Can the STS-1 Very Broadband Sensor Be Replaced?

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broadband seismic sensor workshop

Granlibakken Conference Center
Tahoe City, California
March 24-26, 2004

69 attendees
Govt, industry, academe, NGOs
Attendance from US, Germany, Japan, Canada, France, UK, Russia
Seismologists, physicists, engineers, inventors, managers, owners

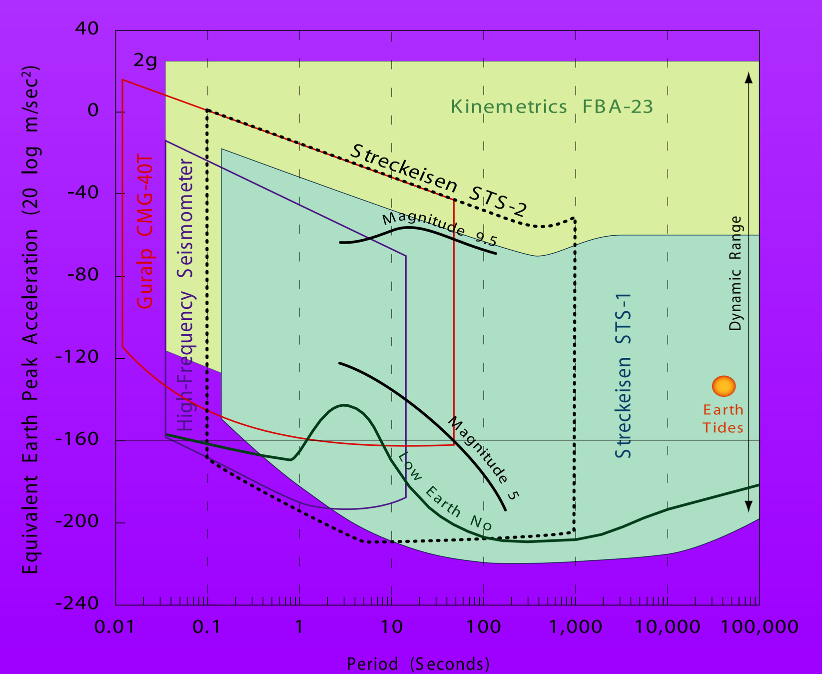
Akito Araya	Earthquake Research Institute
Bruce Banerdt	Jet Propulsion Laboratory
Noel Barstow	PASSCAL Intrument Center
Anatoly Baryshnikov	Res Inst. of Pulse Technique (NIIIT)
Jon Berger	SIO, University of California San Diego
Rhett Butler	IRIS
Stephane Cacho	Kinemetrics
Peter Chang	University of Maryland
John Clinton	California Institute of Technology
John Collins	Woods Hole Oceanographic Institution
Peter Davis	UCSD
Dan DeBra	Stanford University
Riccardo DeSalvo	Caltech
Ronald Drever	California Institute of Technology
William Farrell	SAIC
Fred Followill	Consultant
Jim Fowler	IRIS/PASSCAL
Josef Frisch	Stanford Linear Accelerator Center
Jeffrey Gannon	Applied MEMS, Inc.
Ken Gledhill	Inst. of Geol & Nuclear Sciences, New Zealand.
Cansun Guralp	Guralp Systems Ltd.
Roger Hansen	Geophysical Inst., Univ of Alaska Fairbanks
Chris Hayward	Southern Methodist University
Pres Herrington	Sandia National Laboratories
Gary Holcomb	Albuquerque Seismological Laboratory
Robert Hutt	USGS Albuquerque Seismological Laboratory
Shane Ingate	IRIS
Gray Jensen	U. S. Geological Survey
Doug Johnson	Lamont Doherty Earth Observatory (retired)
Rick Kellogg	Sandia National Laboratories
Thomas Kenny	Stanford Univ Design Division of Mech. Eng.
James Kerr	Geotech Instruments, LLC
Alexei Kharlamov	Moscow Inst. of Phys and Tech - MIPT/DPQE
Richard Kromer	Sandia National Laboratories
Ogie Kuraica	Kinemetircs Inc
Charles Langston	CERI, University of Memphis
Brian Lantz	Stanford Univ.
Gabi Laske	University of California San Diego
Philippe Lognonné	Institut de Physique du Globe de Paris
David McClung	Geotech Instruments
Gregory Neuman	Department of Defense
Yujii Otake	Earthquake Res. Inst., Univ. of Tokyo
Jose Otero	IGPP/UCSD
Paul Passmore	Refraction Technology, Inc.
Bruce Pauly	Digital Technology Associates / Guralp Systems
Randall Peters	Mercer University Physics Department
Jay Pulliam	University of Texas at Austin
Barbara Romanowicz	U.C. Berkeley, Berkeley Seism. Lab.
Selwyn Sacks	Carnegie Inst. of Washington
Vern Sandberg	Caltech LIGO Hanford Observatory
John Scales	Colorado School of Mines
Robert Schendel	Texas Components Corp.
Joe Schrodt	AFTAC
Jim Scott	University of Nevada, Reno
Andrei Seryi	Stanford Linear Accelerator Center
Albert Smith	Lawrence Livermore National Laboratory, L-205
Neil Spriggs	Nanometrics
Ian Standley	Kinemetrics, Inc.
Brian Stump	Southern Methodist University
Akiteru Takamori	Earthquake Res Inst, Univ of Tokyo
Toby Townsend	Sandia National Laboratories
Richard Warburton	GWR Instruments, Inc.
Spahr Webb	LDEO
Daniel Whang	UCLA
Erhardt Wielandt	Inst. of Geophys, Stuttgart Univ, Germany
Mark Zumberge	Inst of Geophysics and Planetary Physics

The Requirements: 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 Mw = 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.



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. Also shows 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.

Abstract

Few fundamental advances have been made in seismometers since the introduction of the broadband feedback systems nearly 1/4 century ago. In the intervening period, academic (and to a lesser extent industrial) research and developments on seismographic instrumentation has declined. Today, adequate sensors to meet the scientific requirements are in short supply. This is particularly true of the GSN; the cornerstone of GSN instrumentation is the STS-1 seismometer, which is no longer in production. Further, the pool of trained scientists working on seismographic instrumentation has dwindled to near zero.

A 2.5 days workshop was held in Tahoe in March, 2004. 69 participants from government, universities, and corporate sectors participated in a mixture of oral, poster and discussion sessions. Through this workshop, the geoscience community interacted with research and development groups involved in sensor technology, material sciences and nanotechnology to assess emerging technologies that have applications in inertial sensors. A goal of this workshop was to consider whether and how such advances might be applied to the design and manufacture of a new-generation, ultra-quiet, mHz – 20 Hz seismic sensors, and the formulation of a plan to revitalize research and development of techniques in broadband seismometry and related seismographic instrumentation. Key discussions included an examination of partnerships and technology transfer, new and innovative designs, testing standards and testing facilities, funding strategies and an educational perspective including new University programs.

Proceedings of the workshop can be viewed at:
http://www.iris.edu/stations/seisWorkshop04/seisWorkshop.htm

Where have all the VBB sensors gone?

The cornerstone of the GSN, the very broadband STS-1 seismometer, is no longer in production. The current production KS54000 borehole seismometer is also a VBB sensor, but does not have the frequency range nor the low-noise characteristics of the STS-1 but is well-suited to siting on island stations. 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.

The IRIS Instrumentation Committee has conducted a preliminary survey of available technologies that may be able to fill this need. Unfortunately, the demand for inertial devices that are both low-noise, have a very large dynamic range and span the seismic signal spectrum is very small, and it is unlikely that new designs will be explored by the commercial sector, without guidance and stimulation from the research community.

This looming crisis has motivated the seismological community to initiate plans for the design and construction of a new very broadband seismometer. The challenge to design and build such an instrument will require expertise and resources in fundamental engineering and technologies that extend well beyond the Earth sciences. The Sensors and Sensor Networks proposal solicitation by NSF may be an ideal opportunity to bring together the engineering and seismological academic communities to solve this problem. This workshop was a first step to fill this void.

What can VBB sensors reveal?

Following large earthquakes, the earth's free oscillations are observed as peaks in the spectra of long-period seismic records in the frequency band 0.3-7mHz; the gravest mode of vibration, 0S2, has a frequency of 0.3 mHz, whereas above 8mHz, normal modes are too closely spaced to be separable, and other techniques, based on propagating wave theory are more adequate for the analysis of seismograms. In recent years, studies of normal modes has shifted to the study of departures from simple spherical symmetry. Some of the exciting research evolving from the use of VBB data include:

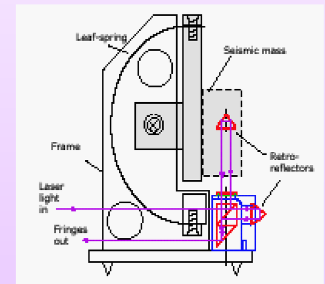
- "Hum" (fundamental mode peaks 2-7 mHz) - faint fundamental mode peaks observed on the vertical component of STS-1 recordings in the period range 2-7mHz, and on gravimeter recordings in the period range 0.3-5mHz, in the absence of earthquakes.
- Low & odd degree elastic structure (e.g., density, Q, etc) from free oscillations below 3mHz.
- Tomographic models at level 2 & 4 heterogeneity from normal modes
- Lower mantle lateral density variations, and especially constraints on the density jump at the inner core/outer core boundary are critical for the understanding of core formation and dynamics.
- Rate of relative motion of inner core with respect to the mantle are constrained by accurate mode-splitting measurements, which can also further constrain core structure and anisotropy.

What next?

The workshop identified that:

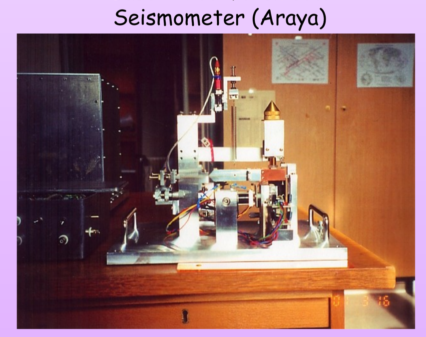
- A critical absence of replacement VBB sensors entails an eventual degradation of the GSN and other networks.
- The market for VBB sensors is small, and of no interest to industry to invest necessary R&D for this community. However joint University-industry relationship may work.
- That future generations of sensor developers must come from universities, and that the last Ph.D in seismic instrumentation development in a US university was 1980.
- A report to NSF is being prepared along with arrangements for a presentation to NSF Officers. IRIS will continue to monitor emerging technologies, and continue the dialog between IRIS, NSF, industry and international partners.

Optical Displacement Transducers

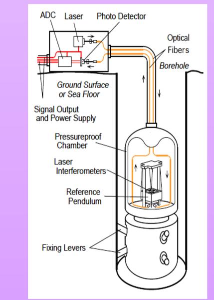

STS-1 with optical fringe resolver (Zumberge et al)

Recent advances in optical fiber technology and digital signal processing offer an alternative to the modern observatory seismometer, enabling the use of an optical fringe resolver to replace the electronic displacement transducer found in modern seismometers. The use of optical fiber interferometry in place of electronics adds other important benefits, including immunity to noise pickup, simplification of remote deployment (in a borehole, for example), the elimination of a heat source in the seismometer—an important cause of noise in the best existing systems, and elimination of electrical connections between the seismometer and the recording system.

Laser Interferometer Seismometer (Araya)

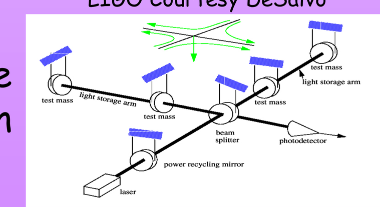


Optical Tiltmeter (Araya)



Several designs for seismometers and a horizontal long-baseline strainmeter were shown. Michelson interferometer & pendulum designs have the potential for self-noise below the NLNM in the frequency range 50mHz - 100 Hz.

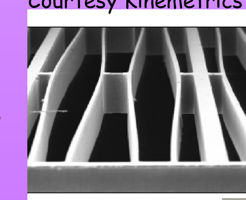
LIGO Courtesy DeSalvo



As an interesting aside, the LIGO gravity wave detector is a 4-km optical interferometer that can measure displacements to 10e-18 m.

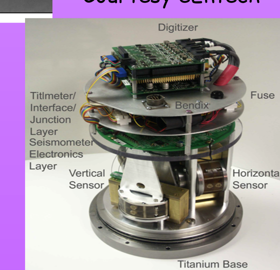
Other Technologies

Courtesy Kinemetrics



MEMS
Full-scale 2 m/s/s, noise floor of 30x10e-9 g/ Hz, ~$2000 3-axis

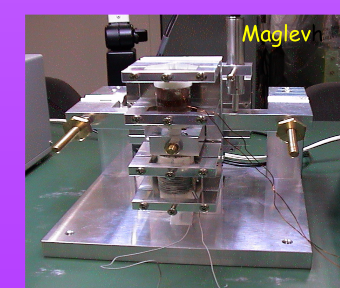
Courtesy eEntech



Electrochemical (MET)
No springs, could be extended to 1000 sec with new "soft" membrane. Convective diffusion of electrolyte between electrodes is converted to electric current. Hydraulic impedance analogous to Nyquist noise of resistor.

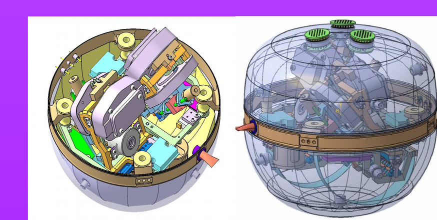
Superconducting Gravimeter (Warburton)
Less noise than STS-1 (5e-3 nm/s), vertical component only. Projected cost for seismic use around $100,000 per unit. The Global Geodynamics Project consists of 22 SCG units.

Ring Laser Gyro
Installed at Black Forest, New Zealand and soon Pinon Flat, used to detect variations in G. UCSD will evaluate.



Magnetic Levitation (Otake, Araya & Hidano)
By isolating barometric effects, should approach STS-2. Has a natural period of 5 sec.

Folded Pendulums (Takamori, Bertolini & DeSalvo)
Used in accelerometers and gravity-wave detectors; need to minimise elastic contributions of flexures.


Courtesy ETH

Martian Seismometers (Logonné)
Triaxials on a weight diet; total weight = 2 kg.

Emerging Technologies

SQUID Displacement Detector
Superconducting Quantum Interference Devices offer 100 x sensitivity than capacitive devices.

Stanford Linear Accelerator and Collider (SLAC) Strainmeter
Uses 200 remote-controlled fresnel lenses along a 3 km light tube to detect deformations over its length. Available for experiments.

Quartz Seismometer Suspension
Operates in very strong magnetic environments (SLAC), close to STS-2 performance

Atomic Fountains
Cold atom fountains have accuracy of 10e-9 G, need to scale for geophysical measurements

Ferro-Fluid Suspension
Suspends magnetic mass to measure ground velocity. Needs to incorporate force-feedback