Background for the VBB Workshop

Contents

Summary

This workshop will be focussed on the design of ultra-quiet, large dynamic range, very broadband (VBB) and broadband (BB) seismometers. The workshop will bring together seismologists, engineers and physicists to discuss design considerations of such a sensor. The workshop will identify current and emerging technologies, and suggest possible partnerships between seismological and engineering/physics research laboratories. The primary goals of the workshop are:

- To define the design goals for a new ultra-quiet, VBB seismic sensor
- To identify current and emerging technologies that may be used
- To form teams of engineers and seismologists interested in this challenge
- To draft a 5-year strategic plan for development of the next generation sensor

The 2.5 day meeting is expected to include a mixture of plenary oral and discussion sessions, poster sessions, breakout sessions, and conclude with formal writing assignments for an implementation and management plan to develop the next generation of ultra-quiet, VBB and BB seismic sensors for surface, deep-borehole and ocean-bottom emplacements.

Seismic Sensors – a primer

The term seismic sensor is used here to connote the mechanical or electromechanical assembly which converts earth-motion into a voltage, which can be recorded. Here, sensors are distinguished from systems, in that the latter may consist of multiple combinations of the former, coupled to recording apparatus. Historically, seismic instruments were separated into long-period sensors and short-period sensors. This reflected not only the free period of the second-order mechanical system, but also dictated that instruments of long free period were utilized to measure seismic surface waves, and instruments of short free period were utilized to measure body waves (seismic waves that travel through the interior of the Earth). The widespread application of force feedback has changed this. Designers today favor broadband (from near zero frequency to around 50Hz) feedback instruments for most applications, but the mechanical sensor can still have either a short free period or a long free period.

There are two basic types of seismic sensors: inertial seismometers which measure ground motion relative to an inertial reference (a suspended mass), and strain-meters or extensometers which measure the motion of one point of the ground relative to another. Since the absolute motion of the ground relative to an inertial reference is in most cases much larger than the differential motion over the short baseline within a vault of reasonable dimensions, inertial seismometers are generally more sensitive to earthquake signals. However, at very low frequencies (periods longer than 100 sec) it becomes increasingly difficult to maintain an inertial reference. For the observation of low-order free oscillations of the Earth, tidal motions, and quasi-static deformations, strain-meters may outperform inertial seismometers. Strain-meters are conceptually simpler than inertial seismometers although their technical realization may be more difficult.

An inertial seismometer converts ground motion into an electric signal but its properties cannot be described by a single scale factor, such as output volts per millimeter of ground motion. The response of a seismometer to ground motion depends not only on the amplitude of the ground motion, but also on its frequency content. This is because the seismic mass has to be kept in place by a mechanical or electromagnetic restoring force. When the ground motion is slow, the mass will move with the rest of the instrument, and the output signal for a given ground motion will therefore be smaller. The system is thus a high-pass filter for the ground displacement. This must be taken into account when the ground motion is reconstructed from the recorded signal.

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 influence from changes in gravity, magnetic, thermal and barometric signals, as well as Brownian motion of the suspended mass.

The signal radiated from a seismic source, be it an explosion or an earthquake, is usually a more or less complicated displacement step function or velocity impulse of finite duration from milliseconds up to a few minutes at the most. While 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, mostly unrelated and often continuous sources, such as wind, ocean waves, cultural, etc. Seismic noise thus forms a more or less stationary stochastic process without a defined phase spectrum (somewhat similar to electronic instrumental self-noise and the Brownian or thermal motion of the seismic mass). The dynamic range of seismic signals is shown in Figure 1. This figure indicates that an acceleration-sensitive seismometer needs a very large dynamic range in order to resolve with full fidelity the broad spectrum of Earth signals from ambient noise to earthquakes as large as magnitude 9.5. As an example, this figure shows that the ambient Earth noise between 10 and 20 seconds is –180 dB relative to 1 m/s^2. This corresponds to average peak amplitude of $10^{-180/20} m/s^2 = 1\ nm/s^2$ in 1/3 octave bandwidth. Accordingly, the total average peak amplitude in this one octave band between 10 and 20 seconds is $3^{-1/2} nm/s^2$.

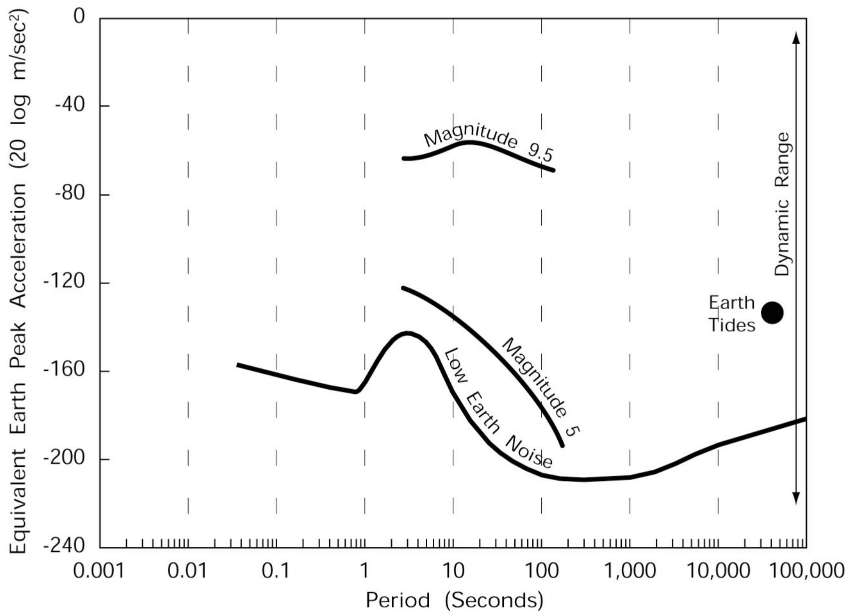

Figure 1: Spectral amplitudes of ambient seismic noise, earthquakes (magnitude 5 and 9 recorded at a distance of 4,500 km), and Earth tides. Units are expressed as RMS amplitudes of ground acceleration in a constant relative bandwidth of one-sixth decade, which corresponds approximately with average peak amplitudes in one-third octave bandwidth.

VBB and BB Sensor Characteristics

VBB and BB sensors are utilized in global seismology studies. Because of their low self-noise, broad-frequency response and large dynamic range, VBB sensors are able to resolve the lowest seismic frequencies such as Earth tides and free oscillations of the Earth (Figure 2). Their primary purpose is in research of the deep interior of the Earth and earthquake dynamics, which has applications in the assessment of earthquake hazards and the reduction of seismic risk. VBB sensors are expensive, fragile, require very elaborate and expensive seismic shelters, and as a rule, require considerable expertise to install. Site selection and preparation for a VBB station requires extensive studies and expensive civil engineering works. Seismic sensors placed in boreholes at depths of 100m or greater have the potential to be much quieter than surface installations because much of the desired low-frequency data may be masked in surface noise.

BB sensors are also attractive for educational seismic networks, but their initial purchase price excludes them from many schools with a geoscience curriculum. The development of a low-cost BB system will allow under-resourced schools to participate in the global community of stations used for the study of earthquakes and the study of the Earth's interior, both through the utilization of global earthquake data and the possibility of providing data to the world of research.

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

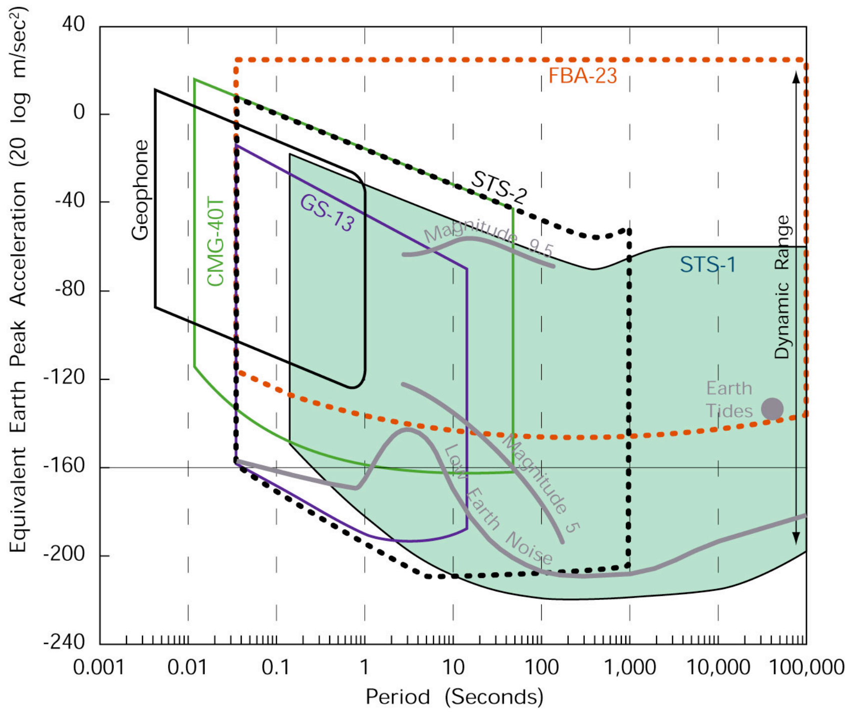

Figure 2: Same as Figure 1, but showing spectral amplitude response characteristics of typical seismometers used in local, regional and global networks, some of which are deployed at many Global Seismographic Network (GSN) sites. The very broadband STS-1 sensor, a cornerstone of the GSN can resolve both low Earth ground noise, as well as record on-scale Earth tides and a magnitude 9.5 earthquake 4,500 km away. The STS-1 sensor is no-longer in production.

Frequency response:

Today's seismometers are roughly divided into three categories.

- Short-period (SP) seismometers and geophones measure signals from approximately 0.1 to 100 Hz, with corner frequency at 1 Hz. They have a flat, ground velocity proportional output above this corner frequency. These units are technically simple, and are readily available. High-quality units without significant parasitic resonance cost around $6,000).
- Broadband sensors (BB) have a flat ground velocity proportional response from approximately 0.01 to 50 Hz and are also readily available, albeit expensive (typically $15,000). They are fragile and require relatively high power (~0.5W).
- Very broadband seismometers (VBB) measure 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), but no longer in production.

The frequency limits shown in Figure 3 are the corner frequencies of sensors' frequency response function. In general, the flat portion of the frequency response function should cover the range of frequencies which are generated by seismic events of interest or which are important in a particular phenomenon studied.

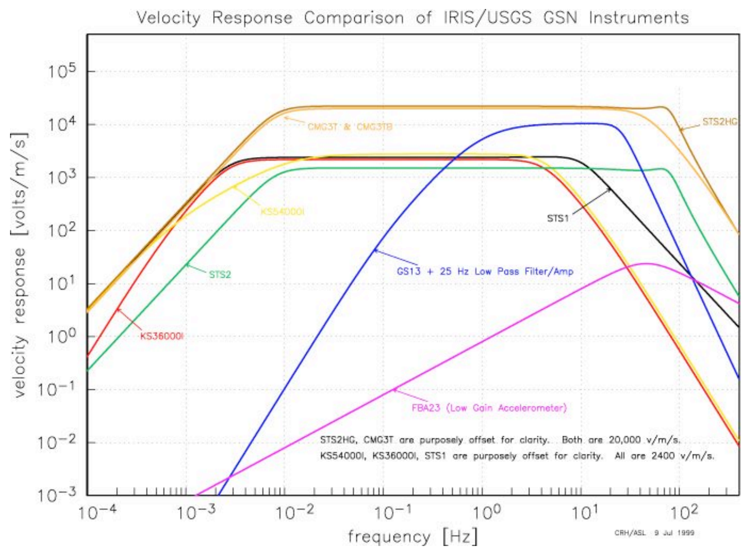

Figure 3: Spectral response of several seismological sensors, showing characteristic response that is flat to velocity (the FBA23is an accelerometer, and is flat to acceleration), with corner frequencies defining the sensor bandwidth (Bob Hutt, USGS/ASL, pers comm.).

Sensitivity:
Seismometers are weak-motion sensors, and are usually orders of magnitude more sensitive than accelerometers, however they cannot record as large amplitudes as do accelerometers. Seismometers can record very weak and/or very distant events, which produce ground motion of comparable amplitudes to natural seismic noise. 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 proportional to ground velocity. For this reason accelerometers stress high frequencies and attenuate low frequencies compared with seismometers.

Seismometer self-noise
All modern seismographs use semiconductor amplifiers which, like other active (power-dissipating) electronic components, produce continuous electronic noise whose origin is 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 VBB sensor for Earth studies is for the self-noise to be considerably less than the lowest

ambient Earth noise. The USGS New Low-Noise Model (NLNM, Figures 1 and 2) summarizes the lowest observed vertical seismic noise levels throughout the seismic frequency band. The NLNM is useful as a reference for assessing the quality seismic stations, for predicting the presence of small signals, and for the design of seismic sensors.

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 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.

Overall Criteria for the VBB Seismometers

The following section is excerpted from the document "Global Seismic Network Design Goals Update 2002", prepared by the GSN ad hoc Design Goals Subcommittee, indicating the functional specification goals of the next generation VBB 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.
>
> 1. 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 of 5.8 m/s rms over the band 10^{-4} seconds (or below) to 15 Hz.
>
> 2. Self-noise below ambient Earth noise
>
> 3. Seismometer linearity of 90 dB or greater.
>
> 4. Bandwidth spanning all solid Earth free oscillations and regional body waves (up to 15 Hz for land stations, 100 Hz for ocean-bottom sites).
>
> 5. Response known to 1% across the bandwidth (adequate for amplitude modeling which at best is good to about 20%).

6. Sensor cross axis coupling less than about 1% (adequate for amplitude modeling). Three mutually orthogonal components of motion should be recorded.
7. Equipment must be robust, sustaining high up-time performance.
8. System environmental requirements should not constrain site selection.

The Engineering Challenge

Developments in miniaturization of broadband sensors have reached designs achieving broadband noise levels of around 10^{-10} m/s^2 Hz$^{-1/2}$ in small packages weighing 1 kg or less. Size reductions have come through shrinkage of conventional spring-mass systems, by micromachining the entire system into a 'chip-based' package of a few grams, by use of high-sensitivity piezoelectric materials. A novel fluid-based design has achieved good noise and bandwidth performance. Fiber optics designs under development a few years back seem to be on hold, reportedly due to consistency of noise performance in production situations. The miniature small-mass sensors require very high Q suspensions and relatively low natural frequencies to achieve suitable noise characteristics for VBB-style applications, and it appears that Q values of 1000-10000 can be reached and maintained in 10 Hz suspension systems.

Sensor technology issues are largely noise floor achievements, dynamic range and stability. Two fundamental limits are 1) suspension noise caused by the Brownian motion of the suspended mass, and 2) Johnson or thermal noise. Current instruments that meet or exceed the NLNM spectrum are not going to be easily surpassed in those specifications. New directions include: 1) Piezoelectric accelerometers, 2) chip accelerometers (good only for strong-motion seismometers), 3) Atomic Force Microscope (AFM) (can measure extremely small motions), 4) Optical (liquid mercury with light passing through pressure transducers), 5) Micro-Electro-Machined Systems (MEMS), 6) Molecular Electronic Transfer (MET) cells, and 7) SAGNAC (a fiber-optic loop that measures rotational acceleration). Other technologies likely exist.

It is unclear which of the technologies behind these sensors, if any, are most appropriate for the development of a new VBB 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 VBB seismometer that we hope to explore in the workshop.