activities and plans.
- Form a two or three member group to manage future activities.
- Form a group to integrate the GST2 summary report plus the results from GST1 and the study groups into a final report. (Draft due 14 months after 09 May 2005. Circulate the report within the sensor testing community for comment (two months), and then publish it in the *BSSA* or some other suitable journal or publication by about May 2007).

3:00 Adjourn

6:30 Meet in lobby for ride to Cervantes Restaurant and Lounge (New Mexican cuisine)

Wednesday May 11 – Morning

8:00–12:00 ASL tour for those interested.

Assemble at 8:00 a.m. in the hotel lobby for van ride to ASL.

7 Appendix B: List of Participants

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8 Appendix C: Working Group I Report

8.1 *Report of WG I: Self-noise, bandwidth, distortion, linearity, clip level, dynamic range, bandwidth, analysis, and reporting*

Jon **Berger**, Eric **Canuteson** (Chair) , John **Evans**, Jim **Kerr**, Dick **Kromer**, Shane **Ingate**, Nathan **Pearce**, Reinoud **Sleeman**, Yuri **Starovoit**, and Rick **Schult**

1. Self-Noise: Measurement, Reporting, and Error Estimation

- 1.1. *Measurement.* The measurement of self-noise received considerable attention in the previous seismometer workshop and report (1990; Appendix G of this report). Although the measurement is much more difficult at long periods, there is no fundamental difference in measurement methodology between most weak-motion seismic sensor types.

However, most strong-motion sensors can be evaluated simply by recording their output under conditions known to have other sources of noise well below that of the sensors. In particular, (1) the site and recording interval must be known to have ambient Earth noise and other seismic signals well below the sensor's self-noise, and (2) the recorder must have self-noise also well below that of the sensor. This method has the advantage of easy execution and no reliance on relative sensor alignment. The "operating range" methods described in the GST1 report have been detailed and expanded somewhat by J.R. Evans, C.R. Hutt, J.M. Steim, and R.L. Nigbor (written commun., 2008), and their method is adopted as the standard for analysis of strong-motion sensor self-noise with potential to apply also to weak-motion sensors with some modifications.

For broadband weak-motion sensors, as was discussed in the 1990 report, there are several common methods for calculating self-noise. The most common is the two-sensor coherence method; Holcomb's (1989) direct method is an accepted standard of this type. A three-sensor coherence method, multi-channel coherency analysis (MCCA) was presented during the workshop and in detail by Sleeman and others (2006); while very promising, it was not yet considered mature enough to be used routinely. The working group decided that it was not appropriate to specify MCCA as a standard method at this time but has hopes that it will eventually become an accepted technique, particularly because it does not require identical sensor models or assumptions about any sensor's transfer function. The three-sensor technique extracts both the self-noise and the relative transfer functions from the measurements only, and does not require any a priori information about the transfer function of each channel.

In all of the coherence methods, relative sensor alignment (alignment of the true active axes under test with respect to one another) is critical. This need is particularly acute in the presence of high background noise. The best known method for sensor alignment is maximizing coherence (γ^2) through adjusting the alignment. For the most accurate measurements of self-noise, it is critical to perform such tests in a very low-noise environment such as a mined vault in a rural, inland area.

- 1.2. *Reporting.* Self-noise should be reported in SI units of root-mean-square (rms) amplitude (velocity or acceleration according to sensor type) and acceleration power spectral density as a function of frequency as described by J.R. Evans, C.R. Hutt, J.M. Steim, and R.L. Nigbor (written commun., 2008). As discussed below in section 2.1, self-noise should be reported from the upper frequency corner of the sensor down to 0.0002Hz (for broadband sensors) or 0.01Hz (strong-motion accelerometers).
- 1.3. *Error Estimation.* There was an extended discussion of the need for error bounds on coherence noise measurements. None of the common coherence estimates yields reliable error bounds (direct computation for strong-motion sensors can make a meaningful estimate from its requisite ensemble-averaging step). The working group believes that placing meaningful error bounds on the self-noise is an important, incompletely solved problem. At low frequencies, measured self-noise is highly dependent upon environmental conditions and testing procedures.

To check for numerical accuracy, all computational methods should be tested using a suitable synthetic input dataset with known power (for example, Gaussian noise, pure sine waves with DFT symmetry, etc.).

2. Bandwidth: Response, Out of Bandwidth Performance, and Reporting

Response. The Laplace transform representation of analog-sensor response (S -plane poles and zeros in rad/s plus a generator constant or equivalent normalization point) is sufficient to characterize frequency response. For digital devices, z -plane poles and zeros may be used instead.

However, bandwidth remains a widely used and desired specification in system definitions. As with any filter, bandwidth can be described as the approximately flat portion of the response curve. Broadband seismometers are bandpass filters, while accelerometers are typically low-pass filters. As bandpass filters, specifying the band between -3 -dB points is sufficient for broadband sensors and the -3 -dB upper corner frequency is sufficient for accelerometers; for open-loop velocity sensors, the pendulum's undamped natural frequency is sufficient for this purpose. Ripple tolerances of ± 3 dB are permissible; however, the amount ripple must be stated, in dB, if the sensor has a response that is not maximally smooth in the passband to within ± 1 dB of a Butterworth filter with the same corners.

- 2.1. *Out-of-Bandwidth Performance.* After considerable discussion, a consensus emerged that some performance information must be included for the out-of-band range. At a minimum, users require self-noise measurements to frequencies of 0.0002 Hz (5,000-s period) for broadband sensors and 0.01Hz (100 s) for strong-motion accelerometers. Furthermore, for all sensor types, the frequency of the lowest-frequency parasitic resonance must be specified.
- 2.2. *Reporting.* S -plane poles and zeros plus a generator constant or equivalent must be reported for analog sensors, and z -plane for digital-output sensors, along with the -3 dB frequencies for the upper and lower corners. Manufacturers should specify a ripple tolerance in the passband if it is not within ± 1 dB of a Butterworth filter with

3. Distortion and Linearity: Strong Motion, Broadband, Reporting

- 3.1. *Strong Motion.* Linearity measurements in strong-motion accelerometers are distinct from those in broadband, short-period seismometers, and strong-motion velocity seismometers. A common test for accelerometers is a $\pm 90^\circ$ tilt test ($\pm 1 g_{local}$), with the nonlinearity expressed as the worst error relative to a linear best fit, as a percentage of the 1-g applied signal. (Although sine or polynomial fits are alternative methods for representing nonlinearity, these are normally of benefit only in applications for which the data will be corrected for these nonlinearities. Such corrections are uncommon in seismology and these techniques are not recommended.) Thus the preferred method of estimating static nonlinearity in accelerometers is a linear fit to input acceleration (preferably with a minimum-likelihood or L1 fit) in a tilt-table measurement of at least nine widely distributed acceleration values spanning $\pm 1 g_{local}$, where the active axis of the accelerometer is very carefully aligned to the tilt axis of the table so as to minimize the apparent error, thus isolating the true nonlinearity of the sensor from sensor-misalignment errors. If available, a low-noise centrifuge can be used to extend this linearity test to the limits of the sensor; this is the preferred technique.

(We note that there are small, several parts per thousand (PPT), differences between g_{local} and $g_{standard}$, which are at the limit of desired precision, <10 PPT, and therefore might contribute apparent errors in absolute sensitivities. Reports therefore should be corrected to $g_{standard}$, 9.80665 m/s^2)

The measurement of total harmonic distortion (THD) is worthwhile for an accelerometer, even if it can only be measured (inferentially and inaccurately) using the calibration input to the sensor. The measurement is made by injecting one or more low-distortion sine tones into the calibration input and measuring the ratio of the power in the first ten harmonics (or mixing products) to the power in the fundamental. Care must be taken to select a source that is highly pure.

For strong-motion sensors, ASL has had success with direct THD tests to -40 dB or better by using a very quiet shake table excited by a very pure sine-wave generator whose frequency is set to be near the table's fundamental frequency. This direct method should be used at least as a complement to excitation *via* the calibration-signal inputs.

In addition to these tests, we recommend that attention be given to developing a standard test for detecting undesirable baseline hysteresis and "popcorn" noise in strong-motion sensors subjected to dynamic loads. Many users have indicated that offsets are present in their strong-motion records and that these are very disruptive to the computation of displacements, in turn critical in strong-motion studies. The simplest proposed test of baseline hysteresis would involve repeatedly, alternately driving the sensor to positive or negative 1 g, then placing it on a precisely level, flat-ground surface (0 g) and measuring the sensor's ability to return precisely to baseline. A more repeatable version of this test would be to repeatedly shake then hold the sensor on a shake table. A viable form of this test may be to input a single cycle of

one-sided cosine beginning and ending smoothly at 0 g, centering and gently clamping the table at a precisely repeatable position and orientation, and measuring the sensor's output between each interval of shaking. By alternating the polarity of the acceleration between each measurement, the hysteresis of the rest state can be determined. In addition to being repeatable, this method also can exceed ± 1 g, driving the sensor closer to its clipping limit.

Finally, a particularly sensitive and thoroughgoing test of strong-motion sensor performance is to inject well controlled signal(s), such as a band-limited displacement square wave of known amplitude, by way of a stable shake table, integrating sensor output to displacement and comparing with the input signal. Baseline offsets, nonlinearities, distortions, and other problems with a sensor are strongly emphasized by this test. The greatest difficulty is obtaining a shake table of sufficient straightness and fidelity, since all faults in the table are also emphasized. Therefore the most likely candidate is a vertical shake table on air bearings; however, these are very costly. Some success has been achieved at ASL by using a precision linear slide (supported on cross-roller bearings) driven by a linear electric motor and using optical displacement sensors for feedback. Tilt errors in this table are high-order polynomial in form and generally can be distinguished from any unacceptable sensor processes. Finally, this table may be turned vertical and supported by constant-force spring motors, which should obviate the effects of these small imperfections in straightness and level.

- 3.2. *Broadband.* The standard measurement of linearity in broadband sensors is a two-tone test at 1.00 Hz and 1.02 Hz, with the signals injected into the calibration system. The difference frequency (0.02 Hz) is typically 80 to 115 dB below the input tones. This method remains the standard, with a recommended standard of -80 dB or better. Additionally, a new method was proposed by Shane Ingate that would involve stimulating with calibration coil with random binary inputs while adjusting the mass offset across the full range of the sensor in order to explore linearity when the mass is not well centered. This method is worthy of further study.

As with accelerometers, Erhard Wielandt and Lennartz have provided a means of applying a well-controlled vertical step to broadband sensors, integrating vertical-sensor output to displacement and comparing to the known input amplitude. As with doubly integrating accelerometer outputs from known signals, this single-integration test verifies many aspects of performance for Z, or U, V, and W components and is recommended. A similar test using the tilt-arm attachments to the Wielandt/Lennartz lift table are effective tests for horizontal components of broadband sensors.

- 3.3. *Reporting.* For broadband sensors, the two-tone test results should be reported in dB relative to the input tones' power. Seismic accelerometer testing should yield the total nonlinearity as a percentage of full-scale and total harmonic distortion (THD) in dB relative to the excitation-tone power. Integrating outputs for known, usually step, inputs should be reported as fractional errors in displacement amplitudes and illustrations of input and output displacement waveforms. A more quantitative statement of waveform fidelity is desirable and an area of further research.

4. Clip Level and Dynamic Range: Discussion and Reporting

- 4.1. *Discussion.* There was consensus that a half-octave bandwidth is the most appropriate interval on which to standardize rms amplitude comparisons between noise and the rms of a just-clipping sine wave. The comparison between the integrated self-noise power over half-octaves (expressed as rms, m/s^2) and the rms of a just-clipping sine wave is the standard expected by users.

This method was proposed in the GST1 report and is accepted by consensus here. J.R. Evans, C.R. Hutt, J.M. Steim, and R.L. Nigbor (written commun., 2008, draft manuscript in process) have precisely defined this method (including PSD computation method, sample rates, and sample durations) and have extended it to also provide an rms spectral density as a formal, detailed statement of self-noise. We recommend this method for standard analysis and reporting.

Note that dynamic range cannot be represented as a ratio of clip level to power spectral density.

- 4.2. *Reporting.* The standard graphical report should, at a minimum, show the half-octave self-noise (rms in m/s , for velocity sensors, and in m/s^2 for acceleration sensors) taken across the full sensor bandwidth, inclusive of the lower frequency bounds indicated above for out-of-band reporting. Such “ampORD” plots must include the clip level (rms of the just-clipping sine wave). (See, for example, Peterson and Hutt, 1989 and Steim, 1986.) A low-noise model must be included as well, selecting either or both the NLNM of Peterson (1993) or the GSN first-percentile model of Berger and others (2004).

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<http://earthquake.usgs.gov/regional/asl/>.
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Steim, J.M., 1986, The very-broad-band seismograph: PhD Dissertation, Harvard University, 184 p.

9 Appendix D: Working Group II Report

9.1 Report of WG II: Transfer function measurement, absolute sensitivity measurement, analysis, and reporting

Noel **Barstow**, Stephane **Cacho**, John **Collins**, Robin **Hayman**, Fred **Followill**, Elu **Martin**, Paul **Passmore**, and Erhard **Wielandt** (Chair)

Since procedures and reporting styles may differ between accelerometers and broadband seismometers, we treat the two instrument types separately. The transfer function of a seismic sensor depends not only on the sensor itself but also on how the ground motion is measured (as displacement, velocity, or acceleration). The natural choice is to refer the transfer function of accelerometers to ground acceleration and that of broadband seismometers to ground velocity so that the response is flat in the band of interest.

Generally, we want a mathematical description of the transfer function that describes the response at any frequency, not just a graph or table. The most commonly used (but not necessarily most intuitive) description is by poles and zeros, plus a generator constant or equivalent. The accuracy of a transfer function cannot, however, be expressed by that of its poles and zeros because these are non unique in practice and may have no significant effect on the response (for example, a zero may effectively cancel a nearby pole).

Broadband seismometers

Manufacturers' specifications

Deviation in sensor response is defined as the absolute value of the difference between the nominal and actual complex responses, divided by the nominal response, and therefore includes deviations of the phase as well as amplitude. The actual response of a broadband sensor should not deviate from the specified response by more than ± 10 percent or 1 dB from one-third of the lower corner frequency (or a specified lowest useful frequency) to mid-band; ± 5 percent or 0.5 dB at mid-band (this number reflects essentially the accuracy of the absolute calibration); ± 20 percent or 2 dB from mid-band to 10 Hz; ± 50 percent or 6 dB from 10 Hz to upper corner frequency (if any), or up to a specified highest useful frequency.

It is acceptable to use different mathematical models to represent the response in different parts of the band. The effect of high-frequency poles on the response at lower frequencies can usually be summarized as a constant delay. But the representation of the response should be continuous across the entire band.

The calibration sheet for any seismometer should describe the actual response to within one-third of the above percentage ranges. Users who need to know the actual response to greater accuracy will be responsible for carrying out their own calibration.

Measuring the frequency response

The frequency response is normally determined by applying suitable test signals to the calibration input of the sensor (which is in some instruments connected to a separate electromagnetic transducer or calibration coil, in others to the summing point of the feedback circuit). We rec-

commend that the digitized actual input be used rather than a mathematical representation of the input, so one does not have to rely on the precision of the signal source; almost any waveform can be used. Also, the response of the digitizer would otherwise be included in the transfer function, which is normally not desirable, and mathematically problematic. The parameters of the transfer function should be determined by fitting the theoretical response to the actual one with a least-squares criterion. Modeling in the time domain (see references) is preferable because it avoids the assumption of periodicity implicit in the discrete Fourier transformation.

As a test signal, a sine wave with a logarithmically swept frequency is especially efficient. Such a signal permits a visualization of the error between the theoretical and the actual responses both as a function of time and as a function of frequency, by simply plotting the residual *versus* time. The plot will also reveal nonlinear distortions.

Another frequently used type of test signal is pseudo-random binary or analog noise. The use of a periodic pseudo-random signal may reduce the importance of windowing and tapering, but the transient response of the sensor at the beginning of the test must still be excluded from the analysis if the latter is done in frequency domain.

While at low frequencies the theoretical equivalence between a current into an electromagnetic transducer and ground acceleration appears to be reasonably accurate, this may not be so at high frequencies. The high-frequency limits of this equivalence should be determined for each type of instrument on a shake table.

Remote measurement of the relative frequency response

For stations in the field, it is desirable to provide a remotely controlled signal source and the capability to record the calibration input signal, either on an additional digitizer channel or by remotely switching the input lines of existing channels¹. If neither is available, one may apply sine waves of varying frequency to the calibration input of the sensor. Even if these are not recorded, it is reasonable to expect that their amplitudes are independent of frequency.

Measuring the absolute sensitivity

We know of no shake table available at reasonable cost that can calibrate a seismometer the size of a broadband sensor over its complete band. At high frequencies, parasitic resonances are common while at low frequencies, tilt will couple gravity into the horizontal components of motion. However, at frequencies of around 1 Hz, a shake table can be used to measure the absolute sensitivity. (We use the word “sensitivity” in the meaning of responsivity, not resolution.) Alternatively, one can use a precision linear stage, a step table, or (for horizontal components) a tilt table. In the case of step-like signals, the method of evaluation should not depend on the time history of the motion but rather use the final positions.

References

Schuessler, H.W., 1981, A signal-processing approach to simulation: *Frequenz*, **35**, 174–184, (ISSN 0016-1136).

¹ An untested option is to connect the output of one sensor to the calibration input of another, and drive the first sensor with such a signal that its output signal has the desired characteristics. This would require only minor changes in the digitizer and avoid switching the sensitive digitizer inputs.

Bormann, P., ed., 2002, New Manual of Seismological Observatory Practice: GeoForschungsZentrum, Potsdam, chap. 5 (ISBN 3-9808780-0-7).

Lee, W.H.K. and others, eds., 2003, IASPEI International Handbook of Earthquake and Engineering Seismology, Elsevier, chap. 18 (ISBN 0-12-440658-0).

Accelerometers

Manufacturers' specifications

Two approaches are demanded by users. One approach is to trim the analog output to a sensitivity of 1 percent over the specified operating band. The other approach is to accept larger deviations from the nominal response but give the customer the precise calibration, accurate to 1 percent over the specified operating band.

Measuring the absolute sensitivity

The fact that the response extends down to static accelerations facilitates the calibration. Measure absolute sensitivity, and if possible linearity, using a static 180° or 360° precision rotation test. Alternatively, a precision linear stage or a step-response tilt table may be used. Present models generate accelerations in the order of 2 g.

Measuring the relative frequency response

Using a shake table, verify for a few sensors that frame input and calibration input generate the same output to the required accuracy, and then use the calibration input.

References

IEEE, 1999, Standard Specification Format Guide and Test Procedure: IEEE Std, **1293-1998**, April 16, 1999 (ISBN 07381-1429-4 SH 94679; for sale at <http://standards.ieee.org/olis>).

10 Appendix E : Working Group III Report

10.1 Report of WG III: Orientation, orthogonality, and cross-axis sensitivity

Jim Fowler (Chair), Gary Holcomb, David McClung, Bruce Pauly, and Leo Sandoval

1. Orthogonality

This is a function of design.

In cases where individually packaged seismometers represent only one component (separate horizontal and vertical components), orthogonality of the two horizontal components relative to each other depends on (1) the accuracy of manufacturer-specified sensitive-axis marking on the case and (2) the accuracy with which the seismometer is oriented (relative to this reference mark). The orthogonality of the vertical component relative to the horizontal components depends on how close to the local gravity vector the sensitive axis of the vertical instrument is installed, and how close to perpendicular to the local gravity vector the sensitive axes of the horizontal components are installed.

In cases where the three components are installed in a single package, the accuracy of orthogonality between components within the package and relative to reference markings on the package should be specified by the manufacturer. There can easily be 1° error between components. A worst case error of 2° between components is not uncommon within a single multi-component unit simply because individual sensors carry ~1° alignment errors relative to their own chassis. Various borehole seismometer arrangements will usually have larger alignment errors between components than for “fixed frame” packages. (“Fixed frame” packages are those meant for installation in a vault or on the surface.)

It should be possible to accurately determine the alignment of each axis of a 1-component or 3-component instrument by comparison of Earth background signals produced by the instrument under test and a reference instrument whose axis alignments are well known.

2. Cross-axis sensitivity

Cross-axis sensitivity should be specified by the manufacturer and should include sensitivity to both off-axis rectilinear motion and rotational motion in all three axes. Cross-axis sensitivity may be measured with shake table, independent of x,y,z and u,v,w systems. Note that this measurement requires a shake table that has known, very low level, off-axis shaking. In general, the problem of measuring cross-axis sensitivity for a broadband seismometer has not been solved. While low-frequency measurements over limited amplitude ranges may be done on a motion table, reliable and accurate measurements of dynamic cross-axis sensitivity spanning the full operating range cannot be done at present. The comprehensive measurement of cross-axis sensitivity is therefore a goal, not a requirement.

Cross-axis sensitivity should be expressed as a ratio (for velocity and acceleration) in dB.

3. *Orientation*

- Manufacturer's packaging orientation indicator — should be manufacturer-specified and is inherent in package design
- Installation issue — any improvement in alignability of the package from the manufacturer would be appreciated
- Note particularly that most instruments are installed in very confined and difficult circumstances — several easily read references should be provided.

11 Appendix F: Working Group IV Report

11.1 Report of WG IV: Environmental and Power Sensitivity, Sensor Stability, Robustness, and Reliability

Igor Abramovich, Kent Anderson, Yang Dake, Jeanine Gagnepain-Beyneix, Takashi Kunugi, Peter Melichar, David Mimoun, Bob Nigbor (Chair), Selwyn Sacks, Al Smith, Michael Thursby, and Tom VanZandt

Goal

Our goal was to identify the important aspects and/or parameters for each of the following general categories:

- Environmental Sensitivity
- Power Sensitivity (including ground-side current and voltage fluctuations)
- Stability of Sensor Parameters
- Robustness
- Reliability

We created a tabular framework to identify, prioritize, discuss, and identify a path to guidelines for each aspect or parameter we identified. Prioritization was 1, 2, or 3, with 3 being the highest priority and 1 the lowest. After initial discussion we separated our prioritization into three general seismic monitoring classes: Broadband, Strong Motion, and Short Period.

Results and Recommendations

Results of our discussions are given in the five tables below. We recommend that future efforts focus on developing guidelines for the highest priority aspects/parameters, as indicated by a priority score of three.

Table 1. Environmental Parameters

Environmental Parameters				
Parameter	Importance for Broadband	Importance for Strong Motion	Comments	Path to Guideline
Temperature (op/nonop)	3	2		Develop-ANSS too broad at low end?
Pressure	3	1		Develop
Humidity	3	3		Adapt IEEE/IEC
Water/Rainfall	3	3		Adapt NEMA
Corrosive Materials	2	2	Salinity is most relevant	Adapt IEEE
Magnetic Field	3	3	Purpose is to alert manufacturer to use care for EM effects	Develop
RF/EMI Immunity	3	3		Adapt CE/IEC
Shock & Vib, Op	1	2		Develop
Shock & Vib, Nonop	3	3	Especially shipping & handling	Adapt IEEE?
Acoustic Noise	1	1		Not needed
Lightning	3	3	System and sensor issue	Develop
Nuclear Radiation	1	1	Special case	Use IEEE

Table 2. Power Sensitivity

Power Sensitivity				
Parameter/Requirement	Importance for Broadband	Importance for Strong Motion	Comments	Path to Guideline
Gain/ΔVolts	3	2	Documented Tests	Adopt IEEE
Offset/ΔVolts	3	2	Documented Tests	
Clip/ΔVolts	3	3	Documented Tests	
FreqResp/ΔVolts	3	3	Documented Tests	
Ripple Sensitivity	3	2	Documented Tests	
Transient Sensitivity	3	1	Documented Tests	
Grounding	3	3	Require 3 separate grounds	Develop
Power Consumption Startup	1	1	Documented Tests	
Power Consumption Steady State	2	2	Documented Tests	
Voltage Requirement (single/dual)	2	3	single	

Table 3. Stability – Need for Recalibration

Stability – Need for Recalibration				
Parameter to be monitored	Importance for Broadband?	Importance for Strong Motion	Comments	Path to Guideline
Mass position	1	1	Systematic Tests	
Gain	3	2	Systematic Tests	
Freq Resp	3	2	Systematic Tests	
Offset	2	1	Systematic Tests	
Noise	2	2	Systematic Tests	

Noise: The measurement of noise for broadband sensors should be considered less important during normal operations than during the test and calibration of the sensor. As mentioned by Working Group I, at least two identical sensors are needed to be co-located for self-noise measurement. Overemphasis of noise recalibration for broadband sensors (too frequently, for example) will cost too many resources and cause too much interference during normal operation.

Table 4. Robustness

Robustness				
Parameter	Importance for Broadband?	Importance for Strong Motion	Comments	Path to Guideline
Shock & vibration, shipping/transport	3	1	Systematic Tests	
Shock & vibration operating	3	3	Systematic Tests	
Water Resistance	3	3	Systematic Tests	
Sensitivity to power fluctuations and response to Power On/Off	2	3	Systematic Tests	
Excess environmental effects	3	3	Survivability after overspec environment	
Permanent/temporary use	3	3	permanent	

Note: The community needs to gather data on failures!

Table 5. Reliability

Reliability				
Parameter	Importance for Broadband?	Importance for Strong Motion	Comments	Path to Guideline
MTBF	3	3	Two years	
Minimum Life-time	3	2	Ten years	
Parts availability	3	3	Ten years	

Note: Proper guidelines and specifications should be followed for design and fabrication (for example soldering) for expected design life.

12 Appendix G: Progress Report from 1989 Working Group (GST1)

Standards for Seismometer Testing

A Progress Report

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September 1990

INTRODUCTION

A small working group composed of representative seismometer manufacturers and key U.S. Government agencies has been formed to develop and formulate a set of uniform test, evaluation, and reporting procedures for seismometers. This group will attempt to identify a standard set of sensor parameters with which any seismic sensor system can be fully characterized and to formulate a uniform format in which to present the parameters of a given system.

The proposed standard for seismometer test and evaluation is intended to serve several purposes. It will serve as a uniform standard for developing detailed specifications for competitive request for procurement documents and for testing and evaluating sample instruments from individual manufacturers competing in a procurement process. It will also provide a uniform basis with which manufacturers can present representative data for systems they produce to facilitate interpretation of the specifications by potential customers. The standard should also simplify the exchange and interpretation of sensor test data between user organizations.

(The above was essentially repeated from Appendix II, the minutes of the first meeting of the SST workshop group.)

THE FIRST SST WORKSHOP

The first Standards for Seismometer Testing (SST) workshop was held at the Albuquerque Seismological Laboratory (ASL) on July 19-20, 1989. It was attended by an ad hoc group of the following interested seismometrists:

- Jim **Durham** (Sandia National Laboratories - consultant)
- Fred **Followill** (Lawrence Livermore National Laboratories)
- Cansun **Guralp** (Guralp Systems)
- Gary **Holcomb** (USGS/ASL)
- Bob **Hutt** (USGS/ASL)
- Bob **Nigbor** (Kinematics, Inc.)
- Jon **Peterson** (USGS/ASL)
- O. D. **Starkey** (Teledyne-Geotech)
- Joe **Steim** (Quanterra)
- Erhardt **Wielandt** (University of Stuttgart)

The stated purpose of the SST workshop was:

To develop a set of recommended testing and reporting standards that may be used by seismometer manufacturers and instrumentation users.

The group adopted a set of one-year goals, which are listed below:

1. Still be functioning as a group and be progressing toward workable seismometer testing standards.
2. Have identified the important seismometer parameters to be evaluated and agreed on acceptable methods for conducting the appropriate measurements to determine these parameters.
3. Have documented the proposed standards and circulated them among the interested seismological community for comment. Be writing the final standards for adoption by the community.

Although the group has not met all of the one-year goals, there has been a significant amount of continuing interest among the group members and a number of other people. A progress report was presented at the Spring 1990 SSA meeting in Santa Cruz, California, which was well attended and generated even more interest.

The workshop began with an outline (Appendix I) entitled PROPOSED STANDARDS FOR SEISMOMETER TESTING - Major points of discussion. This outline included minimum performance standards for the digitizer, but the group soon concluded that it should restrict its discussions to seismometer testing only, as can be seen in the minutes of the first meeting (Appendix II).

The parameters being considered for measurement and reporting in a standard way include the following:

1. Sensitivity
2. Self-noise
3. Bandwidth
4. Clip level
5. Transfer function
6. Stability
7. Cross-axis coupling
8. Linearity and distortion

9. Dynamic range
10. Environmental noise sensitivity (temperature, pressure, external magnetic fields, etc.)

TRIAL RECOMMENDATIONS

The group discussed ways of measuring and reporting most of the parameters listed above. However, due to heightened interest in a few of these and a lack of time, there was little or no discussion of environmental noise sensitivity, stability, and cross-axis coupling. The following paragraphs describe some examples of the group's trial recommendations. See Appendix II for additional ones.

Operating range plot (reporting standard):

Clip level, noise level, bandwidth, and dynamic range may all be specified on one plot.

- Plot clip level and noise level in same units.
- Clip level: Specify using RMS acceleration units of m/s^2 . (This is easy to calculate as $(1/\sqrt{2})$ times the 0-P clip level.)
- Noise level: Therefore use the calculated RMS value in standard-width bands to express the noise level in each band.

Standard bands for RMS calculations would be one-half octave or one-sixth decade, since they are nearly equal. (One-half octave is $0.15 \log_{10}$ units, and one-sixth decade is $0.167 \log_{10}$ units.)

- On a \log_{10} scale, plot RMS amplitude on the vertical axis and frequency in Hz on the horizontal axis. Indicate bandwidth by stopping the plot at the "band edges." ("Band edge" has yet to be defined.)
- Dynamic range is a function of frequency, not a single number. It would be defined as the difference between the clip level and the noise level on the plot, at each frequency in the band of the instrument. Dynamic range may be plotted as a separate curve.

- Optionally, plot Peterson's Low Noise Model (LNM) and RMS amplitudes from a standard suite of "typical" earthquakes on the Clip Level/Noise Level/Bandwidth plot. Note: Peterson's Low Noise Model is obtainable from Jon Peterson at ASL.

Instrument "Self-Noise" (measuring standard):

How does one measure the "self-noise" of the instrument when it is expected to be below Earth noise at measuring site? Possible approaches and methods are listed below, but need further discussion:

- Theoretical noise model.
- Calculated "actual" noise by comparing seismometers in presence of lowest possible ambient Earth noise.
- Calculated "actual" noise by comparing seismometers in presence of much higher ambient Earth noise.
- Also measure total noise.
- Calculation methods
 - Coherence methods
 - Holcomb's direct method (N_1+N_2) — requires accurate knowledge of transfer functions H_1 and H_2 . (For a complete description of this method, see *USGS Open File Report 89-214*, "A Direct Method for Calculating Instrument Noise Levels in Side-by-Side Seismometer Evaluations," by L. G. Holcomb. Available from ASL.)

Transfer Function (reporting standard):

- List factored transfer function poles and zeros in units of radial frequency (ω). This transfer function should be for acceleration input, velocity input, or other "natural" inputs — see next item. Input units shall be specified.
- Give seismometer gain at a reference frequency f_0 in terms of volts per m/s^2 , volts per m/s , or other "natural" Earth input units. (Use the units to which the seismometer re-

sponse is the "flattest" or most constant. For example, Streckeisen STS-1 seismometer gain would be given in terms of volts per m/s.)

- Plot relative amplitude response and phase response:

-AMPLITUDE RESPONSE: On a \log_{10} scale, plot relative amplitude on the vertical axis and frequency in Hz on the horizontal axis. The term "relative amplitude" means the absolute amplitude response at each frequency divided by the absolute amplitude response at the reference frequency f_0 , at which the seismometer gain is given.

-PHASE RESPONSE: Plot θ in degrees on the vertical axis (linear scale) and frequency in Hz on the horizontal axis (\log_{10} scale).

-HORIZONTAL AXIS: Many would argue that it makes more sense to plot PERIOD instead of FREQUENCY on the horizontal axis of the plot, because a seismogram analyst would measure the PERIOD of the waveform of interest and would then find it easier to consult an AMPLITUDE RESPONSE VS. PERIOD plot to find the magnification or sensitivity at that period. Although this point needs further discussion, one possibility is to use both: a frequency axis across the bottom of the plot and a period axis across the top of the plot.

Transfer Function (measuring standard):

- Calibration circuit methods, using single frequency sine inputs, white noise, random telegraph signals, swept sine, etc.
- Frame input methods, such as shake table, tilt table, weight lift, shaking ground with white noise, etc.
- Fitting the model transfer function to the measurements.

-Wielandt arbitrary calibration signal method. (See "Calibration of Seismometers Using Arbitrary Signals," by Erhardt Wielandt, 1986, unpub. manuscript.)

-HP3562A Spectrum Analyzer (pole/zero fitting routine).

-Manual methods (perturbation of poles and zeros, compare with measurements).

-Workshop recommendation: Study the three methods.

- The reported transfer function and seismometer gain should be qualified by a description of the measurement method and expected accuracy.

SHAKE TABLE

In discussing procedures for measuring and documenting some of the parameters on the list, the group identified the need for improved shake tables that would make some measurements easier. These include:

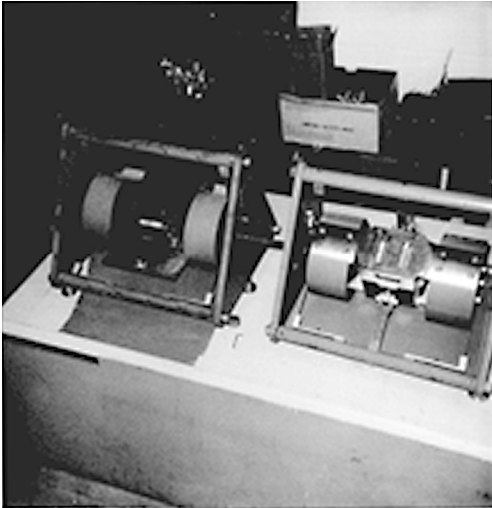
- Off-axis coupling under dynamic conditions.
- Gain measurements using real frame inputs instead of calibration circuit "equivalent" inputs.
- Clip level measurements using real frame inputs.
- Distortion measurements using large two-frequency frame inputs.

The group concluded that most shake tables or shaking devices available today are either low-level (micron-level) or very high-level (several Gs) devices. Not many shake tables exist that will produce the 0.01 to 1 m/s² levels of acceleration suitable for testing modern, high dynamic range, broadband seismometers.

ASL has built a trial shake table that may partially fulfill some of the perceived requirements. It has the following characteristics:

- 0.5 to 1.0 m/s² maximum acceleration
- Off-axis shaking less than 0.1 percent of on-axis shaking (-60dB)
- Capable of handling a seismometer up to 9 inches in diameter and 10 inches tall

- Relatively easy to reproduce, since it is built from a commonly available (to a seismologist) piece of equipment: a horizontal big Benioff seismometer



ASL medium-motion shake table made by modifying a standard big Benioff horizontal seismometer. Shown with a Geotech SL-220 LP seismometer on the test platform (left photo). Right photo is with no seismometer on test platform. The standard big Benioff at the right in each photo is used as the driver.

TARGET DATES

The workshop group made a list of target dates for some key milestones that it wished to achieve, as follows:

- 30 Sep 1989: Draft standards document written and distributed to members of the key group for review.
- Oct-Nov 1989: Assemble a larger group of interested parties to review the draft standards document.
- Dec 1989: Key group meets to do final review and integration of all ideas and comments from the larger community.
- Feb 1990: Submit USGS Open-File Report.
- May 1990: Present preliminary Standards for Seismometer Testing at the SSA meeting.

These milestones have, for the most part, not been achieved. No draft standards have been written, a larger group has not been assembled, and no USGS Open-File Report has been written or submitted. However, a progress report was presented at the May

1990 SSA meeting, as mentioned. In addition, interested parties have occasionally been in communication with this author, with valuable suggestions and requests for copies of what has been done so far. When time permits, the author plans to assemble these comments for circulation to the interested parties, along with some form of short draft standards document.

13 FIGURES

The following pages contain plots and figures representing various aspects of measuring and representing seismometer self-noise, clip level, and dynamic range.

Figure 1. Time series plots showing examples of recorded instrument noise and simulated clip level:

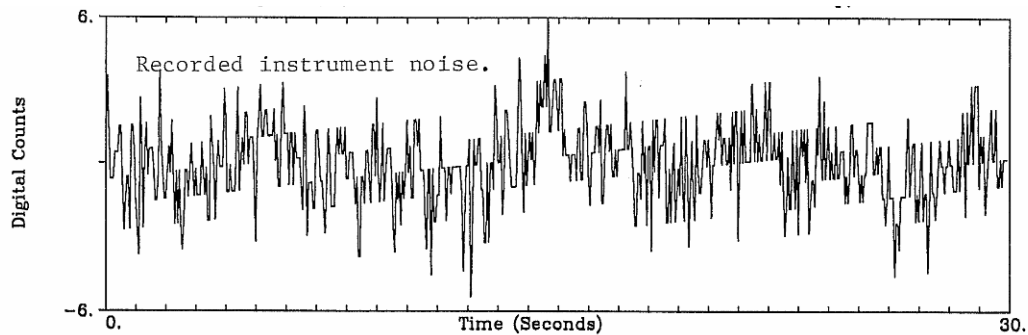


Figure 1A. Recorded instrument noise. In this case, there was no need to derive or calculate the instrument noise because it was significantly above earth background noise at the testing site. The RMS value of this time series in a one-half octave band around 0.25 Hz is 0.197 counts, or $1.59 \times 10^{-7} \text{ m/s}^2$.

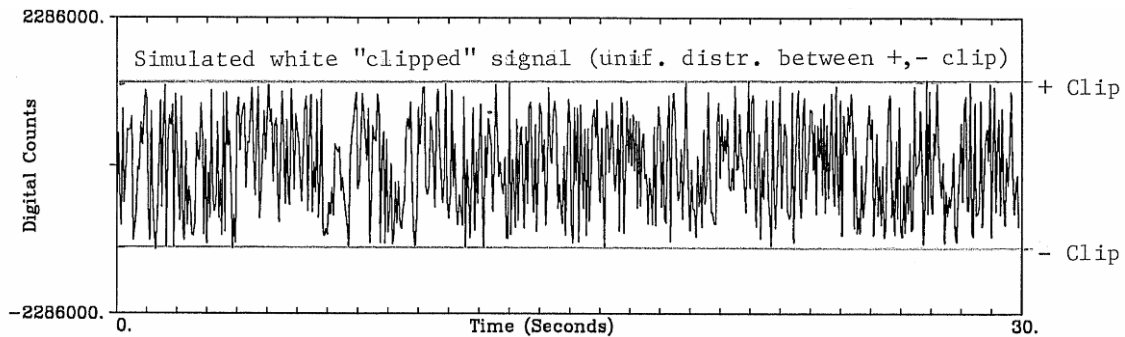


Figure 1B. Simulated white noise "clipped" signal for the same instrument. The clip level of this instrument is 0.1 g or approximately 1 m/s^2 . One possible way of calculating dynamic range for this instrument would be to calculate the ratio of maximum peak amplitudes in A and B. This ratio is $(1.265 \times 10^6 \text{ counts}) / (6 \text{ counts})$, which is 106.5 dB. This method is known here as "Method 1."

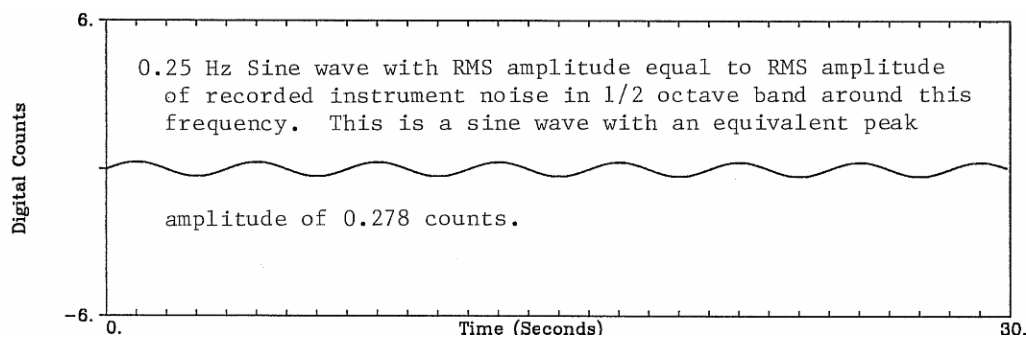


Figure 1C. A 0.25 Hz sine wave whose RMS value is the same as the RMS value of the waveform of the instrument noise in A., in a one-half octave band around 0.25 Hz. This RMS value is 0.197 counts, or $1.59 \times 10^{-7} \text{ m/s}^2$.

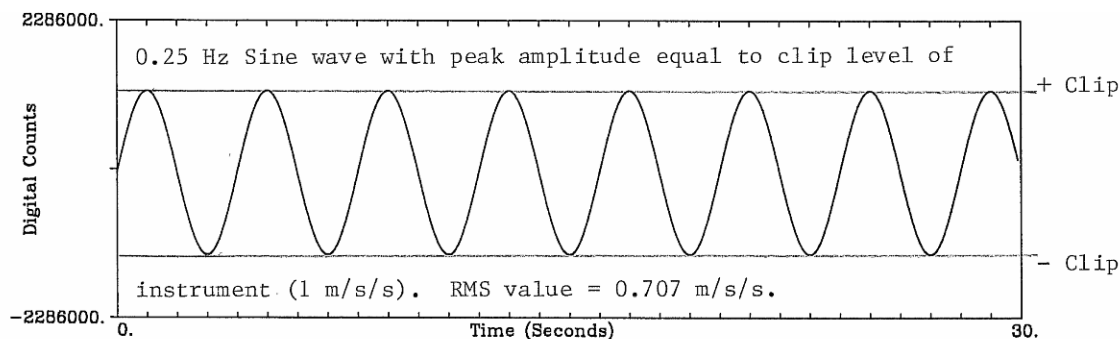
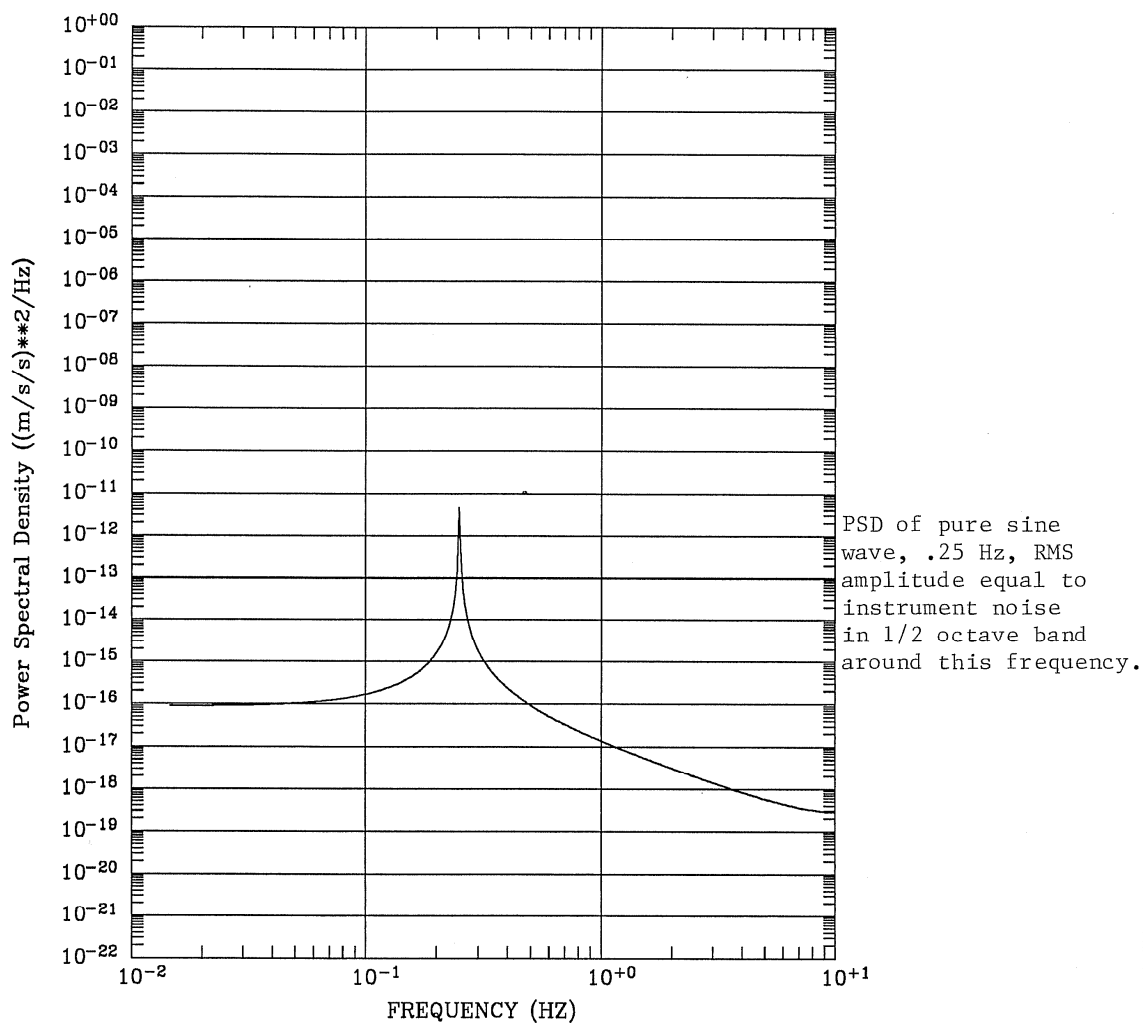


Figure 1D. A 0.25 Hz sine wave whose peak value is equal to the clip level of the instrument (and therefore whose RMS value is equal to .707 times the clip level). The proposed standard way of calculating the dynamic range at a particular frequency (in this case, at 0.25 Hz) is to calculate the ratio of the RMS amplitudes of these two sine waves. This ratio is $(0.707 \text{ m/s}^2) / (1.59 \times 10^{-7} \text{ m/s}^2)$, or 133.0 dB. This method of calculating the dynamic range, known here as "Method 2," produces larger numbers than Method 1 shown in B above, because the RMS value of the instrument noise in a one-half octave band is always lower than the peak noise.



PSD for station: .25 Hz Sine Wave, .278 counts peak
 Component: RMS Ampl. = RMS Ampl. of noise Rate: 0.2000E+02 sps
 Sensitivity: 0.1240E+07 counts per m/s/s at 0.1000E-01 Hz.
 Start time: 90,113,17:00:00 Segment length: 0hr 3min 24.800sec

Figure 2. The power spectral density (PSD) of the sine wave in figure 1C.

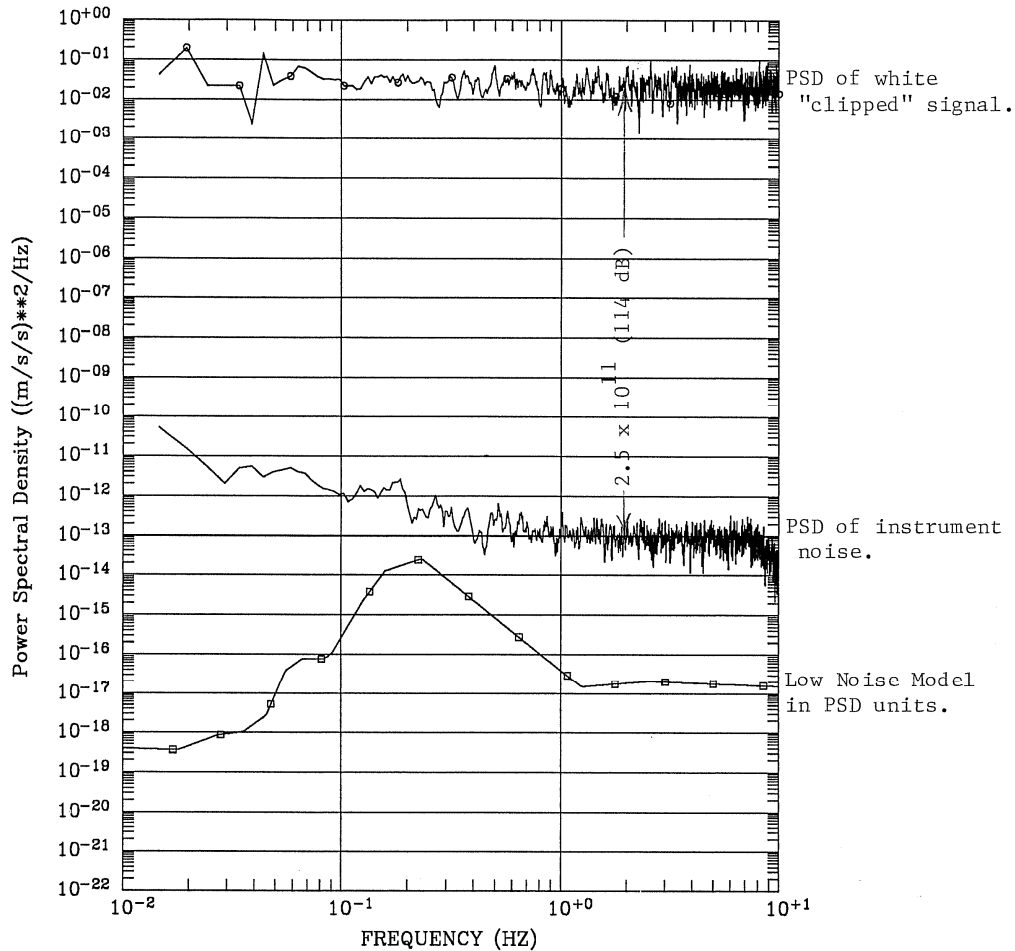
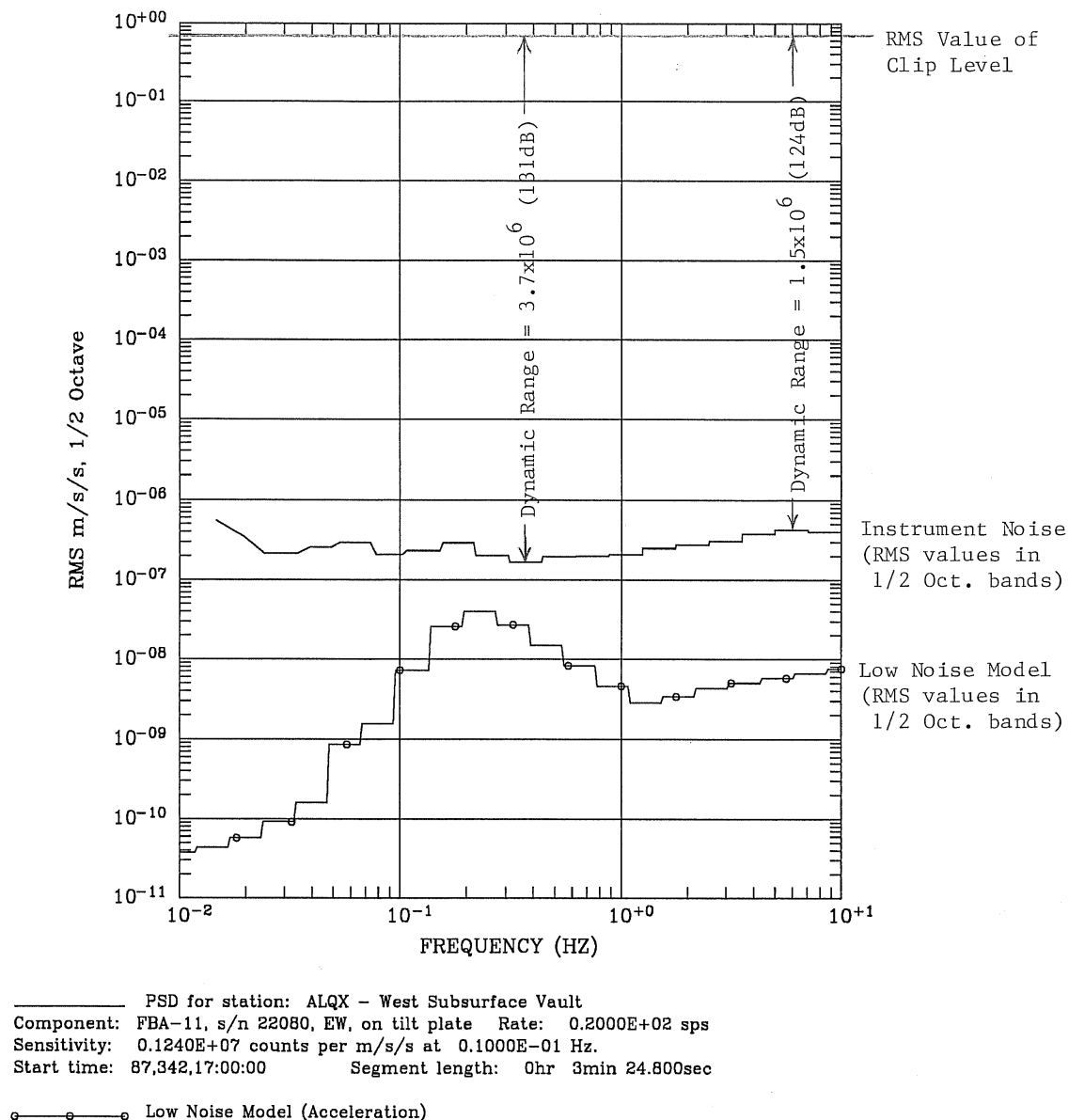


Figure 3. The PSDs of the two time series shown in figures 1A and 1B. plotted together with Peterson's Low Noise Model (LNM). The "flat" portion of the PSDs of the "clipped" signal and the instrument noise are separated by about 114 dB. This is a third alternative way of expressing dynamic range: in terms of a ratio of power spectral density units. This method, known here as Method 3, produces dynamic range numbers that are between those produced by Methods 1 and 2. The PSD of the sine wave in figure 2 may be superimposed upon figure 3 for comparison.



EXAMPLE OF STANDARDIZED "CLIP LEVEL/NOISE LEVEL/BANDWIDTH" PLOT.
 (Perhaps this could be called the "Dynamic Range/Bandwidth Plot.")

Figure 4. An example of an "Operating Range" plot. This figure has the RMS value of the clip level, the one-half octave RMS noise levels, and the one-half octave RMS values of the Low Noise Model shown on the same plot. The clip level and the noise levels shown are for the data in figure 1. The dynamic range figure of 131 dB shown at 0.37 Hz is different from that calculated in the text for figure 1D because the center of the band is at a slightly different frequency.

System Operating Range
 SSR-1 Solid State Recorder with
 FBA-23 Accelerometer, 2g Full-Scale

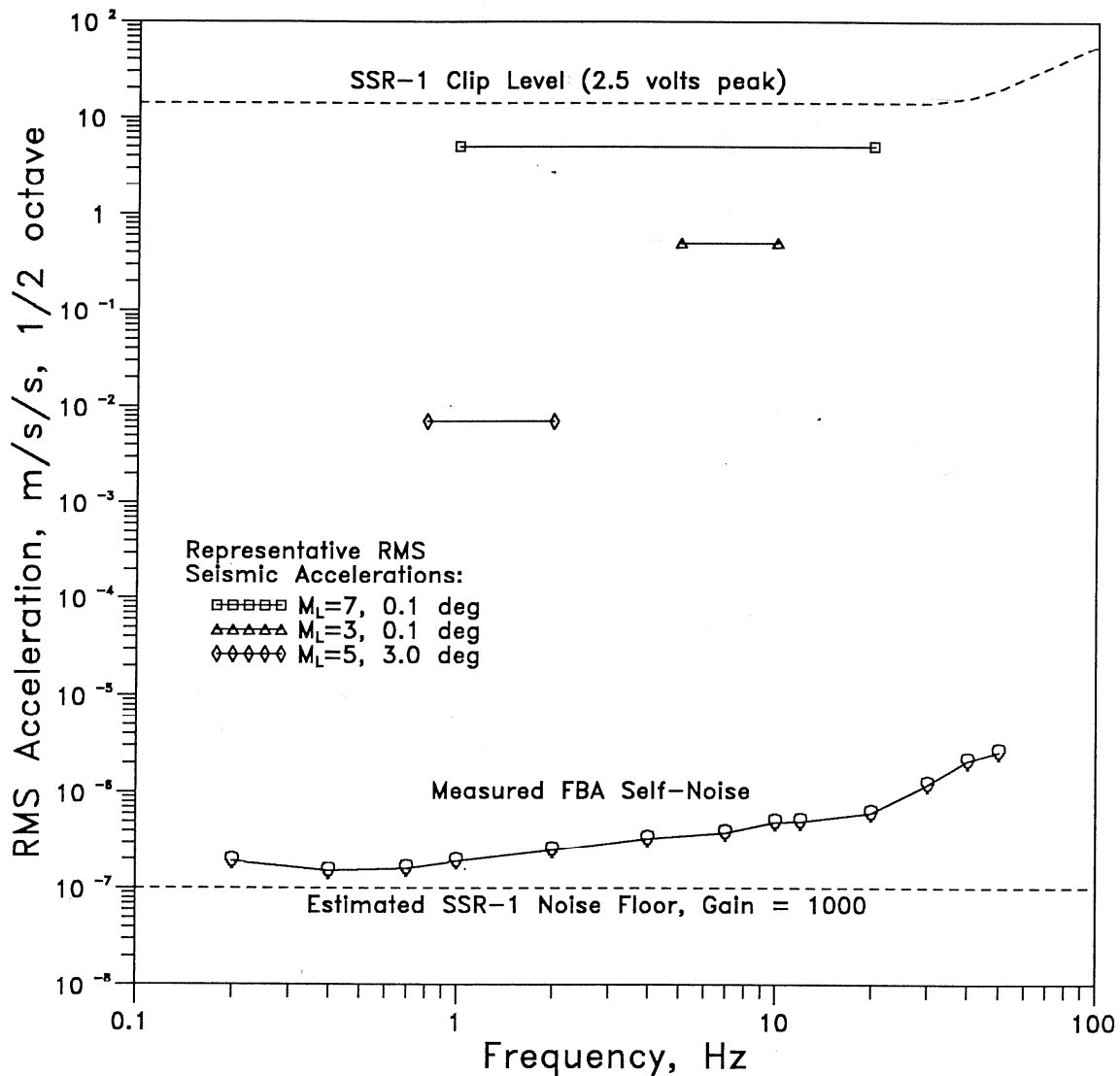
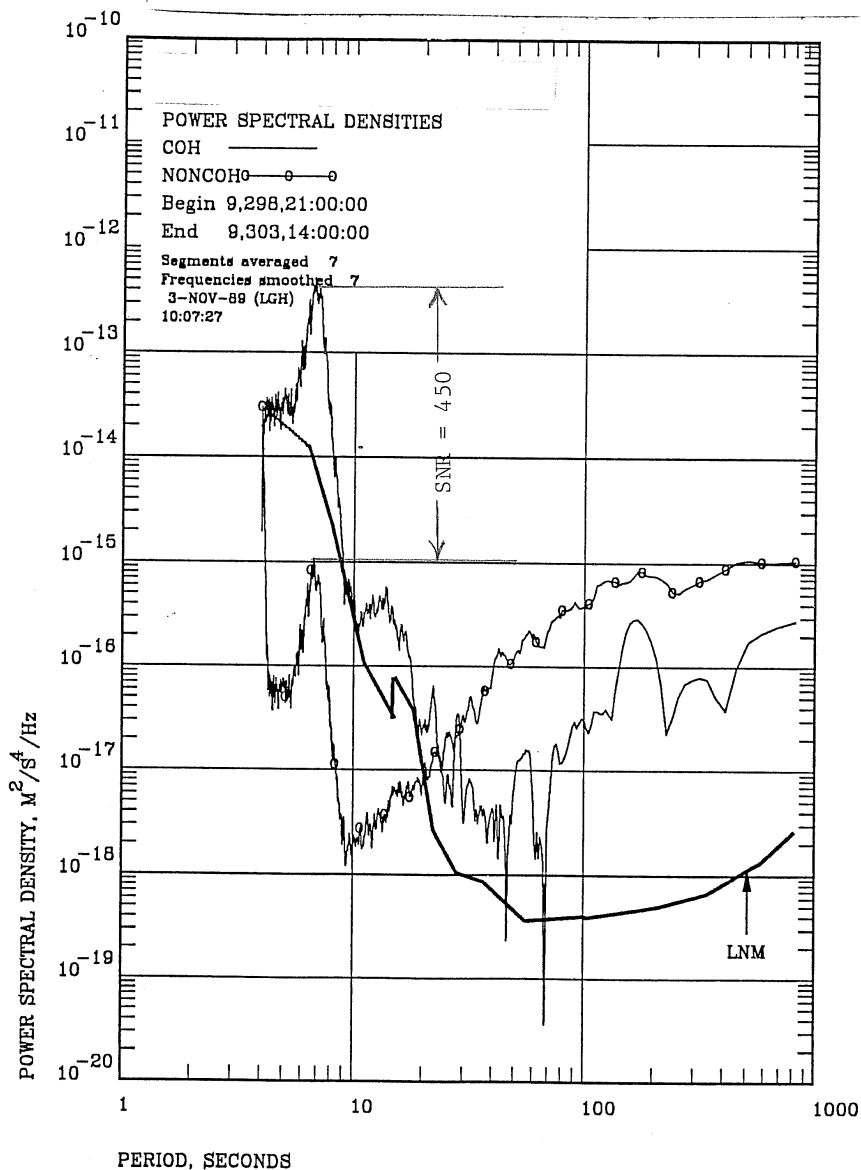


Figure 5. A copy of a System Operating Range plot for a Kinematics SSR-1 Recorder with an FBA-23 Accelerometer (courtesy of Robert L. Nigbor, Agbabian Associates). This plot is shown as an example of an operating range plot that was produced nearly in accordance with the proposed standard. (The clip level is shown as a peak value instead of an RMS value.)



EXAMPLE OF "SELF-NOISE" (NONCOH) CALCULATION THAT FOLLOWS THE SHAPE OF THE ORIGINAL POWER SPECTRA. THIS COULD RESULT FROM MISALIGNMENT OF THE SENSORS BEING COMPARED.

Figure 6. An example of a seismometer self-noise calculation for which the seismometer noise over at least a portion of the band of interest is below the earth noise at the measuring site. We note that the non-coherent noise PSD follows the shape of the coherent noise. This could result from misalignment of the sensors being compared, as demonstrated in figures 8 through 13.

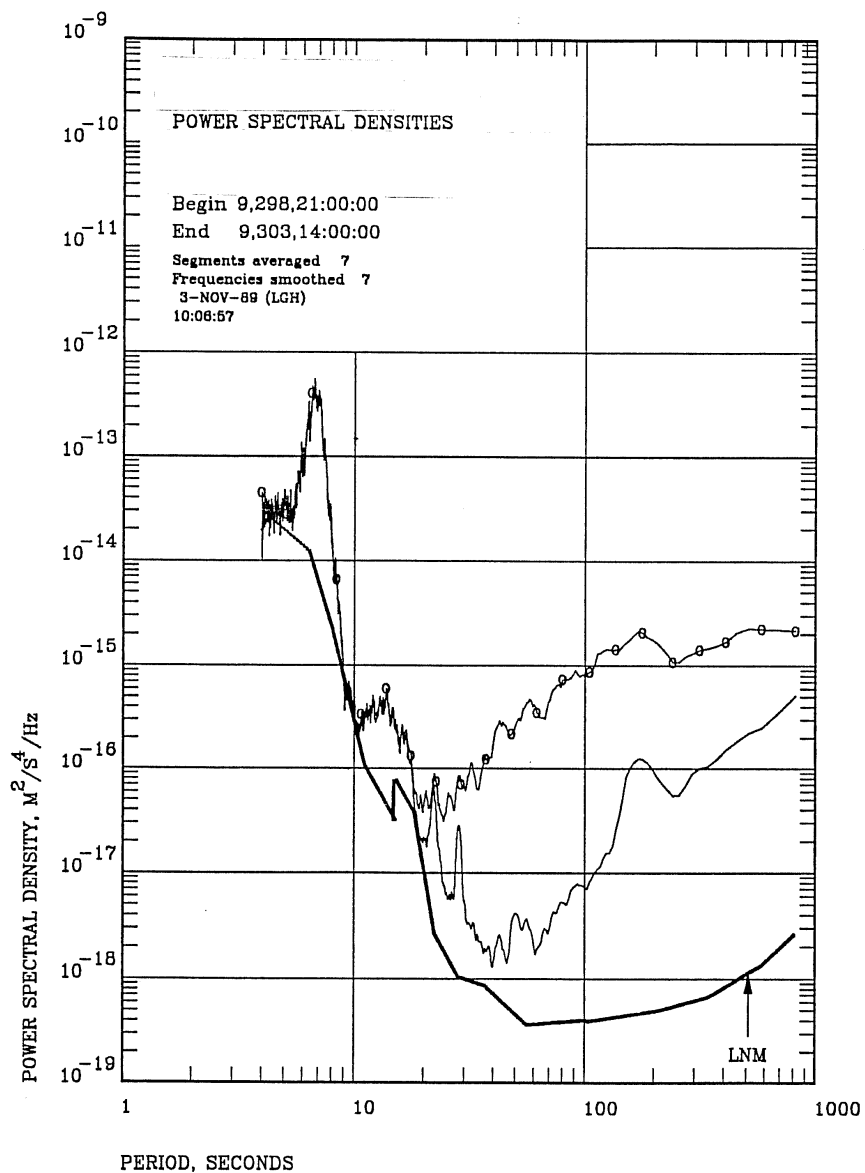
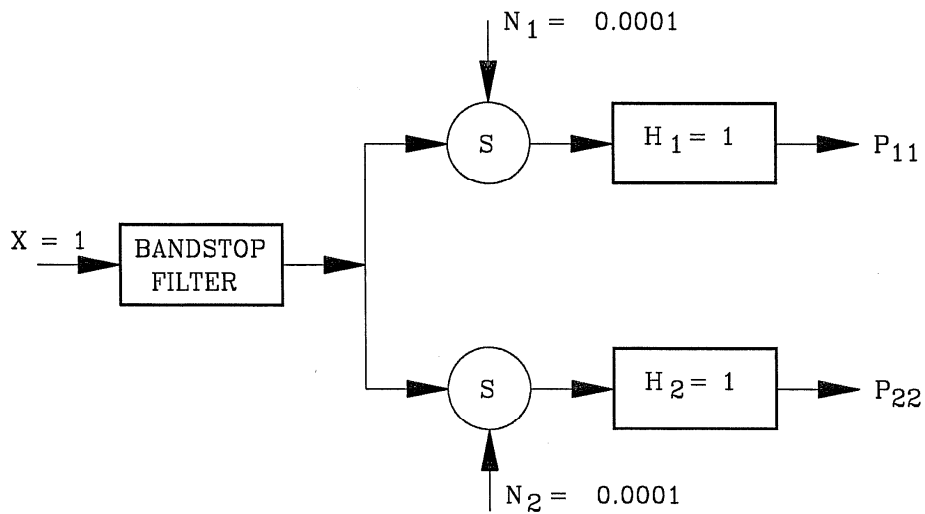


Figure 7. An example of total noise power spectra for two horizontal seismometers operating in parallel so that self-noise may be calculated. These are the data from which the plots in figure 6 were derived.

Model for finding white sensor noise in
band-shaped background data.

SNR 10,000



(Sensors are perfectly aligned.)

Figure 8. A model for finding sensor noise in an environment of band-shaped seismic background noise, assuming that the sensors are perfectly aligned with each other. The "S" inside the circle denotes a summing junction.

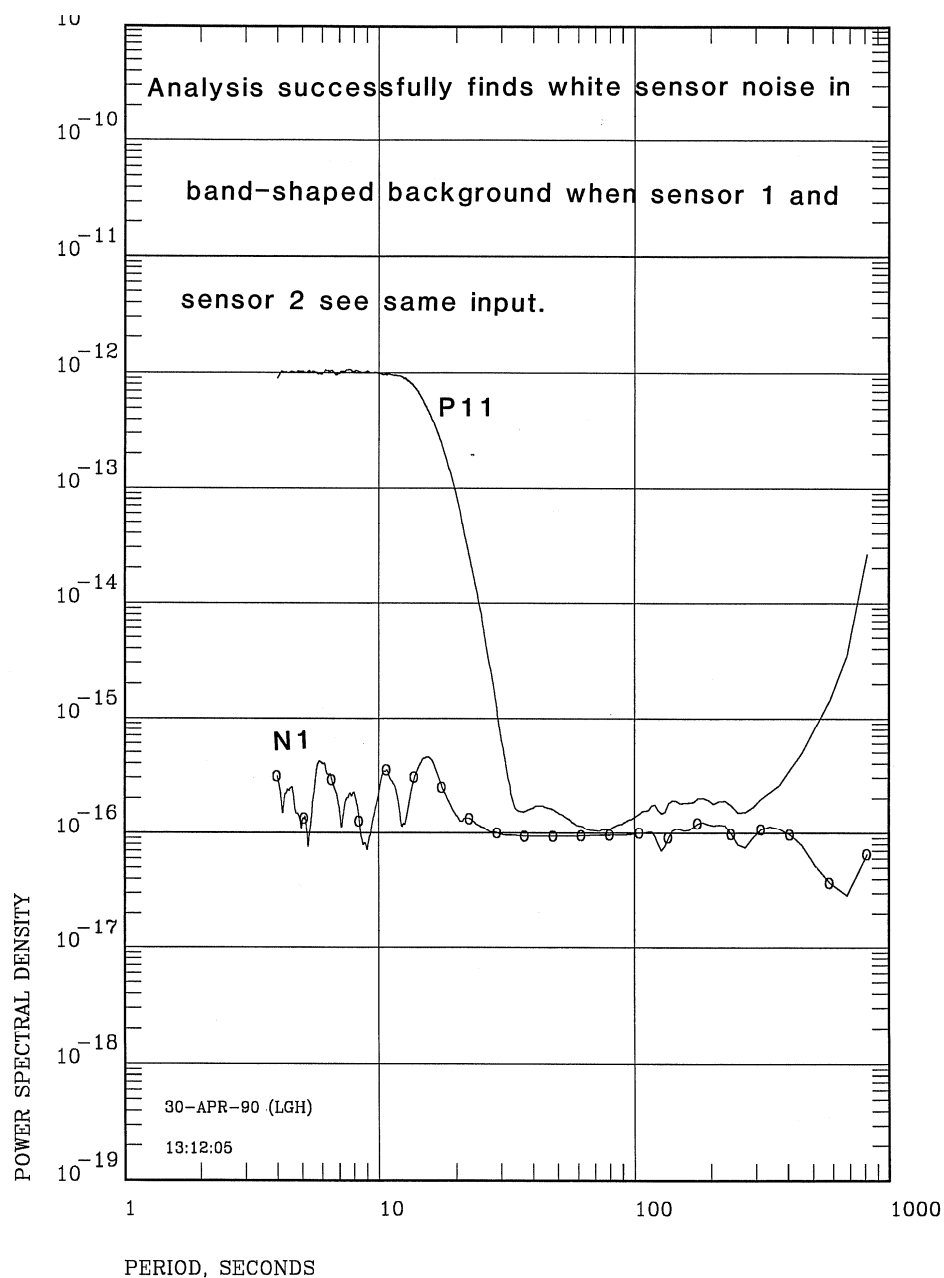


Figure 9. A plot of the total noise P_{11} and the calculated self-noise N_1 of the model in figure 8. When the sensors are perfectly aligned as in the model, the analysis calculates N_1 essentially correctly. The analysis used here is that described in USGS Open-File Report 89-214, "A Direct Method for Calculating Instrument Noise Levels in Side-by-Side Seismometer Evaluations," by L. G. Holcomb, available from ASL.

Simulation of two "perfect" (noise-free) sensors in an environment of orthogonal band-shaped noise.,
with one sensor mis-aligned by 1 degree.

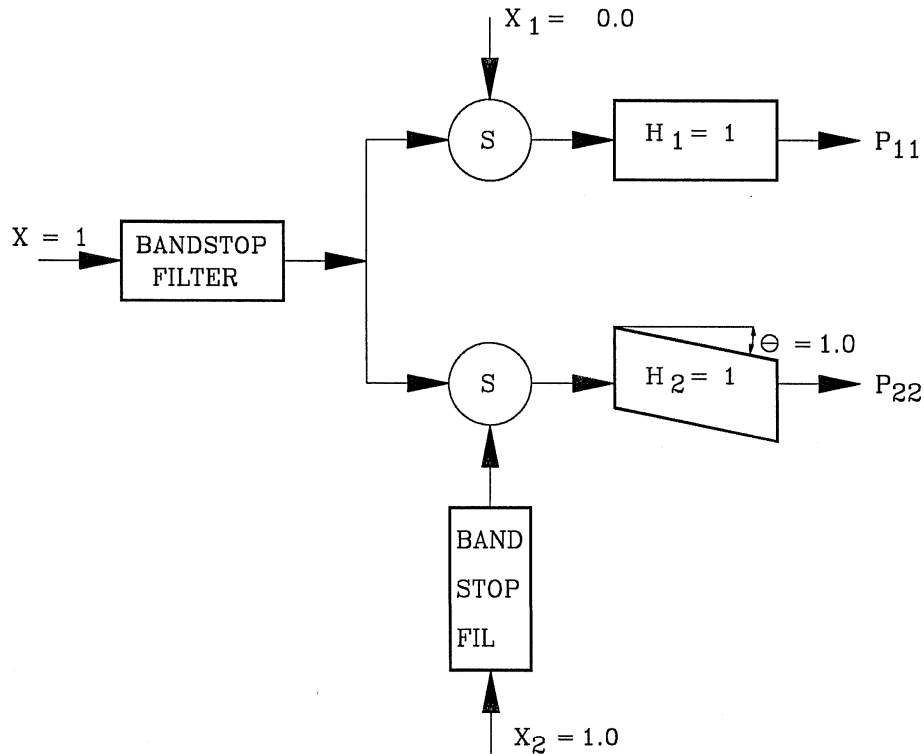


Figure 10. A model for two "perfect" (noise-free) seismometers installed in an environment of orthogonal horizontal band-shaped noise. The model assumes that the sensitive axis of seismometer 2 is misaligned with that of seismometer 1 by 1° .

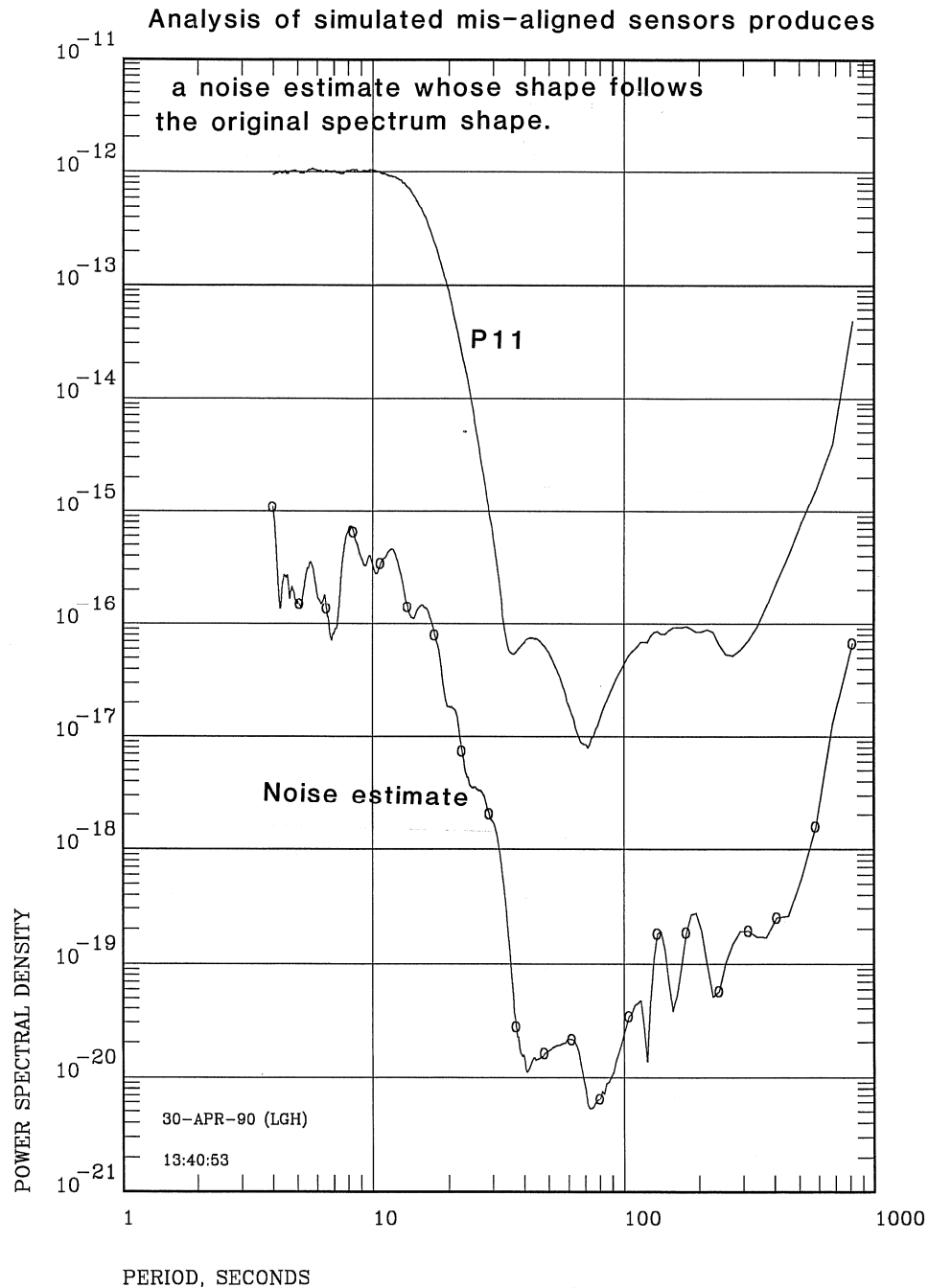


Figure 11. A plot of the total noise P_{11} and the calculated noise estimate N_1 as in the model in figure 8, but using data produced by the simulation model in figure 10. This plot demonstrates that, even with "perfect" sensors, a misalignment of the sensors by 1° will not allow a self-noise calculation more than about 35 dB below the level of the total power.

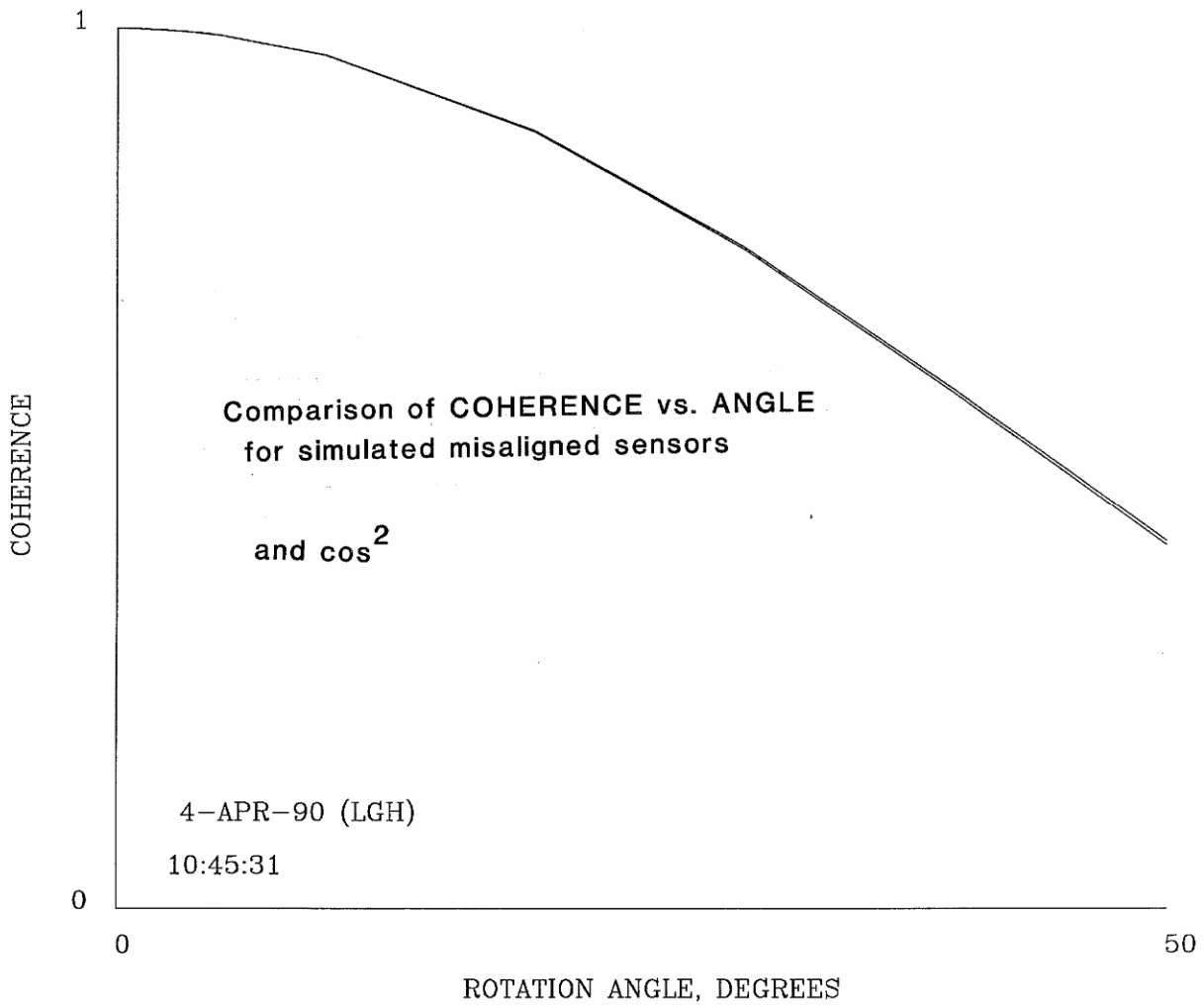


Figure 12. A plot of coherence (γ^2) vs. misalignment angle (θ) superimposed on a plot of $\cos^2(\theta)$. The coherence function plotted here was calculated for data generated by the simulation model in figure 10. This plot shows that coherence is proportional to $\cos^2(\theta)$.

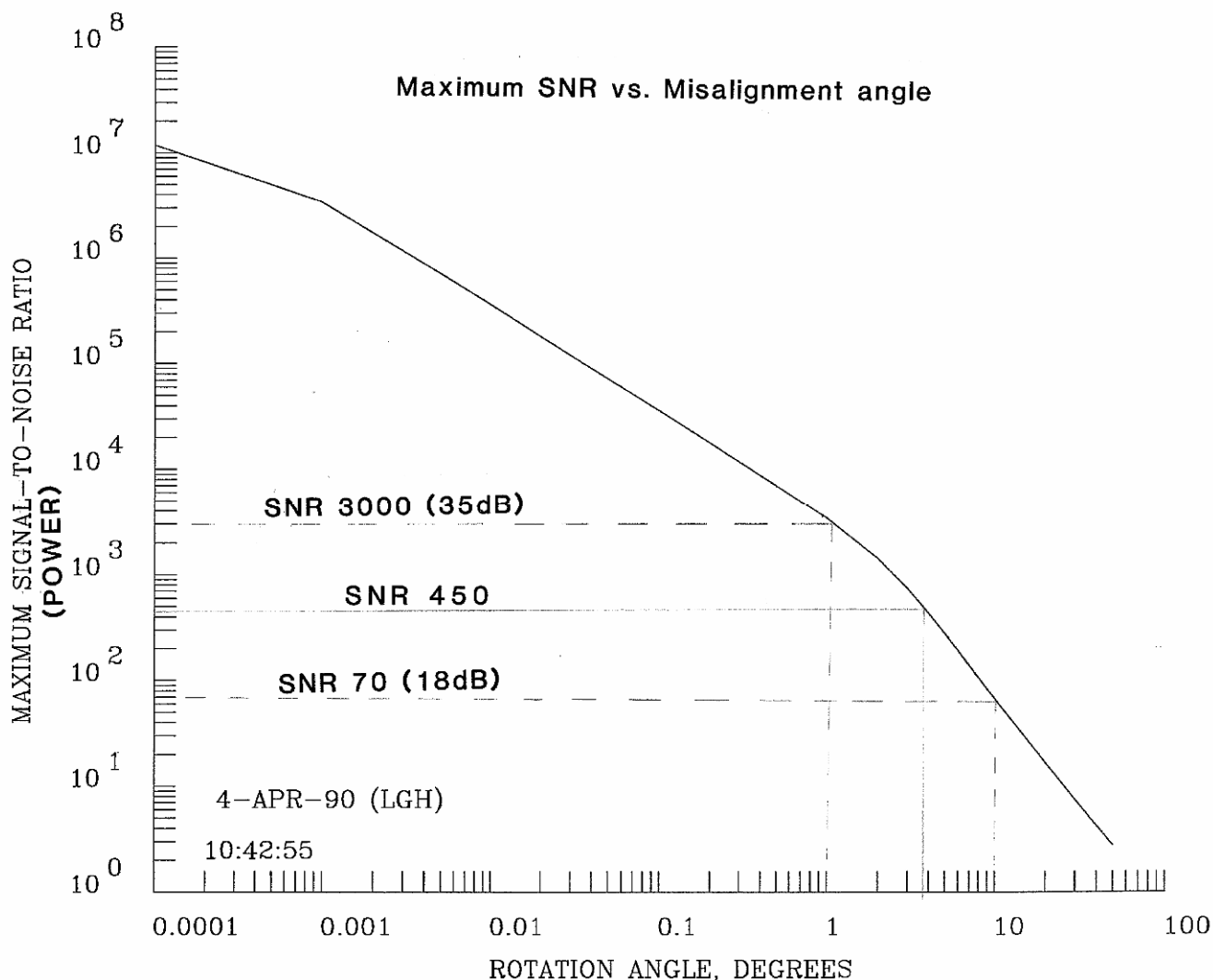


Figure 13. A plot of maximum possible signal-to-noise ratio (SNR) vs. seismometer misalignment angle. If two seismometers misaligned by 10° were being compared in order to derive their self-noise by coherence analysis or by Holcomb's direct noise calculation method, the noise thus derived could not be less than 18 dB below the background signal with which they were being driven. In figure 6, we had a SNR of 450. In the plot of figure 13, we see that this SNR could have been caused by misalignment of 3.8° of the sensitive axes of the seismometers being compared.