



**PROSPECTS
FOR LOW-FREQUENCY
SEISMOMETRY**

**A REPORT OF THE IRIS BROADBAND
SEISMOMETER WORKSHOP**

Held March 24-26, 2004
Granlibakken, California

Edited by S. Ingate & J. Berger

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Workshop Presentations and Discussion

Background material provided in advance of the workshop, and the record of presentations and discussions may be found on the included CD and also at:
<http://www.iris.edu/stations/seisWorkshop04/seisWorkshop.htm>

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Executive Summary

For nearly a quarter of a century, the development of seismic sensors with low noise and high resolution in the normal mode frequency band (0.3-7 mHz) has languished. The seismometer of choice for this field of seismology is now over 20 years old, and is no longer being manufactured. Newer sensors, albeit more portable and physically robust, more energy efficient, and less expensive, are less capable of recording Earth motions in this frequency band. Over the same time period, the training of seismic instrumentalists in departments of Earth science has languished; no longer do academic seismologists design and build new sensors. Outside of traditional science departments, however, a number of innovative ideas have been proposed for novel seismic instruments.

In March 2004, IRIS sponsored a workshop on the future of long-period seismometry, which brought together over 60 participants from government, academic, and business sectors of eight countries. Representatives of groups involved in sensor technology, material sciences, and nanotechnology were all present. The workshop's goals were to assess emerging technologies that may have seismometric applications and formulate a plan to revitalize research and development of techniques in seismometry and related seismographic instrumentation in the United States.

Workshop participants made several important observations and recommendations:

- The cornerstone sensor of the Global Seismographic Network (GSN), the Streckeisen STS-1, is aging and no longer in production. There are no sensors currently in production or in development that match its performance.
- Industry is unwilling to develop a substitute sensor for this frequency band due to the anticipated unfavorable return on investment. (A total production run of 200 units only is projected.)
- Many workshop participants have come to believe that the goal to develop an all-purpose sensor, spanning the frequency band from millihertz to decahertz, should be abandoned, and that two separate transducers should be used to cover this range. Such a decision might ease the technological challenge and reduce the burden on industry.
- An innovative program involving academia, industry, and government is recommended to nurture development of the next generation instruments and to educate the next generation of US seismic system developers.
- A program total of \$10M-\$20M over a period of 5-10 years is envisioned.
- Development needs to commence now to prevent significant deterioration of the GSN over the next 5-10 years.

1. Introduction

Seismology provides the only direct method for measuring the properties of the deep interior of our planet. Seismic sensors range from mass-produced geophones, costing a few hundred dollars and used by the oil industry by the thousands, to low-noise, high-sensitivity instruments that require careful installation in boreholes or underground vaults and cost up to \$75,000 or more.

Seismic sensors are the mechanical or electromechanical assemblies that convert Earth motion into electrical signals that can then be digitized and recorded for later analysis. Here, sensors are distinguished from systems, in that the latter may consist of multiple combinations of the former, coupled to a digitizing and recording apparatus.

Few fundamental advances have been made in seismic sensors since the deployment of force-feedback systems near-

ly a third of a century ago (see Box 1). In the intervening period, academic (and to a lesser extent industrial) research and development of seismographic instrumentation has declined. Today, adequate sensors to meet some important scientific requirements are in short supply (see Box 2). Further, the pool of trained scientists working on seismographic instrumentation in the United States has dwindled to nearly zero.

Following a brief introduction, this report summarizes discussions of the following workshop subjects.

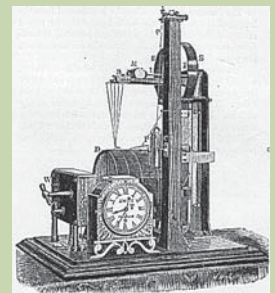
- Seismological Requirements
- Manufacturing Issues
- Testing and Testing Facilities
- Partnerships between Industry and Academia
- Education and Agency Support

Box 1: When Was the First Broadband Seismograph Built?

Dewey and Byerly (1969) credit the Italian Cecchi with building the first recording seismograph around 1875. This sensor recorded on a drum and may well have been the first broadband seismograph. However, it is widely accepted that the Gray and Milne seismograph (see right) is the first successful broadband seismograph. Between 1881-1882, Gray, Ewing, and Milne figured out how to extend the period of a seismometer to about 12 seconds (horizontal "garden-gate" suspension), thus producing a seismograph that had a flat response to Earth displacement from 12 seconds to shorter periods.

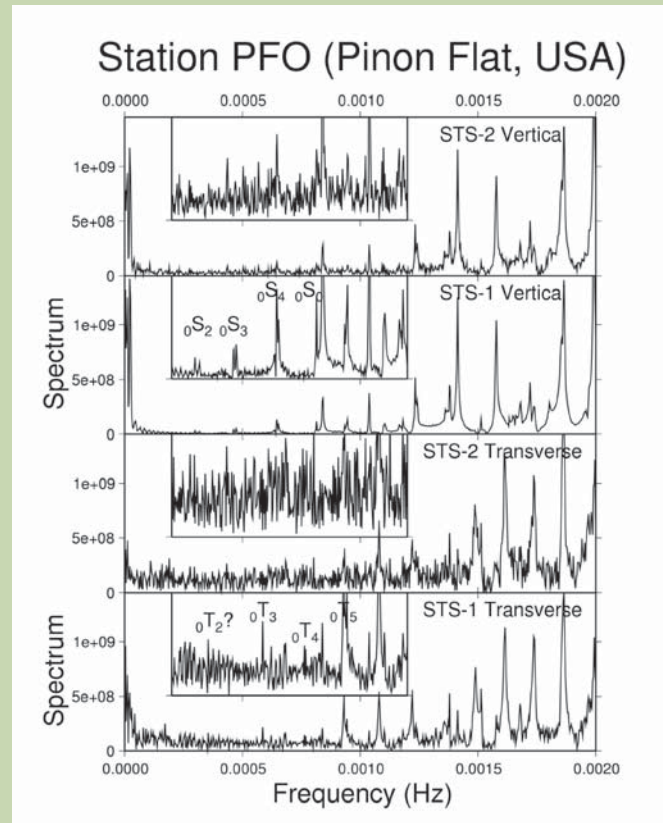
However, the lineage to present broadband or very broadband sensors includes a few other branches. Von Rebeur-Paschwitz introduced continuous photographic recording with a 15-second period, which was responsible for the famous first recorded teleseism in 1889 (see right). One of Milne's students in Japan, Omori in 1899, created a fairly sensitive 60-second mechanical displacement seismograph that recorded some remarkable records of large teleseisms (see the front cover of this report for Omori horizontal recordings in Tokyo of the Alaska 1899 earthquake, showing one-minute period signals that are remarkable in their resemblance to modern very broadband seismograms).

Wiechert introduced viscous damping in 1898. Credit for the first feedback-stabilized broadband sensor probably goes to the remarkable 21-ton de Quervain and Piccard mechanical system at Zurich, 1926, an important development towards force-balance systems. The first direct digital recording seismograph was operational at Caltech around 1961. The Graefenberg array was the first modern digital broadband array in the late 1970s, and prompted development of the Wielandt and Streckeisen 20s STS-1. Plesinger was the first to implement a very broad velocity response, 0.3-300s, although the utility was hampered by analog recording available in the early 1970s. Plesinger's research, however, inspired Wielandt and Steim to develop the digital VBB concept, leading in the mid 1980s to the IRIS/GSN's 360s STS-1/VBB.



Box 2. Science Without Very Broadband Sensors

What if the GSN consisted solely of broadband sensors (such as the STS-2) rather than very broadband sensors (such as the STS-1, which is no longer in manufacture, nor are there any plans to resume production)? Are there any useful signals that would not be recorded? The once-in-a-lifetime Mw 9.3 Sumatran event of 12/26/04 enabled scientists to observe rarely seen gravest free oscillations such as ${}_0S_2$. These signals are rare because smaller sources do not generate the gravest modes with sufficient amplitude to be detected. The plot is a spectrum computed for collocated STS-1 and STS-2 sensors at station PFO in California. The inset boxes are enlargements of the main spectra to show amplitudes of the gravest modes. STS-2 vertical went nonlinear on the first Rayleigh wave for this event, so the first surface wave arrivals were removed before spectrum estimation for the vertical component. The STS-2 did not record the gravest modes below ${}_0S_3$ with sufficient signal-to-noise-ratio, yet the signals are easily seen in the STS-1 spectra. Figure courtesy of J. Park, Yale University.



2. Background

2.1. The Seismic Spectrum

Earthquake-generated elastic waves that are transmitted through the Earth and along its surface range in frequencies from less than a millihertz (the gravest eigenfrequency of the solid Earth has a period of 54 minutes, or 0.31 mHz), to about 30 Hz. Higher frequencies are attenuated so rapidly that they do not travel appreciable distances. These five frequency decades constitute the seismic band; the term broadband is used by seismologists to indicate this entire frequency band.

The seismic source, whether a man-made explosion or earthquake, usually has a duration ranging from milliseconds up to a few minutes only, but the motions excited by the largest events can last days. Although the transient seismic signals radiated by localized sources of finite duration are coherent with a well-defined phase spectrum, this is not the case for ambient seismic noise. The latter is often caused by a diversity of different, spatially distributed, and often continuous sources such as wind, ocean waves, and cultural. Seismic noise thus forms a more or less stationary stochastic process without a defined phase spectrum.

The dynamic range of the seismic spectrum extends from the level of the background ambient noise to the largest signals generated by seismic sources. Both limits are frequency dependant, and the signal levels are also dependant on the distance between source and receiver. The bounds on signals and noise are well established by observation.

2.1.1. Earthquake Signals

Traveling waves from earthquakes are traditionally divided into three categories depending upon the source-receiver distance. Earth's free oscillations, or normal modes, form an-

other category. Due to the effects of internal friction, the frequency content of the signals also varies with source-receiver distance. The categories are roughly described in Table 1.

Figure 1 plots representative earthquake spectra recorded at local, regional, and teleseismic distances for a range of earthquake magnitudes. To make meaningful comparisons between deterministic signals and random noise, the spectral unit is root-mean-square (RMS) acceleration in frequency bands with a width of one octave.

Of particular importance for long-period seismometry are Earth's free oscillations, or normal modes. Following large earthquakes, Earth's free oscillations are observed as spectral peaks in the frequency band of 0.3-7 mHz. The gravest mode of vibration, ${}_0S_2$, has a frequency of 0.3 mHz, and splitting of this peak is frequently observed. At higher frequencies, the split modes overlap, and spectral resolution decreases. Above approximately 7 mHz, normal modes are too closely spaced to be resolvable, and other techniques, based on propagating wave theory, are more appropriate for the analysis of seismograms.

The development of spectral techniques for the analysis of Earth's free oscillations was prompted by the 1960 M 9.6 Chile earthquake. Over the last 40 years, the deployment of global networks of sensors, together with advances in theory, have markedly improved our understanding of the average (1-D) Earth.

For example, measurement of the eigenfrequencies of free oscillations sensitive to Earth's core has confirmed the existence of a solid inner core (Dziewonski and Gilbert, 1971). Eigenfrequency measurements have led to the development of reference 1-D Earth models for elastic-wave velocities,

Table 1.

Category	Distance	Frequencies	RMS Amplitudes
Local Signals	up to ~30 km	.3 to 30 Hz	to ~ 10 ms ⁻²
Regional Signals	~ 1000 km	~10 ⁻¹ to ~10 Hz	to ~10 ⁻¹ ms ⁻²
Teleseismic	~ 10,000 km	~10 ⁻² to ~1 Hz	to ~10 ⁻³ ms ⁻²
Normal Modes	Whole Earth	3x10 ⁻⁴ to ~10 ⁻² Hz	to ~10 ⁻⁵ ms ⁻²

The Earthquake Spectrum

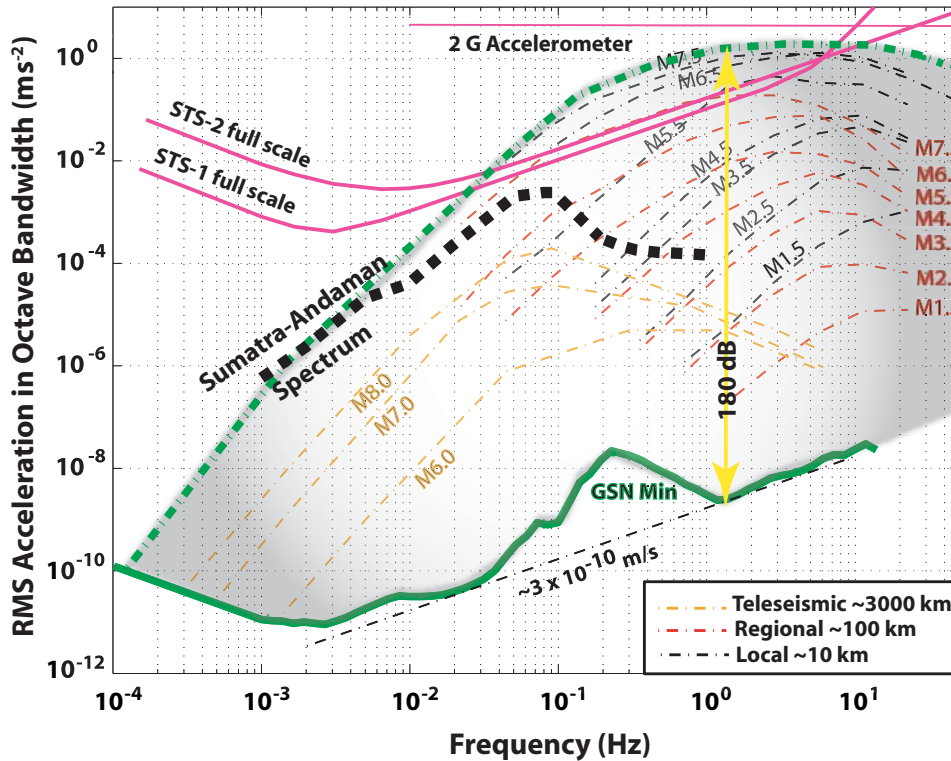


Figure 1. Representative earthquake spectra as recorded at various source distances and for a range of magnitudes. The plot also compares these signal levels to ambient Earth noise. To make meaningful comparisons between deterministic signals and random noise, the spectral unit is RMS acceleration in one-octave bands. The shaded area indicates the spectral range of earthquake signals and includes the signals from the December 26, 2004 Sumatra-Andaman earthquake observed at the closest stations (1585 km to 2685 km). The lower green line illustrates the minimum noise observed on the GSN stations (Berger et al., 2004). The pink lines indicate the full-scale dynamic range of the principal GSN sensors. Figure courtesy of J. Berger, UCSD, after Clinton and Heaton (2002).

density, and attenuation (Q) that are still widely used today (e.g., the Parameterized Reference Earth Model [PREM]) (Dziewonski and Anderson, 1981). Most importantly, the little information we have about Earth's radial density structure comes primarily from normal mode data analysis.

In the last 20 years, attention has shifted to the study of departures from simple spherical symmetry. The earliest indications that free-oscillation data contain important information on heterogeneities were two-fold. Buland and Gilbert (1979) first observed splitting due to lateral heterogeneity in low degree modes, in particular, in the gravest mode ${}_0S_2$. A few years later the “degree-2” geographical pattern in the frequency shifts of fundamental spheroidal modes was discovered, which has been traced back as originating in the upper mantle transition zone (Masters et al., 1982). Anomalous splitting of core sensitive modes was one of the key observations in the discovery of inner-core anisotropy (Woodhouse et al., 1986).

There is now renewed interest in the analysis of normal mode data. This has come with the deployment of dozens of very broadband seismometers along with the advent of digi-

tal, high-quality (low noise and high dynamic range) recording at low frequencies. These advances in observational capability have been coupled with advances in the theory of wave propagation in a 3-D Earth. High-quality data have made it possible to observe the static response to the great 1994 deep Bolivia earthquake (Ekström, 1995). More accurate mode-splitting measurements have helped put definitive constraints on the rate of relative rotation of the inner core with respect to the mantle (Laske and Masters, 1999). These improved splitting measurements have also been used to constrain core structure and anisotropy (e.g., Romanowicz and Breger, 2000; Ishii et al., 2002)

Constraints from normal modes have been used in the development of the latest generations of tomographic models of Earth's mantle (e.g., Masters et al., 1996; Resovsky and Ritzwoller, 1999a). These models provide unique constraints on the longest-wavelength (spherical harmonic degrees 2 and 4) heterogeneity. Normal mode data are the only hope for constraining long-wavelength lateral variations in density in the lower mantle, the subject of recent vigorous debate (e.g., Ishii and Tromp, 1999; Resovsky and Ritzwoller, 1999b; Ro-

manowicz, 2001). Normal-mode constraints on the density jump at the inner core/outer core boundary, critical for the understanding of core formation and dynamics, have been reanalyzed and improved (Masters and Gubbins, 2003).

There is still a wealth of information about low-degree elastic structure, particularly odd-degree structure as well as density, anelastic, and anisotropic structure, to be obtained from free-oscillation data. Making these discoveries requires high-quality, low-noise measurements at the lowest frequencies (i.e., below 0.8 mHz). Large, deep earthquakes that excite the gravest, low angular modes sensitive to Earth's deepest parts are rare (such as the 1994 M 8.3 Bolivia or the 2001 Mw 8.4 Peru events), and each of them provides different and unique constraints due to different source depths, mechanism, and locations. These events need to be observed at many different stations so as to allow the separation of source and propagation effects.

Also notable is the surprising discovery, six years ago, of Earth's "hum"—faint fundamental mode peaks seen even in the absence of recent earthquakes. They were first observed on the vertical component of STS-1 recordings in the period

range 2-7 mHz (Suda et al., 1998; Tanimoto et al., 1998) and on recordings of a superconducting gravity meter in the period range 0.3-5 mHz (Nawa et al., 1998). The mechanism exciting this hum is still the subject of vigorous research, but the existence of seasonal variations in the level of signal suggests an atmospheric or oceanic origin (Tanimoto and Um, 1999; Fukao et al., 2002; Ekström, 2001). Discovery of the "hum" was made by stacking many days' recordings from quiet stations. Recently, an array technique using the properties of propagating surface waves has shown promise in determining that a significant portion of the hum may originate in the ocean (Rhie and Romanowicz, 2004).

2.1.2. Ambient Noise

The most recent study of ambient seismic noise was a comprehensive analysis of a year's worth of data from 118 GSN stations (Berger et al., 2004). The frequency range was divided into many bins, and noise-power histograms were developed for each bin. The position of each station's power in each bin varied from bin to bin. The resulting noise model is illustrated in Figure 2.

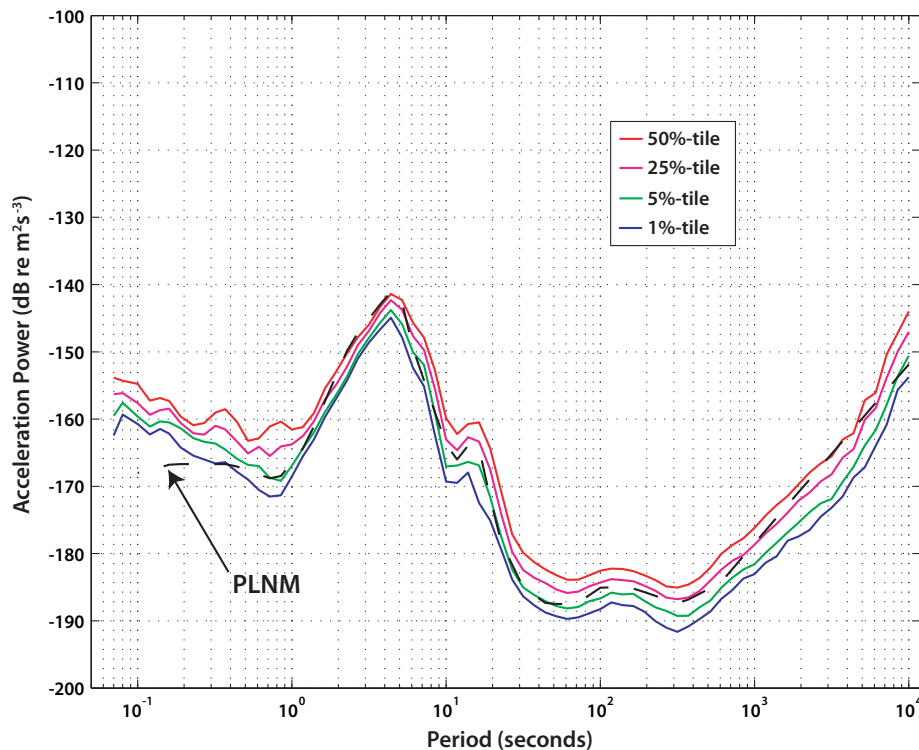


Figure 2. The GSN Low-Noise Model (from Berger, 2004). The plot shows the noise power at the 1st, 5th, 25th, and 50th percentiles for all GSN stations and channels. The dash curve in the figure is the Peterson Low Noise Model, or PLNM (Peterson, 1993). This plot shows that the Earth is even quieter at long periods than previously thought, reinforcing the need for a good long-period seismometer to replace the STS-1. Figure courtesy of J. Berger, UCSD.

2.2. Seismic Networks

The original seismic instrumentation (see Box 1) evolved into a highly specialized sensor, the Streckeisen STS-1. The STS-1 was a very broadband device designed to take fundamental research into Earth's deep internal structure and earthquake physics to new levels of resolution, and yet remain sufficiently sensitive to also record local earthquake activity with a fidelity approaching that of sensors specifically designed to monitor local activity in narrow spectral windows. The STS-1 was the ultimate sensor for probing the internal structure of the whole Earth, representing 100 years of technological advances in thermally stable metallurgical and electronics development.

The primary application for the STS-1 was in global and continental-scale networks deployed to record large earthquakes for studies of deep Earth structure and earthquake physics. Two networks that do use, or intend to use, the STS-1 are:

- The Global Seismographic Network (GSN), which operates and maintains 132 permanent stations globally.
- The USArray Backbone Network, one component of the new EarthScope program (<http://www.earthscope.org>). USArray is a large North American seismographic network currently being constructed under NSF auspices. It will eventually be operated by the US Geological Survey.

2.2.1. The Global Seismographic Network (GSN)

The Federation of Digital Broadband Seismograph Networks (FDSN) (www.fdsn.org) is an international organization for the exchange of data from global seismic observing systems. The Global Seismographic Network (www.iris.edu/about/GSN), operated by the IRIS Consortium and the US Geological Survey, is the largest network within the FDSN. The cornerstone of the GSN, the very broadband STS-1 seismometer, is no longer in production. The GSN is now faced with an aging technology base of equipment that cannot be replaced. Thus, unless steps are taken now to explore new and innovative technologies, the GSN will increasingly be unable to meet the scientific demands of the community.

GSN leadership has been aware of this problem for some time. The following paragraphs, excerpted from "Global Seismic Network Design Goals Update 2002," was prepared by

the GSN ad hoc Design Goals Subcommittee, chaired by T. Lay (http://www.iris.edu/about/GSN/docs/GSN_Design_Goals.pdf):

The design of today's Global Seismographic Network (GSN) dates back to 1985. The original design goals emphasized 20 sample/sec digital recording with real-time or near real-time data telemetry of all teleseismic ground motions (assuming about 20 degrees station spacing) for earthquakes as large as $M_w = 9.5$ (equivalent to the 1960 Chile earthquake) by a uniform global network of about 100 stations, with low noise instrumentation and environment, standardization of system modules, and linearity of response. These design goals were framed within the context of both scientific goals of the research community and by general philosophy of network design and recording system attributes that service the scientific applications of the recorded data. The intent was for total system noise to be less than the ambient Earth noise over the operating bandwidth, and to record with full fidelity and bandwidth all seismic signals above the Earth noise.

Adaptation of GSN design goals to accommodate emerging scientific directions has been, and should continue to be, an ongoing process. However, since 1984 there has not been a community-wide discussion of scientific directions to guide or modify a future vision of GSN instrumentation. Renewal proposals for IRIS funding from NSF have included updated applications of GSN data, but there has not been a forum for broad thinking on expanded roles or capabilities for GSN in the future. Thus, there is a general sense that, at a minimum, the existing instrumentation strategy is serving the community rather well and the original design criteria need to be sustained.

Further, there is increasing scientific interest in ultra-long period signals, such as the Earth's spectrum of continuously excited modes and tides. For example, superconducting gravimeters have demonstrated superior response to existing GSN instrumentation for very long-period free oscillations, and inclusion of a subset of these gravimeters at very quiet sites in the GSN may prove very attractive in the future. The value of high fidelity recording throughout the tidal band is not self-evident, and community discussion of the role GSN should play in data collection at frequencies below the normal mode band (as for some ocean oscillations) should be undertaken.

2.2.2. USArray & EarthScope

EarthScope is a set of integrated and distributed multi-purpose geophysical instrumentation that will provide the observational data needed to significantly advance knowledge and understanding of the structure and dynamics of the North American continent. One element of EarthScope is USArray, a dense array of high-capability seismometers that will improve greatly our resolution of the continental lithosphere and deeper mantle.

USArray's Backbone Network serves as a reference for the continental-scale imaging being performed by USArray's transportable components. As an integrated resource both for EarthScope science and seismic monitoring, the Backbone Network has been designed in close collaboration with the USGS Advanced National Seismic System (ANSS) (see www.ANSS.org). The proposed national broadband network component of the ANSS will consist of approximately 100 stations, of which USArray will contribute 9 new GSN-quality stations and 27 ANSS-quality stations.

USArray has been unable to acquire STS-1 sensors and consequently, the Backbone has been de-scoped and will use enhanced-performance STS-2 broadband sensors instead of the preferred STS-1 sensors.

2.2.3. Other Networks

Seismic sensors find application in a number of other fields; however, the design requirements for these systems are less demanding than for low-frequency sensors, and the engineering and production challenges tend to be driven by cost minimization and environmental factors (size, ruggedness, reliability). Seismic networks to monitor nearby activity require moderate sensitivity, but only at higher frequencies, of order 0.1 to 10.0 Hz. Engineering seismology applications focus on higher signal levels ("strong motion") and frequencies up to 100 Hz. Sensors for the petroleum exploration industry must cover the band from 4 to 500 Hz, be cheap, small, rugged, and easily deployed.

2.3. Today's Sensors

Historically, seismic sensors were separated into two general classes: those with long (15-30 sec) and short (1 sec) free periods. The former were used to measure long-period Earth motion such as those characteristic of surface waves, while

the latter sensors were used to measure high-frequency Earth motions characteristic of body waves (seismic waves that travel through Earth's interior). The widespread application of force feedback has made this distinction less important than in the past. More recent designs favor broadband (from near zero frequency to around 50 Hz) feedback instruments for most applications, but the mechanical sensor can still have either a short free period or a long free period. However, this approach is undergoing reappraisal.

Although the mass-and-spring system is a useful mathematical model for a seismometer, it is incomplete as a practical design. The suspension must suppress five out of the six degrees of freedom of the seismic mass (three translational and three rotational) but the mass must still move as freely as possible in the remaining direction. Furthermore, it must suppress the disturbing influence caused by changes in gravity, magnetic, thermal, and barometric pressure. Careful manufacture is essential in order to reach the Brownian limit in the motion of the suspended mass.

The dynamic range of the signals to be measured is large. Figure 1 showed that an acceleration-sensitive seismometer needs a very large dynamic range in order to resolve with full fidelity signals ranging from those barely above the noise to those from earthquakes of magnitude 9.5.

Excellent reviews of the history of seismometer design are given by Melton (1981a, 1981b), Farrell (1985), and Howell (1989). The design of the so-called very broadband seismometer is well described by Wielandt and Streckeisen (1982) and Wielandt and Steim (1986).

Seismic sensors can be characterized by their frequency response, sensitivity, self-noise, and dynamic range.

2.3.1. Frequency Response

Today's seismometers can be divided into three rough categories. Figure 3 shows the frequency response of a number of seismic sensors.

Short-period (SP) seismometers and geophones measure signals from approximately 0.1 to 250 Hz, with lower corner frequencies between 1 and 10 Hz. Their response is usually flat with respect to ground velocity above this corner frequency. These units are technically simple and are readily available. High-quality units without significant parasitic resonance cost around \$6,000; geophones cost a few hundred dollars.

Velocity Response Comparison of IRIS/USGS GSN Instruments

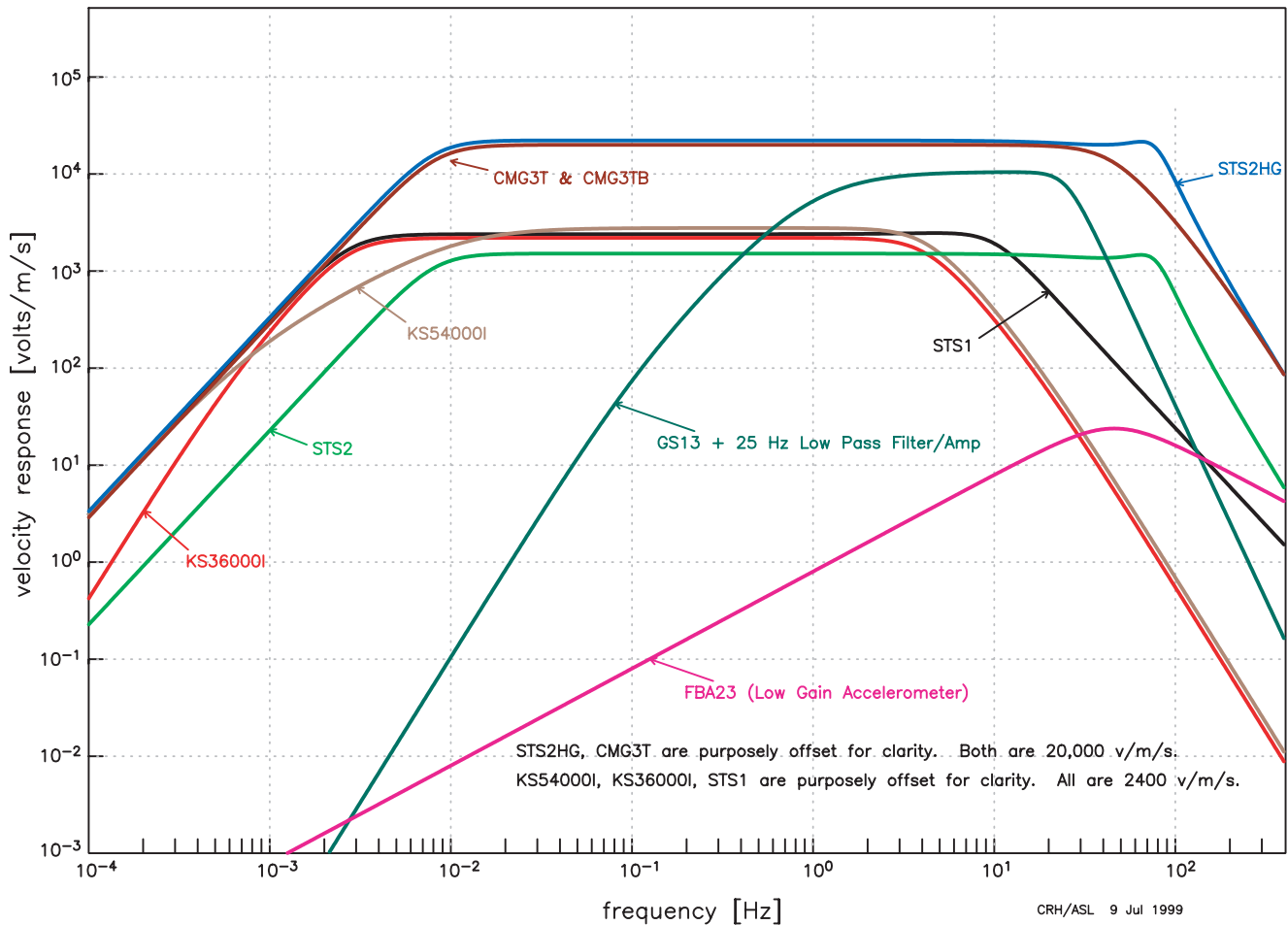


Figure 3. Frequency response of representative seismometers. Figure courtesy of R. Hutt, USGS/ASL.

Broadband sensors (BB) have a response shifted down in frequency by about two decades with respect to SP sensors. Usually, their transfer function is flat to velocity from approximately 0.01 to 50 Hz. Sensors in this class are also readily available, though they are somewhat more expensive (typically \$15,000). They are fragile and require relatively high power (~0.5 W or more).

So-called very broadband seismometers measure ground motion at frequencies from below 0.001 Hz to approximately 10 Hz and are able to resolve Earth's tides. They are extremely fragile and high power consumers (~several watts). They are expensive (typically \$45,000 for a surface sensor, \$100,000 for a borehole sensor and installation).

2.3.2. Sensitivity

Seismometers are weak-motion sensors, usually orders of magnitude more sensitive than accelerometers, though they cannot record as large amplitudes as accelerometers. Seismometers can record local but small events and/or large but distant events. The goal for a VBB seismometer is to measure ground motion smaller than the amplitudes of the lowest natural seismic noise found anywhere in the world.

Accelerometers are strong-motion sensors, and in geophysical and earthquake engineering applications, measure seismic signals between near-DC to up to 50 Hz. However, output voltage of an accelerometer is proportional to ground acceleration, whereas seismometer output is generally pro-

portional to ground velocity. For this reason, accelerometers stress high frequencies and attenuate low frequencies compared with seismometers.

2.3.3. Self-noise

All modern seismographs use semiconductor amplifiers that, like other active (power-dissipating) electronic components, produce continuous electronic noise whose origins are manifold but ultimately related to the quantization of the electric charge. The contributions from semiconductor noise and resistor noise are often comparable, and together limit the sensitivity of the system. Another source of continuous noise, the Brownian (thermal) motion of the seismic mass, may be noticeable when the mass is very small (less than a few grams). Seismographs may also suffer from transient disturbances originating in slightly defective semiconductors or in the mechanical parts of the seismometer when these are subject to stresses. An important goal in constructing a very broadband sensor for Earth studies is for the self-noise to be considerably less than the lowest ambient Earth noise. The GSN Low-Noise Model (Figure 2) summarizes the observed seismic noise levels throughout the seismic frequency band. This model is useful as a reference for assessing the quality of seismic stations, for predicting the presence of small signals, and for the design of seismic sensors.

Comparing self-noise of very broadband and broadband seismometers is instructive. The very broadband STS-1 seismometer has a theoretical noise of around $4 \times 10^{-11} \text{ m/s}^2/\sqrt{\text{Hz}}$ at a period of around 8 sec, and $5 \times 10^{-10} \text{ m/s}^2/\sqrt{\text{Hz}}$ at 1000 sec. The broadband STS-2 can achieve a noise level of $2.5 \times 10^{-9} \text{ m/s}^2/\sqrt{\text{Hz}}$ at 1000 sec.

2.3.4. Dynamic range

In a conventional passive seismometer, the inertial force produced by a seismic ground motion deflects the mass from its equilibrium position, and the displacement or velocity of the mass is then converted into an electric signal. This classical mechanism is now used for short-period seismometers only. Broadband seismometers usually are of a force-feedback design, which provides greater linearity but sometimes at the expense of reduced dynamic range. Here, the inertial force is compensated (or “balanced”) with the electrically generated

force required to constrain the seismic mass. The feedback force is generated with an electromagnetic force transducer. Due to unavoidable delays in the feedback loop, force-balance systems have a limited bandwidth; however, at frequencies where they are effective, they force the mass to move with the ground by generating a feedback force strictly proportional to ground acceleration. When the force is proportional to the current in the transducer, then the current, the voltage across the feedback resistor, and the output voltage are all proportional to ground acceleration. Thus, acceleration can be converted into an electric signal without depending on the precision of the mechanical suspension.

2.4. Overall Criteria for the GSN Seismometers

A characterization of current seismological instrumentation capabilities is shown in Figures 1, 2, and 3. A combination of sensors is often used to realize a full response, and if advances in sensor design can achieve greater performance (while retaining linearity, resolution, bandwidth, and dynamic range) over the full seismic spectrum, it would be attractive to incorporate such instrumentation into the GSN in the future. The GSN design goal is to achieve at least the bandwidth and dynamic range indicated in these figures, as is presently achieved by the current optimal GSN instrumentation. This should guide the development of instrumentation specifications for all future GSN instrumentation.

Table 2 was excerpted from the 2002 GSN ad hoc Design Goals Subcommittee document (www.iris.edu/about/GSN/docs/GSN_Design_Goals.pdf), indicating the functional specification goals of the next-generation GSN sensor. The functional specifications are derived from the design goals by considering detailed limits of the general scientific goals. In general, it's worth making the instrumentation about an order of magnitude better than our ability to model the parameters being measured. Thus, if it is intended to model amplitudes to 20%, the aggregate sources of amplitude error (gain stability, cross-axis coupling, and cross talk) should be less than 2% and individual contributions should be even less.

Table 2. GSN Sensor Requirements.

Dynamic range	On-scale broadband recordings of earthquakes as large as $M_w = 9.5$ (equivalent to the 1960 Chile earthquake) at 4,500 km.
Clip level	5.8 m/s RMS over the band 10^{-4} seconds (or below) to 15 Hz.
Self-noise	Below ambient Earth noise.
Linearity	Total harmonic distortion < 80 dB at 50% maximum acceleration and frequencies within the pass-band of the feedback loop.
Bandwidth	Earth free oscillations to regional body waves (up to 15 Hz for land stations, 100 Hz for ocean-bottom sites).
Calibration	Known to 1% and stable across the bandwidth (adequate for amplitude modeling which at best is good to about 20%).
Cross-axis coupling	Less than about 1% (adequate for amplitude modeling).
Degrees of freedom	Three mutually orthogonal components of motion should be recorded.
Reliability	MTBF of years.
Shock and vibration	Equipment must be robust to survive shipping and installation.
Other environmental	Environmental susceptibility (to temperature, pressure, magnetic fields, electromagnetic and audio fields, etc.) should not constrain site selection or deployment technique.

3. New Ideas and Concepts

This section summarizes emerging designs and concepts for very broadband seismometers that were presented at the workshop. Abstracts, presentations, and posters are given in full in the accompanying CD.

Engineering challenges for seismic sensor design are largely noise floor, dynamic range, and stability. Two fundamental limits in achieving a low noise floor are: (1) suspension noise caused by the Brownian motion of the suspended mass, and (2) Johnson, or thermal, noise. The overview of emerging technologies given below shows that it will be a complex, but not overwhelming, challenge to meet or exceed the noise floor of the STS-1 sensor.

It is unclear which of the technologies behind these sensors, if any, are most appropriate for the development of a new GSN seismometer. The geoscience community alone is not in a position to adequately assess the suitability of these emerging technologies. It is these advances and their possible application to the design of the next-generation GSN seismometer that participants explored in the workshop.

3.1. Micro Electro Mechanical System (MEMS) Seismometer

Developments in miniaturization of broadband sensors have reached designs achieving broadband noise levels of around $3 \times 10^{-9} \text{ m/s}^2/\sqrt{\text{Hz}}$ (compared with STS-1 and STS-2 seismometers in section 2.3.3) and full-scale acceleration of around 2 m/s^2 in small packages (2 cm x 2 cm) weighing 1 kg or less. Size reductions have come through shrinkage of conventional spring-mass systems. This reduction is carried out by micromachining the entire system into a “chip-based” package of a few grams using high-sensitivity piezoelectric materials. Some sensors are internal to the sigma-delta converter and serve as the summing junction, producing digital data. These miniature, small-mass sensors require very-high-Q suspensions and relatively low natural frequencies to achieve suitable noise characteristics for GSN-style applications. It appears that Q values of 1000-10000 can be reached and maintained in 10-Hz suspension systems. At present, MEMS do not provide a force-feedback mechanism, which may limit their dynamic range.

3.2. Electrochemical Transducer Suspension Design

Unlike a traditional mass-on-a-spring seismometer design, Molecular Electronic Transfer (MET) seismic sensors have elastic membranes instead of springs, and a significant part (or even all) of the inertial mass is liquid. The output of these sensors is inherently independent of the inertial mass position, so no mass locks or mass centering is required. Another feature of a mass-position-independent output is the simplified force-balanced feedback circuit design that contains no integrators, thus is a lower-noise operation at long periods. Current designs have a natural frequency of about 3 Hz that allows for a velocity-flat response from 120 sec to 50 Hz. There is no theoretical limitation for expansion of the pass-band to at least 1000 sec, but it will require a special, very “soft” membrane design.

3.3. Magnetic Levitation Seismometer

To remove a pendulum’s high-frequency noise that results from the parasitic resonances of a suspension spring, and to reduce the thermal dependence of the spring, permanent magnet levitation for a pendulum weight may be employed. Current implementations of this technology achieve noise levels in a vertical-component seismometer near $10^{-9} \text{ m/s}^2/\sqrt{\text{Hz}}$ near 1 Hz. Such systems have been shown to be extremely sensitive to barometric effects, necessitating installation within a pressure chamber. Isolated in this manner, these sensors may demonstrate noise levels similar to that of an STS-2 sensor.

3.4. Ferro-Fluid Suspension

The unique feature of this design is that it makes use of a suspended magnetic mass to measure ground velocity (i.e., it does not make use of springs or noise-producing mounting suspensions). Positioning a permanent rod magnet within a cylindrical cavity containing a ferromagnetic fluid is a frictionless and noiseless way to configure a velocity sensor proof mass. Positioning a coil around the housing is an easy way to measure the velocity of the case. In addition, this implementation provides for very large deployment forces with-

out changing the characteristics of the device. The potential to force-balance the proof mass offers even greater low-frequency performance.

3.5. Quartz Seismometer Suspension

The proposed 1 TeV X-band electron/positron linear collider at SLAC (Stanford Linear Accelerator Center) will produce beams with approximately 1 nanometer vertical sizes at the collision point. The final focusing magnets for this accelerator must be held at the nanometer level relative to each other. Beam-beam interactions provide a signal for a high gain feedback for frequencies below ~ 1 Hz, but additional stabilization is required at higher frequencies. One option is to use inertial sensors (geophones) to provide a feedback signal. The high magnetic fields mean that the seismometer must not be sensitive to magnetic fields, preventing the use of temperature-compensated spring materials, and so a novel quartz suspension system was developed. Temperature variations probably are a major noise source below 0.1 Hz. Preliminary testing against a STS-2 sensor shows that the noise floor is below $10^{-8} \text{m/s}^2/\sqrt{\text{Hz}}$, and that the $1/f$ noise corner is ~ 0.1 Hz.

3.6. Folded Pendulum

Folded pendulums are classical suspension systems first developed more than a century ago. Their modern development is partly related to gravity wave research. These systems are too large to fit into the limited space of boreholes and seafloor packages, basically because of the compromise between the residual elasticity and the suspended load. Recent progress in precision micro-machining allows extremely soft flexures at the pendulum's hinges. A broadband folded pendulum with reasonable size and natural frequencies (< 1 Hz) has already been developed and tested for gravitational wave-detection experiments. Additionally, studies of the flexures involved finite-element modeling to suppress their elasticity. As a result, it may be possible to fabricate folded pendulums with dimensions on the order of a few centimeters, which is required for borehole and seafloor seismic sensor applications.

3.7. Electrochemical Displacement Transducers

MET technology features an innovative transducer design suitable for low-noise translational and rotational seismic

sensors. The transducer consumes extremely small amounts of power (down to 30-50 mW), has a very low self-noise level, and is insensitive to strong magnetic fields. MET transducers consist of four microscopically thin platinum mesh electrodes separated by thin-film microporous spacers placed in a tube filled with an iodine-based electrolyte. A small DC-offset is applied between each pair of electrodes. The convective diffusion phenomenon is used to convert the flow of the electrolyte to the electric current. This transducer has a symmetric configuration and a differential output that allows for linear operation with 120-130 dB dynamic range. With force-balanced feedback (electrodynamic or magneto-hydrodynamic type), dynamic range can be extended to 150-160 dB. The electrochemical transducer features an acceleration-flat noise power spectral density that is determined by its hydraulic impedance (similar to Nyquist noise of a resistor). In a 2-inch diameter rotational sensor, noise spectral density is about $3 \times 10^{-7} \text{rad/s}^2/\sqrt{\text{Hz}}$. Translational sensors have noise levels below $3 \times 10^{-9} \text{m/s}^2/\sqrt{\text{Hz}}$. Lower noise levels can be achieved by development of a lower hydraulic impedance electrochemical transducer.

3.8. SQUID Displacement Detector

Superconducting Quantum Interference Devices (SQUIDs) are intrinsically quieter than room-temperature displacement sensors due to material property improvement that temperatures below 10 K can provide, providing theoretical limits as small as two orders of magnitude lower than capacitive detection. To date, no seismic sensors have been constructed using this technology.

3.9. Optical Displacement Transducer

The laser interferometric displacement sensor has several advantages such as high resolution, low drift, low heating, and *in situ* calibration with reference to the wavelength of light. A wideband seismometer using a Michelson interferometer and a long-period pendulum has been developed by Japan's Earthquake Research Institute ERI. This seismometer has a self-noise level below NLNM at 50 mHz to 100 Hz and has 1% *in situ* calibration accuracy. The optical-fiber-linked version, which may be used in high-temperature environment such as deep borehole, is under development. Scientists at Scripps Institution of Oceanography developed a wideband optical seismometer with an STS-1 pendulum and a bi-directional inter-

ferometer, and successfully operated it with a phase decoding system using digital signal processing. Another approach for a horizontal seismometer is a long-baseline laser strainmeter that is essentially insensitive to local ground tilt. Although its large scale makes it difficult to spread into many observatories, a significant self-noise improvement of horizontal seismic observation would be possible if a highly frequency-stabilized laser is used. A 100-m laser strainmeter installed in Kamioka Mine (Japan, 1000 m underground) attained an effective background noise level of $1 \times 10^{-9} \text{ m/s}^2/\sqrt{\text{Hz}}$ at 10 mHz and $4 \times 10^{-9} \text{ m/s}^2/\sqrt{\text{Hz}}$ at 0.5 mHz.

3.10. Superconducting Gravimeter

Several superconducting gravimeters (SCG) operating in the Global Geodynamics Project network demonstrate lower noise levels than the STS-1 for frequencies below 1 mHz. Increasing the mass from about 6 g (2.5-cm diameter) to 80 g (5-cm diameter) will decrease Brownian noise by at least a factor of 100 and will be well below the NLNM for frequencies in the normal-mode band. Current versions of the gravimeter are made in small quantities and sell for \$350,000. It is possible that versions optimized for seismology could be manufactured for about \$100,000 if quantities ordered were roughly five per year. It was noted at the workshop that the SCG can record vertical ground motion only.

3.11. SLAC Strainmeter

SLAC has a 2-mile-long linear accelerator (linac) that was built about 30 years ago. The alignment system of this accelerator consists of a “light pipe,” which is a 60-cm diameter, 2-mile-long straight evacuated pipe, with the laser source (shining through a pinhole) and a quadrant photo-detector located at opposite ends. About 200 remotely controlled Fresnel lenses are located along the linac, and can be inserted into the pipe one by one. Such a system can detect lateral Earth deformation over distances of 3 km, with a resolution of around 20 nm.

3.12. Feasibility of Using LIGO Facilities as Strainmeters

At the LIGO Gravity-Wave Observatory sites at Hanford, WA and Livingston, LA there are sensitive laser interferometers that monitor the distance in a vacuum between pairs of suspended test masses 4 km apart in two perpendicular directions, in terms of the wavelength of light from an NdYAG la-

ser. This laser is stabilized to a reference cavity whose length is modulated slightly by adjusting its temperature to partially compensate for the changes in the 4-km baselines arising from Earth tides. To use one of these interferometers to monitor Earth strain with the highest possible precision would require some additional equipment: one sensor to reference the position of each suspended test mass to some point in the ground, and another to continuously monitor and record the slowly varying frequency of the light from the NdYAG laser. Such systems may be non-trivial, though simpler compromise solutions with lower precision are possible.

3.13. Ring Laser Gyro

In 2000, a joint New Zealand-German program obtained very encouraging results in measuring angular rates of deformation within the Earth’s crust. Located in a vault in Christchurch, NZ a block of low CTE (coefficient of thermal expansion) material about 1 meter square, implemented as a ring laser gyro, has achieved a level of sensitivity that appears to be detecting tilt due to tides. A second gyro has been installed at the Piñon Flat Observatory in California by the German group. This technology may provide the orientation information needed to separate the tilt-horizontal coupling that limits interpretation of horizontal seismometer data.

3.14. New Forcing and Sensing Methods for Seismometers

New sensing and forcing schemes should be investigated for seismometers. Techniques that use over-sampling (256 times or more), correlated double sampling, and fully differential circuits can cancel or greatly reduce sensing noise at low frequencies. Similar techniques could be applied to forcing circuits to reduce noise in the feedback loop.

3.15. Atomic Fountains for Inertial Sensors

Atomic fountains receive their name because atoms are launched upwards and fall back under gravity. Such fountains demonstrate an accuracy of around 10^{-9} m/s^2 as a gravity meter. Stanford is leading a development effort for a family of inertial instruments based on this technology for field application in inertial navigation and gradiometry. The technology is currently being developed at ESA for orbital flight for a science experiment of unusual sensitivity. Properly scaled, this technology has promise for geophysical measurements.

4. Testing and Test Facilities

4.1. Introduction

The Testing & Testing Facilities (T&TF) Breakout Group began discussions by reviewing the highlights of discussions of a small group that met in 1989 at the USGS Albuquerque Seismological Laboratory to discuss Standards for Seismometer Testing (SST) in order to compare short period, broadband, and very broadband seismic sensors. Results and minutes of this meeting were presented at the 1990 Annual Meeting of the Seismological Society of America, and at subsequent IUGG meetings and IRIS meetings (Hutt, 1990). Building upon the SST results, the Testing & Testing Facilities Breakout Group suggested that “Standard Parameters and Standards for Reporting Measured Parameters of VBB Sensors” were needed for users of seismic data.

The group also expressed the need to identify different kinds of tests. For example, manufacturers have specific tests that they use in research and development and in production testing and certification. The suite of tests used by manufacturers may be different from the suite of tests used for acceptance testing by the purchasers of the sensors. The station or system operators may have yet a different suite of tests that they prefer or need after the GSN sensors are installed and operating.

Some relevant tests for GSN sensors were discussed by the T&TF Breakout Group, and the results of the 1989 SST meeting were discussed in the context of defining parameters that might need to be measured and the frequency of re-measuring these parameters after installation and operation of the GSN sensors. The T&TF Breakout Group has two recommendations:

1. Establish a working group (or standing committee) similar in composition to the group included in the 1989 SST meeting in Albuquerque and in the T&TF Breakout Group at Granlibakken.
2. Upgrade an existing testing facility with support for instrumentation and staff that could provide a needed service to the GSN user community.

Together, the GSN sensor working group, testing facility, and staff should provide standard parameters and measurements of GSN sensors for the manufacturers, developers, and users of GSN sensors and data.

4.2. Test Facilities

Adequate testing of sensitive seismometers must be performed, in part, at remote field facilities. The two premier sites for seismometer testing in the US are the UCSD Piñon Flat Observatory in California, and the USGS Albuquerque Seismological Laboratory in New Mexico. They meet most of the desiderata for high-accuracy testing including experience and technician support, infrastructure (e.g., buildings, isolated pillars, electricity, laboratory space, Internet access), low-enough seismic noise, accessibility, and suitable reference instrumentation. At both sites the ambient noise is many dB higher than the global minimums, but with pairs of comparable instruments, cross-spectrum analysis can pick out the sensor noise if enough data are recorded. These two facilities have been sporadically improved over many years. New requirements for next-generation instruments may require further development. This might include data-acquisition equipment, additional vaults/pillars, isolation tables, calibration tables, and environmental chambers.

Other test facilities are established and fulfill a number of purposes, but their use should not supplant some level of testing at the premier facilities noted above. Among these secondary sites are the FACT site of Sandia National Laboratories at Kirtland Air Force Base, New Mexico and the Pinedale Seismic Research Facility at the Air Force Tactical Analysis Center in Wyoming. Most manufacturers have seismometer test facilities (e.g., Nanometrics in Canada, and Guralp in England). Overseas academic facilities of note include the Black Forest Observatory in Germany, the Conrad Observatory in Austria, and an accelerometer test facility related to gravity-wave detectors in Florence, Italy.

4.3. Test Procedures

Test procedures and the method of reporting test results should consider the procedures and templates described in ANSI (2003). Many of the sections are as applicable to seismometers as they are to accelerometers for inertial guidance systems. The Albuquerque Seismological Laboratory documented their approach some years ago (Hutt, 1990), and it would be appropriate to review and update these written guidelines. A revision should consider all phases of testing, including development testing, design qualification testing, acceptance testing, operational testing, and post-installation testing.

4.4. Support and Access

Top-notch field facilities are not cheap. As national resources they should be funded, not only for the manager's parochial interests, but also for use of the whole community— academic and commercial, national, and international. Thus, managers should be accommodating to all potential users and provide visitors a range of support. However, there must be an understanding of the limits of default support, and provision made for recharge to handle exceptionally long or arduous visits.

In general, open circulation of test results, including peer-review publication, is to be encouraged. However, vendors may have proprietary interests in test results, whether favorable or unfavorable, and these concerns about intellectual property (IP) will need to be respected.

5. Partnerships Between Industry and Academia

5.1. Historical Background

Effective partnerships between industry and academia have given Earth scientists their best instruments for low-frequency seismology. The LaCoste-Romberg gravity meter, on which Earth's free oscillations were first observed, grew from a graduate student thesis into a major geophysical corporation. The superconducting gravity meter was first developed in an academic department and later commercialized. But these two examples are decades old, and there are no recent instances in the United States of connections between industry and academia for development of sensors suitable for low-frequency seismology. This is not the case in Europe, where both the Guralp and Streckeisen companies have their roots in university research.

By far the most significant work in the United States over the last half century on seismic sensors has been directed toward systems for nuclear test detection. These were superb for the need, and some systems or sub-systems developed for nuclear monitoring have been deployed in the Global Seismographic Network. However, it is clear that these sensors are not the best at the lowest frequencies. Furthermore, test-detection programs ceased developing new sensors more than a decade ago.

We believe the collaboration in the United States between industry and academia for developing novel seismic sensors needs to be revitalized. This collaboration should be shaped by realizing that exciting discoveries in low-frequency seismology are more likely to come from large-scale deployments of quantities of sensors than from highly sophisticated, but one-off systems. Industry, rather than the academic research department, is the place to manufacture commodity instruments.

Researchers will get the instruments they need only if each side understands the requirements and limitations of the other. Industry must see an opportunity for profit. Academics seek new knowledge, and almost always, their science-based research is advanced by new instrumentation. A

deep understanding of the capabilities and limitations of instrumentation is fundamental to progress.

5.2. What is an Appropriate Relationship?

The market for long-period sensors is so small, and the units that can be sold per year so limited, that industry can not be expected to perform the necessary R&D for this community on speculation. This situation does not apply for instruments in higher-frequency bands. In the oil business, the market can justify investment of many millions by sensor manufacturers, because, if successful, they will sell many thousands of units a year. In the smaller community of body wave seismology, it is also true that manufacturers have been able to fund research and development internally, even for sales of a few hundred units a year or less.

In the low-frequency seismology community, we generally require quantities of a few score, at most, to be delivered over many years. This combination of market size and production rate means that our most important task is for industry and academia to work together to obtain the R&D funds necessary for progress.

For some years there has been the hope that an instrument targeted to the higher-frequency market (frequencies $> .01$ Hz, say) would, almost as a side effect, have adequate performance at the very lowest frequencies. Experience has shown that this is generally not the case. The very best low-frequency sensors are purposely designed. Thus:

- Superior low-frequency seismic sensors are not likely to be developed from R&D funds internally generated by manufacturers.

Thus, the foundation of the academic/industrial partnership will continue to be an academic evangelist with a compelling science question whose answer requires state-of-the-art instrumentation. This person is someone who is obsessed by the science, is successful at fund raising, sits on the right committees, and is viewed as a dynamo in their field. They

provide the scientific basis and enthusiasm that will be used to motivate support from the funding agencies.

The process of cooperative instrument development between industry and academia begins with the conceptual design and continues through prototype production into testing. As previously noted, the academic member of this team is responsible for the science while the industrial partner has the manufacturing plant. Ideally, they collaborate on the common ground of instrument design. This delineation is blurred in actuality, for one hopes both partners are involved to some extent in all aspects.

The following paragraphs list three activities that can jointly involve academics and industry. For each activity we define the contribution of each partner, and the benefit of the contribution to the other partner.

Activity: Development of New Sensor Concepts

New sensors might be based on traditional electro-mechanical concepts, or involve novel technologies, including micro-machining and application of atomic and quantum physics.

Academic Contribution and Benefit to Industry

Concepts can arise in departments of Earth Science or other academic departments, and then brought to industry.

Benefit to industry:

- New, marketable instrumentation ideas.
- Academic laboratories a source of employees with instrumentation experience.

Industrial Contribution and Benefit to Academe

Concepts can arise internally. Academics can be involved as consultants, or non-commercial ideas handed over under suitable condition.

Benefit to academe:

- Exposure of faculty and students to industry practice.
- Access to engineering support, e.g. machining, electronic design, prototypes.

Activity: Field Testing of Sensor Prototypes

Testing of sensitive instruments must be conducted in low-noise settings, preferably with simultaneous recording of reference sensors and environmental conditions.

Academic Contribution and Benefit to Industry

Field observatories, especially observatories in low-noise settings and with diverse instruments and digital data acquisition systems.

Benefit to industry:

- The best field observatories have a level of infrastructure support greater than industry can afford.
- Ability to cross-correlate data from new sensors with data from other seismic and environmental sensors.
- Experience of academic team in multichannel data processing.
- Operation of instruments by third party under realistic field conditions.
- Independent verification of instrument performance.
- Feedback from academic community for improved instruments.

Industrial Contribution and Benefit to Academe

Loan of prototype or pre-production sensors for operation and evaluation.

Benefit to academe:

- Early familiarity with novel instruments.
- Ability to influence sensor design and performance.
- Challenging projects for students.
- Possible financial support while conducting evaluations.

Activity: Sponsorship of Research Parks

University administrators are increasingly interested in fostering the migration of research results into commercial enterprises. Research parks are incubators of startups.

Academic Contribution and Benefit to Industry

Several universities have established research parks as incubators for new businesses. Among those with notable departments in the Earth Sciences are: Stanford University, University of Colorado at Boulder; University of Texas at Dallas, and New Mexico Tech. An example from overseas is the University of Reading in the UK.

Benefit to industry:

- Continuing relationship with host university.
- Availability of business-related consultants and support services (management, accounting, legal).
- Availability of technical support services (software, hardware, mechanical).
- Reduced risk through possible cost sharing with university.
- Royalties and jobs for graduates if the venture is successful.

Industrial Contribution and Benefit to Academe

Royalties and jobs for graduates if the venture is successful.

Benefit to academe:

- Endowment.
- Jobs and growth.
- Continuing relationship with industry.

5.3. Respect for Intellectual Property

It is important that intellectual property rights be settled before collaboration begins. Industry will be secretive about their most valuable ideas. Academics will focus on open discourse and publication in peer-reviewed journals. Finally, university administrators are increasingly eager to protect and promote the discoveries of their faculty for financial return. This three-way tension requires careful delineation of these issues early in the cooperative process.

The following are the principal mechanisms for protecting intellectual property. (For more information, go to http://law.freeadvice.com/intellectual_property/)

- **Patents:** Patenting is a costly and lengthy process. A technology that is patentable may, in fact, become obsolete before a patent is issued. For these reasons, this industry tends not to patent inventions in this technology. However, if an idea is patentable, the rule must be patent before publish.
- **Trade Secrets:** This broad category includes almost anything of economic value. Industry can be expected to forbid publication of trade secrets.
- **Licensing Agreements:** Licensing agreements allow one party to use, and possibly market, intellectual property of another party. They can work both ways: universities can license discoveries of faculty and staff to industry for commercial use; industry can license intellectual property to academics for non-commercial research. However, in the latter case, a non-disclosure agreement might be more appropriate.
- **Non-disclosure Agreements:** Non-disclosure agreements are used by the owner of intellectual property to disclose information to a second party for their exclusive use.
- **Contracts:** In the case where industry contracts with an academic for some research or development activity, the intellectual property issues would be included in the terms and conditions.

The foundation of the university is the discovery and exchange of knowledge. This exchange may indeed be advantageous to both groups as it accelerates progress and provides

new scientific and economic opportunities that each group is free to explore on their own. If the market for some product is small, an open relationship between industry and academia can provide a solution that benefits both parties. The recent development of the unique “Texan” seismic recorder, developed jointly by the University of Texas, El Paso and Refraction Technology, is an example of such an open cooperation. These sorts of exchanges can lead to additional ideas for product development. The success of such projects benefits from the acceptance of risk and the sharing of cost by both industry and academia.

5.4. Student Involvement

Student training is one of the strongest reasons for industry and academia to cooperate. Historically, industry has sponsored scholarships, intern programs, and cooperative projects in order to support students at the interface between academia and industry. Although the numbers and types of these programs have decreased in recent years, it is recognized that they need to be maintained and possibly extended.

Student support by industry provides industry with young and energetic resources. These students can bring seismological expertise to industry under close cooperation. They also provide a resource to industry for future employment. Industry provides engineering, design, and manufacturing experience to the student, thus providing them with a broader understanding of practical issues associated with instrumentation.

This involvement is not without a burden on both the academic and industrial participants. Industry will always consider the opportunity cost of accepting student employees, for professional staff will need to devote some effort to their training and supervision. The academic participants need to understand the requirements that industry has for students in their work environment. Unique collaborative oversight of this cooperation may be required such as industry-supplied ideas and academic monitoring of the students.

Access to students by industry offers a secondary advantage in that they can be a conduit by industry to the vast resources at the university beyond individual departments or programs. Students can provide a venue for developing additional collaborations or sharing of resources at the university because of their exposure to courses and faculty across the university.

6. Education and Funding

The future generations of sensor developers must come from the universities. There is always a need for innovation in instrumentation, and there are many instances of science and understanding advancing when data, previously unobtainable, are provided by new instruments. The seismology community, however, is faced with the potential of reduced access to some signals from Earth (see Box 2), which are vital for increased understanding. As detailed elsewhere, the seismometer providing most of the low-frequency data is no longer being manufactured.

This lack of new sensor designs is symptomatic of a rather serious situation in universities. There is rapidly disappearing expertise in sensor design. Sensor design projects are difficult to fund through normal NSF research proposals. There are special programs within NSF, but they tend to be focused on cutting-edge technologies and may not be receptive. As a result, all of the surface-installed broadband seismometers in the GSN and PASSCAL programs, and in EarthScope's USArray, have been manufactured overseas. This situation is very different from that of the first major global seismology project, the WWSSN (World-Wide Standardized Seismographic Network). At that time (late 1950s), it was natural to buy all the sensors from US manufacturers because they led the world.

Clearly, some action is needed to improve the situation. At least two approaches are necessary. First, there must be graduate fellowship support available for sensor development. This opportunity must be publicized to the community. Second, because faculty expertise no longer exists widely, faculty internships to industry and other institutions will be effective. This kind of program has been very effective in other countries, such as Japan.

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