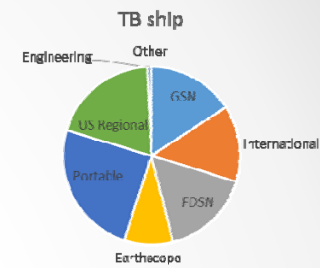
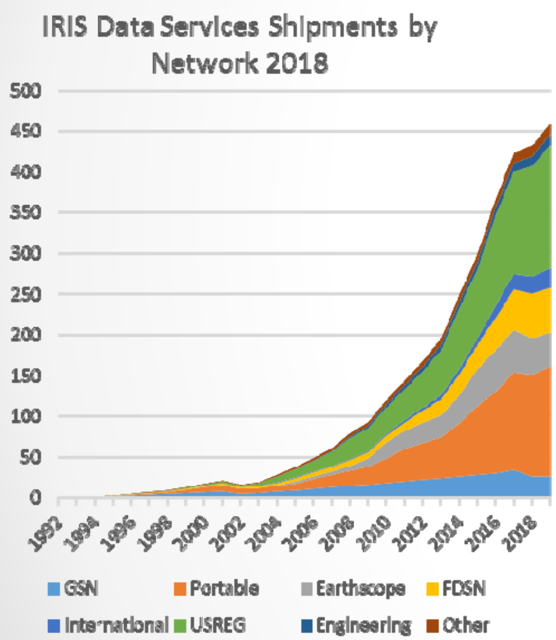
Instrumentation and network design for global and regional seismology.

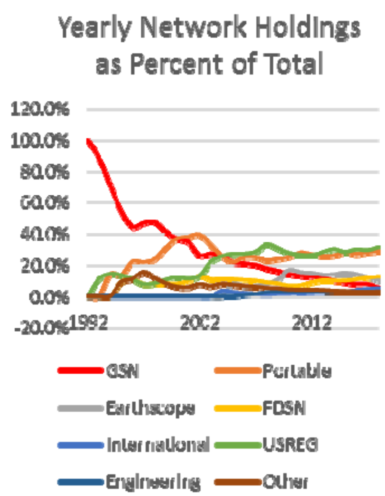
JM Steim
President
Quanterra, Inc.

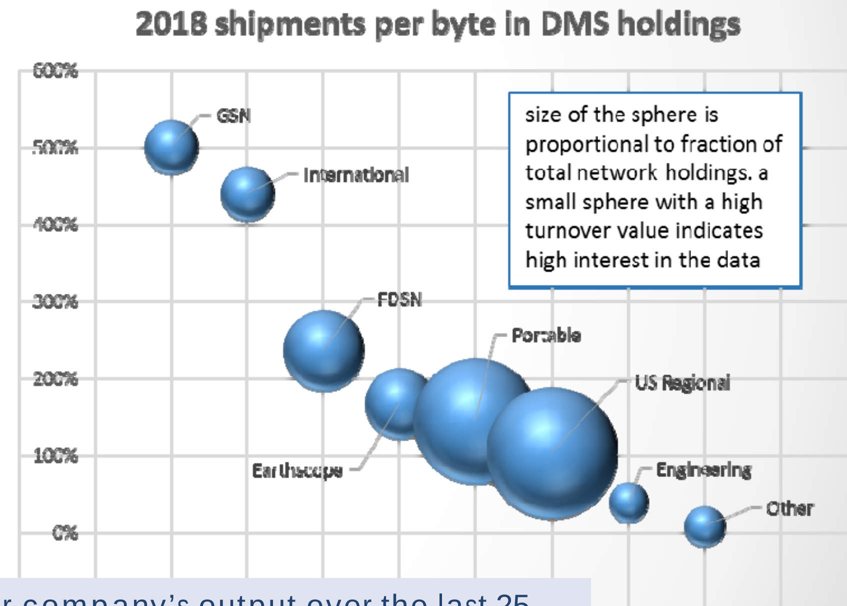
GSN data sets standards

In addition to innumerable fundamental seismological analyses, GSN data has provided the most basic tool for instrument development, the Low-Noise Model

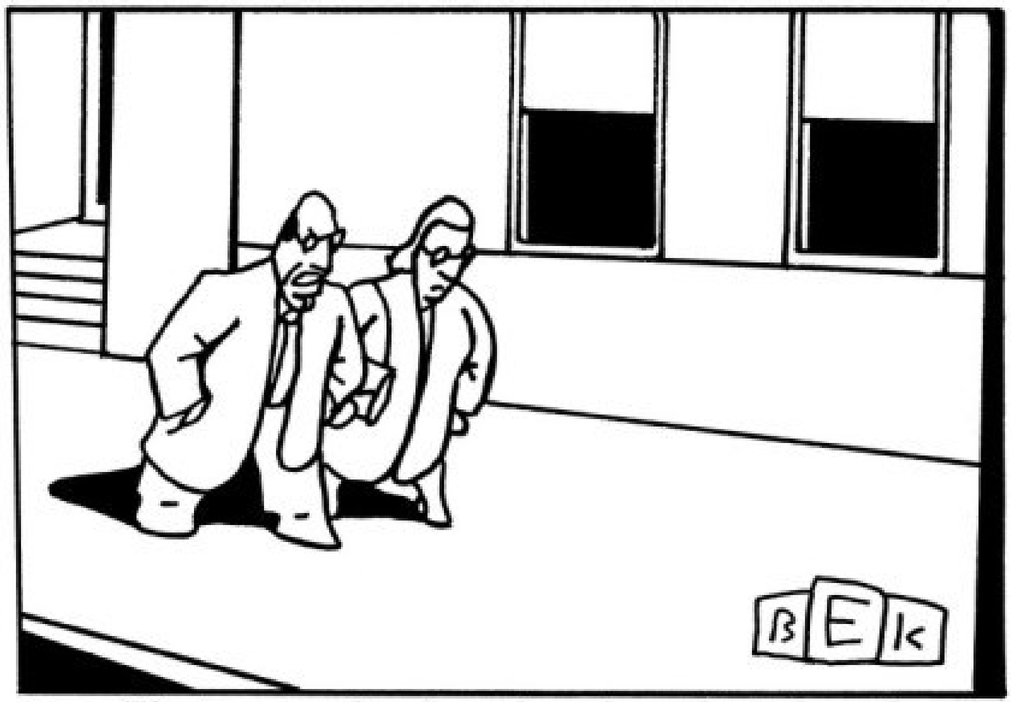






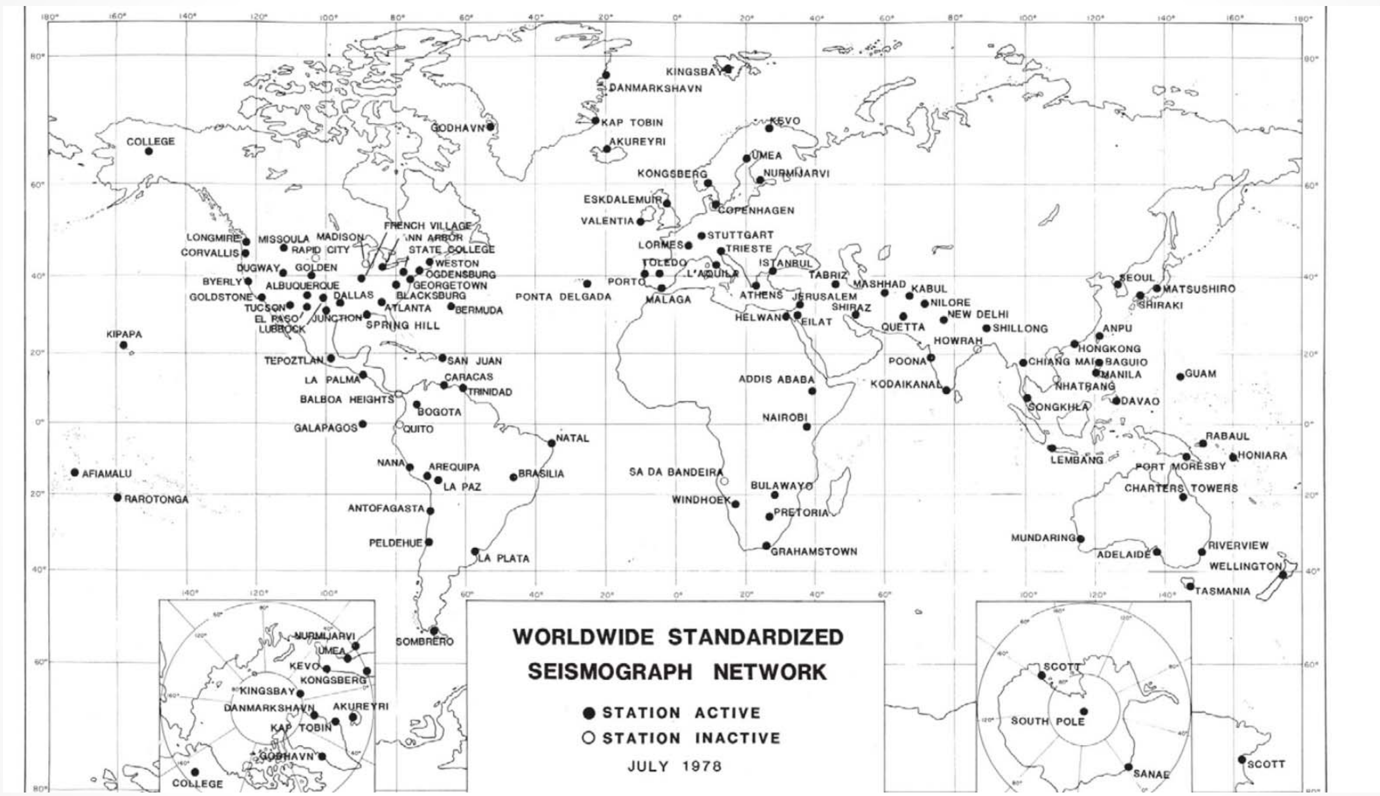


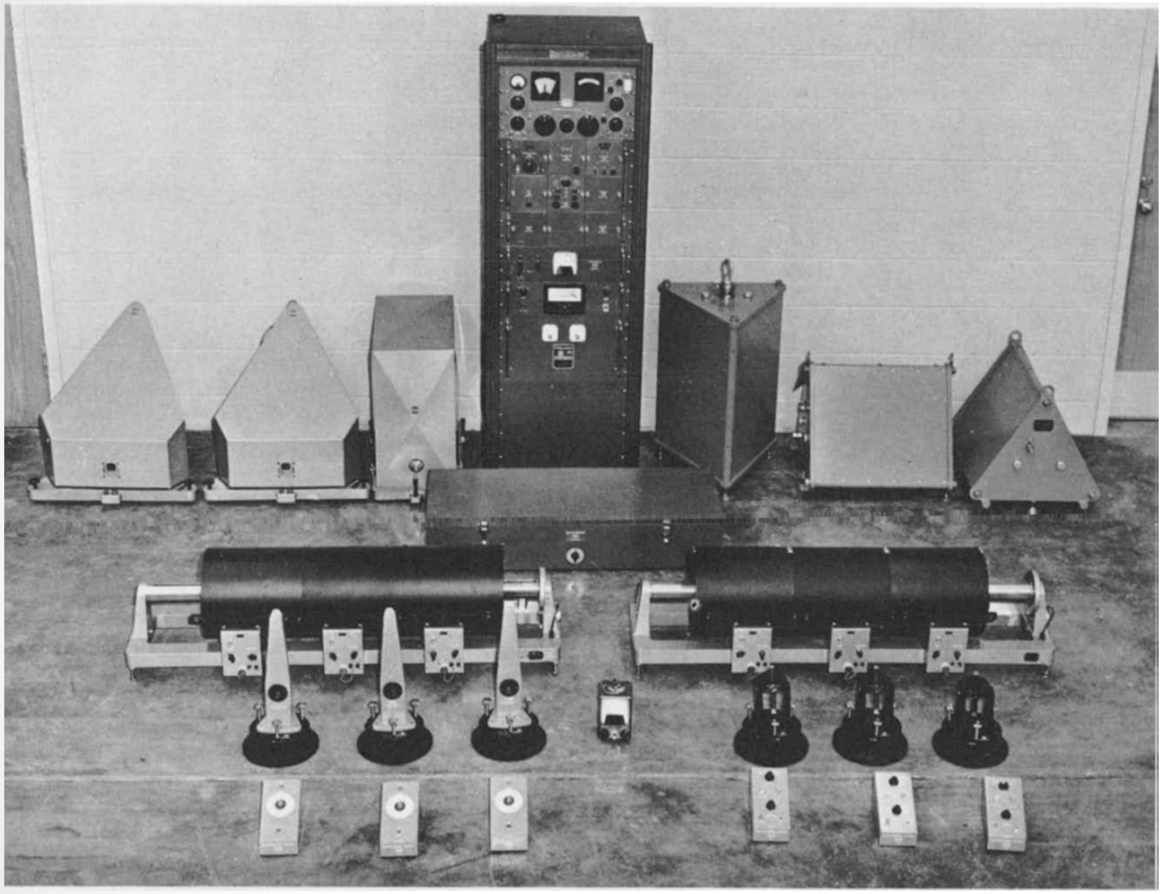
GSN represents about 1% of our company's output over the last 25 years. GSN, however, represents a major, if not the major, input setting goals and defining the problems to be solved to create workable, reliable hardware to achieve them.



"If you want something done right, you have to live in the past."

WWSSN – 1940's technology in the early 1960's and ancestor of GSN





WWSSN standardized system based on thoroughly proven components. Success!

FIGURE 3 Components of the WWSSN station. Encased long-period seismometers are shown in the upper left and long-period photographic recording equipment in the lower left; encased short-period seismometers are shown in the upper right and short-period photographic recording equipment in the lower right. The instrument rack in the center contains a crystal-controlled clock for timing, the calibration instrumentation calibration system, and other electronic gear. The contact printer used to duplicate seismograms is shown as a rectangular box at the base of the rack. (Photo U.S. Geological Survey, Jon Peterson.)

Gräfenberg – first digital BB array - 1976

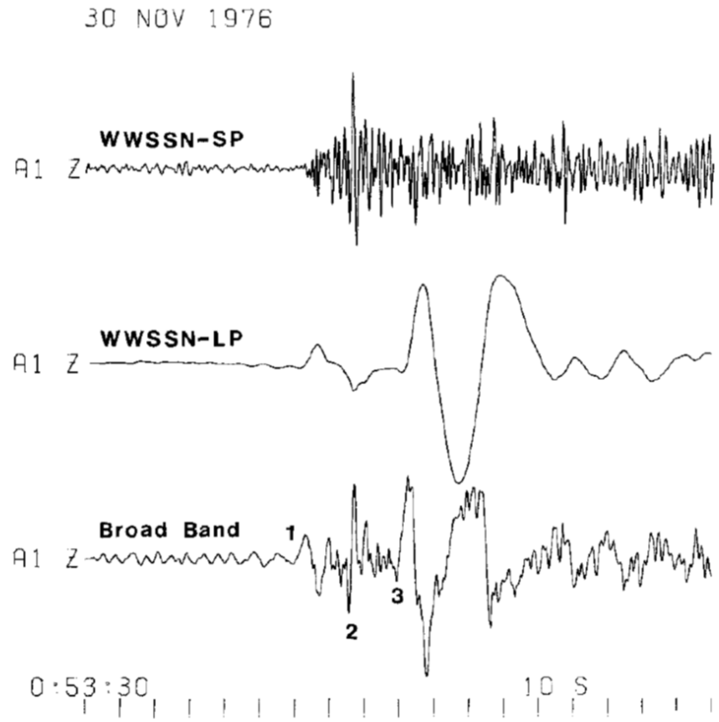
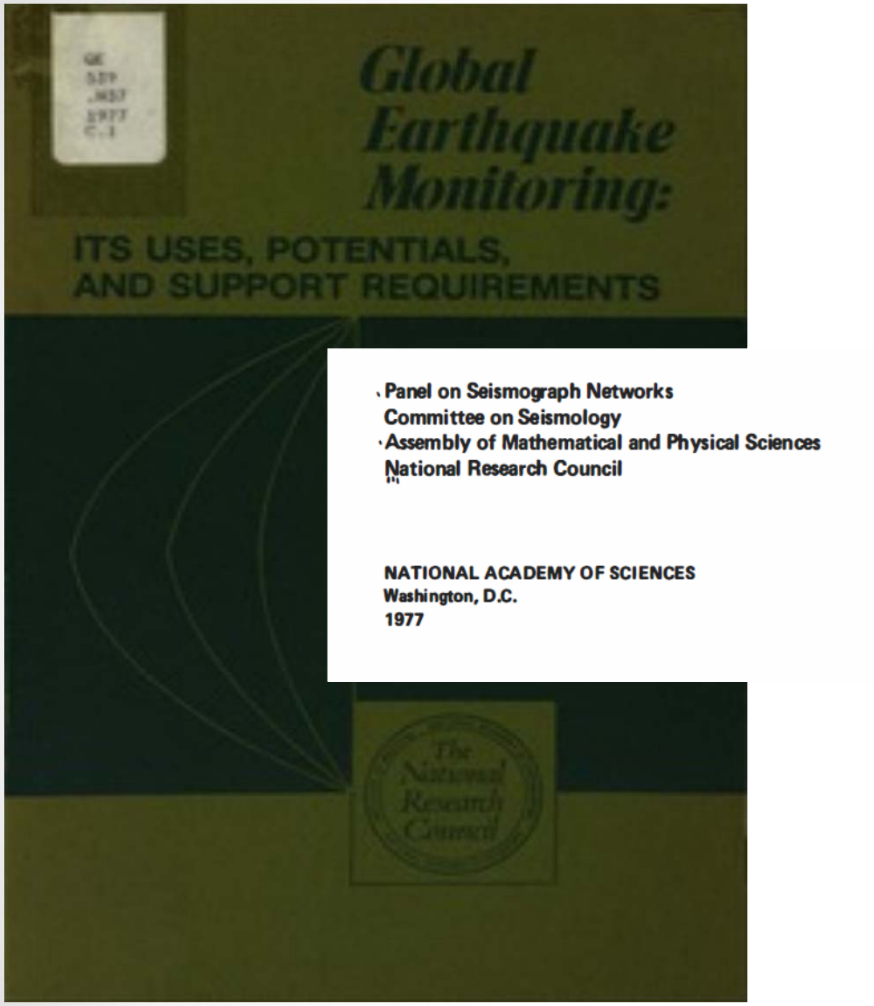


FIG. 3. Broadband record of the same event 2 as in the previous figures and digital simulation of WWSSN long- and short-period systems from the broadband record. The *P* phase is marked in this and in all following figures as 1, the phase *bP* as 2, and the depth phase *pP* as 3.

*Nineteen (13 vertical and 6 horizontal) broadband **WIELANDT** seismometers with a flat velocity response between 20 sec and 5 Hz have been installed. The dynamic range of the data acquisition system is 132 dB, and its resolution is 66 dB.*

BSSA, 72, (6), pp. 2131-2145, December 1982
ANALYSIS OF BROADBAND SEISMOGRAMS FROM THE CHILE-PERU AREA BY RAINER KIND AND DIETER SEIDL

What came to be known as the STS-1 exists today because as a condition for its use at GRF, it had to duplicate the response of the Sprengnether S5100 seismometer used in the WWSSN. In the new network, the STS-1 would be recorded digitally, without the WWSSN frequency shaping and galvanometric recording.



The future as we know it starts here…

PANEL ON SEISMOGRAPH NETWORKS - 1977

E. R. **Engdahl** , NOAA/University of Colorado , Chairman
Shelton S. **Alexander**, The Pennsylvania State University
Michael A. **Chinnery** , Lincoln Laboratory , MIT
Adam **Dziewonski** , Harvard University
J. Freeman **Gilbert** , University of California , San Diego
Donald V. **Helmberger**, CalTech
Bryan L. **Isacks** , Cornell University

The time is at hand to take full advantage of the new , improved seismic stations by combining them, under a **specific program and under a single agency for management purposes, into an improved WWSSN** .

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Test and Calibration
of the
Seismic Research Observatory

by
Jon Peterson,
Charles R. Hutt,
L. Gary Holcomb

Open-File Report 80-187

This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards and nomenclature.

Albuquerque, New Mexico

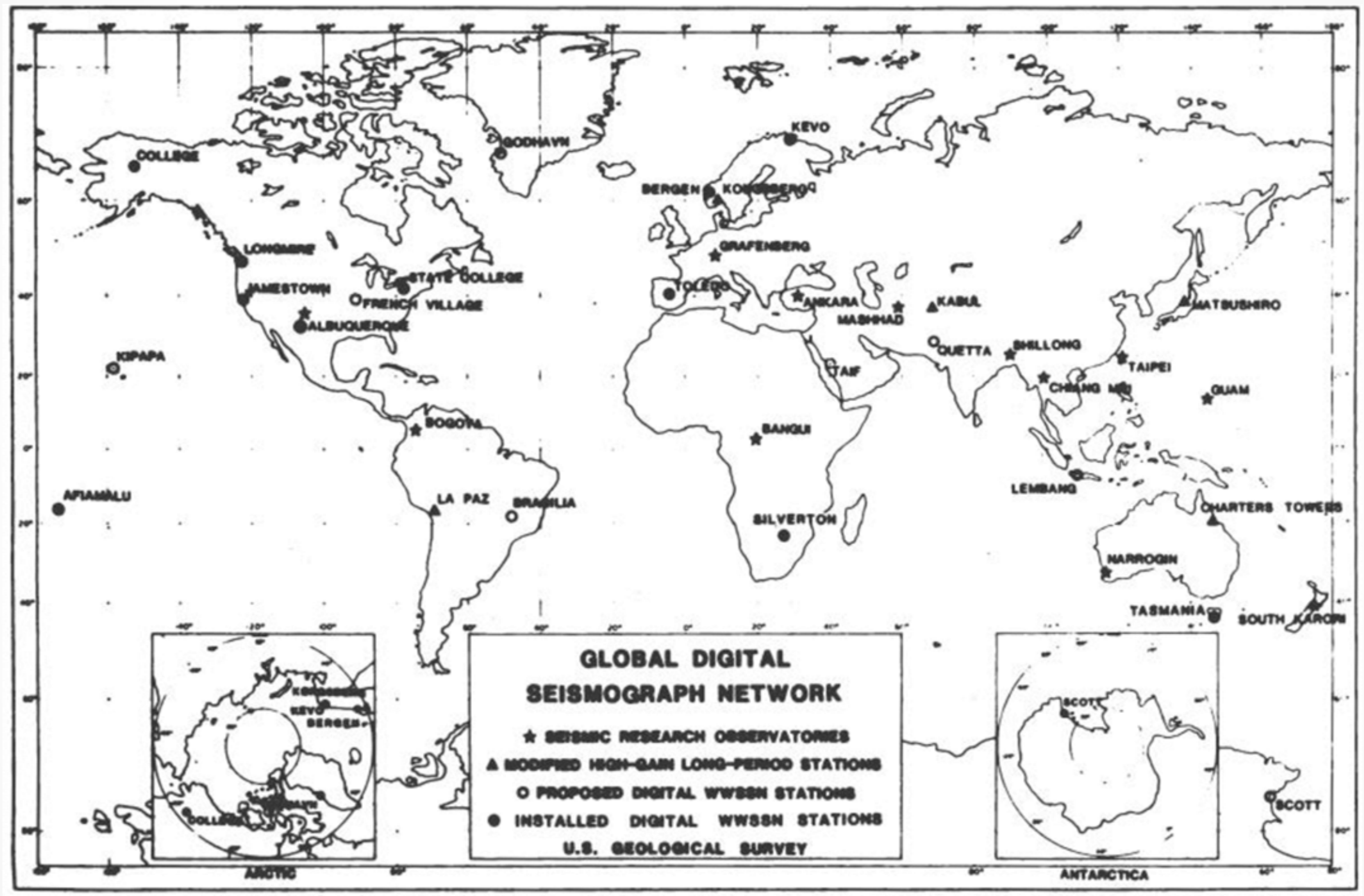
1980

Great Science and Engineering!

In September, 2017, the KS-36000 was replaced by an STS-6A

Removing the KS-36000 at Standing Stone, PA after about **40 years**

Global Digital Instrumentation ca. 1982



As the new volumes of digital data were routinely processed for CMT solutions, limitations emerged.

U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

A NOTE ON TRANSIENTS IN THE
SRO AND ASRO LONG-PERIOD DATA

by
Jon Peterson

Open-File Report 82-702
1982

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards.

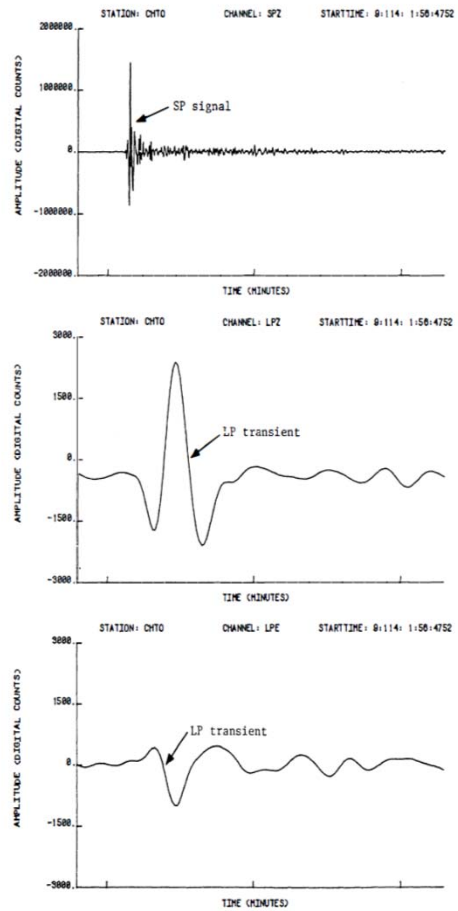


FIG. 1.

Data users have occasionally observed **pulse-like transients** in the long-period waveforms recorded at the Seismic Research Observatories (SRO) and at the Modified High-Gain Long-Period (ASRO) stations. In a recent paper, Dziewonski *et al* (**1981**) reported transients associated with earthquake signals recorded at some SRO stations.....

Seismographic Networks:
Problems and Outlook for the 1980s

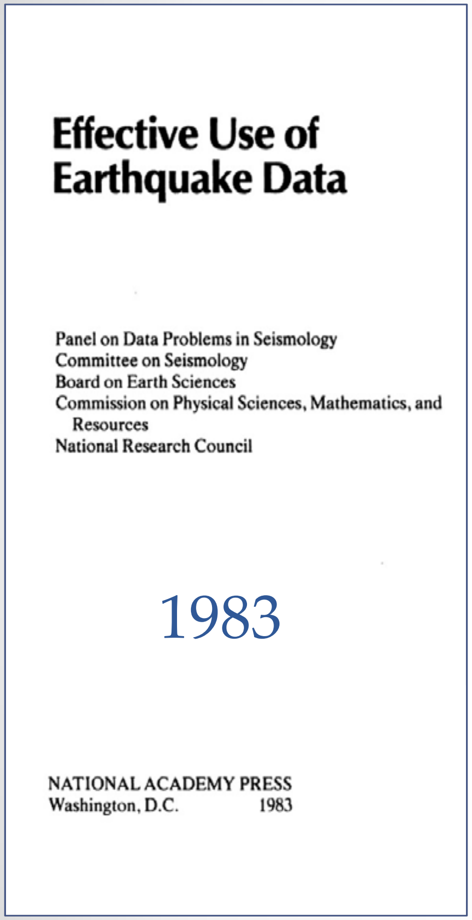
Report of the Workshop on Seismographic Networks
Committee on Seismology
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1983

"….there aren't going to be any observatories…"
- Ray Buland

*"**Research** and **network operation** are usually not evaluated by different standards, but they should be. For the **former the standard is scientific merit,** whereas for the **latter** it should be **stability, quality, and service**."*

*"There exists a **disturbing range of quality** among regional network operations. Different networks currently operate to quite different standards. While some operators can produce on demand a bulletin updated to within a few days prior to a request for information, others have essentially no bulletin. Some produce seismicity maps with accurate information on magnitudes and focal mechanisms, but others have been **operated with ignorance of instrument gain or polarities**"*

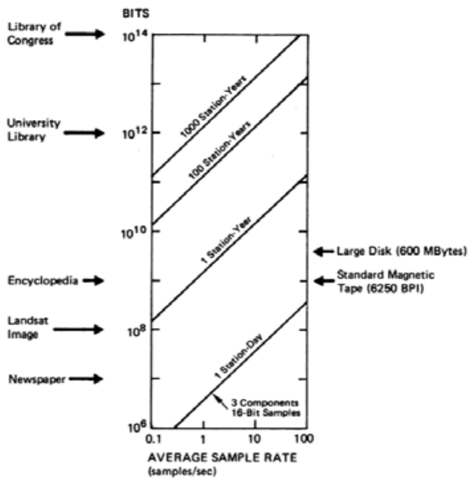


Effective Use of Earthquake Data

Panel on Data Problems in Seismology
Committee on Seismology
Board on Earth Sciences
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

1983

NATIONAL ACADEMY PRESS
Washington, D.C. 1983

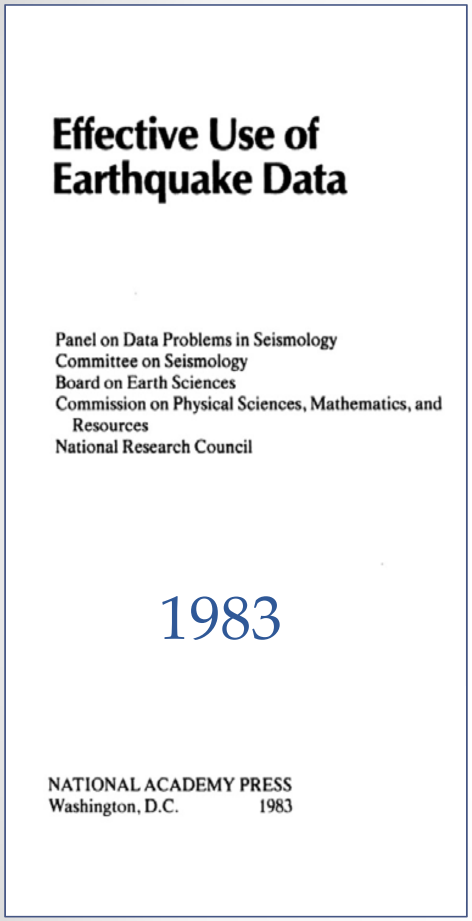


RIGHT!

The number of seismometers in regional and local networks is very large already, although most are not yet digital. In the United States alone there are some 1,600 stations in such networks [....] Based on this we will assume that there might be as many as **2,000 digital stations at some future time**.

WRONG!

In the case of global networks, the total amount of data may be **impractical to save using current technology** and reasonable funding expectations. But by **selecting short-period event windows** to save permanently, the quantity of waveform data is reduced to a feasible level for archiving.



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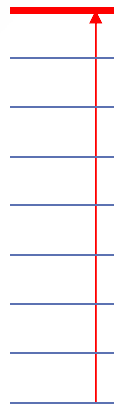
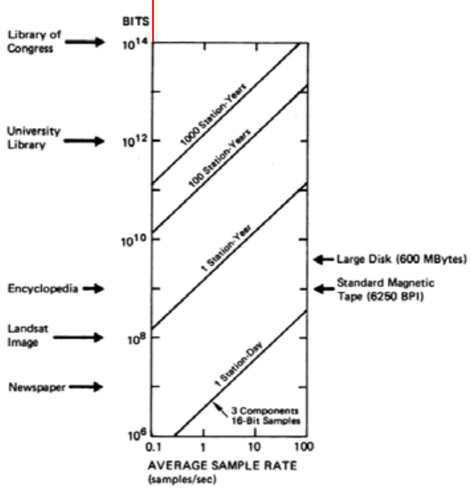
Washington, D.C. 1983



Annual global data center IP traffic will reach 20.6 Zettabytes (ZB) by the end of 2021.

1ZB = 10^{22} bits

In 2018, annual seismic data collection by DMS is __~1 part per billion__ of global data center traffic!



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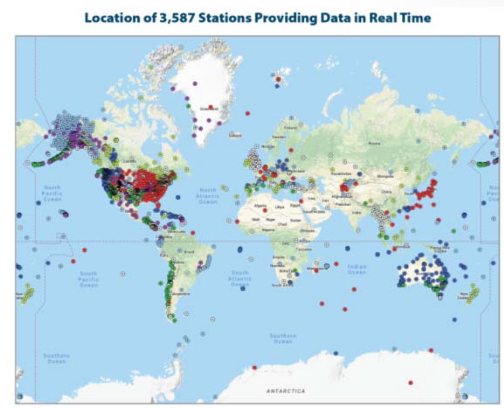

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Formative Meeting: 1983

REVIEWS OF G EO PH YSICS, VOL. 25, NO. 6, PAGES 1203-1207, JULY 1987

U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS 1983- 1986

IRIS - A University Consortium for Seismology

STEWART W. SMITH

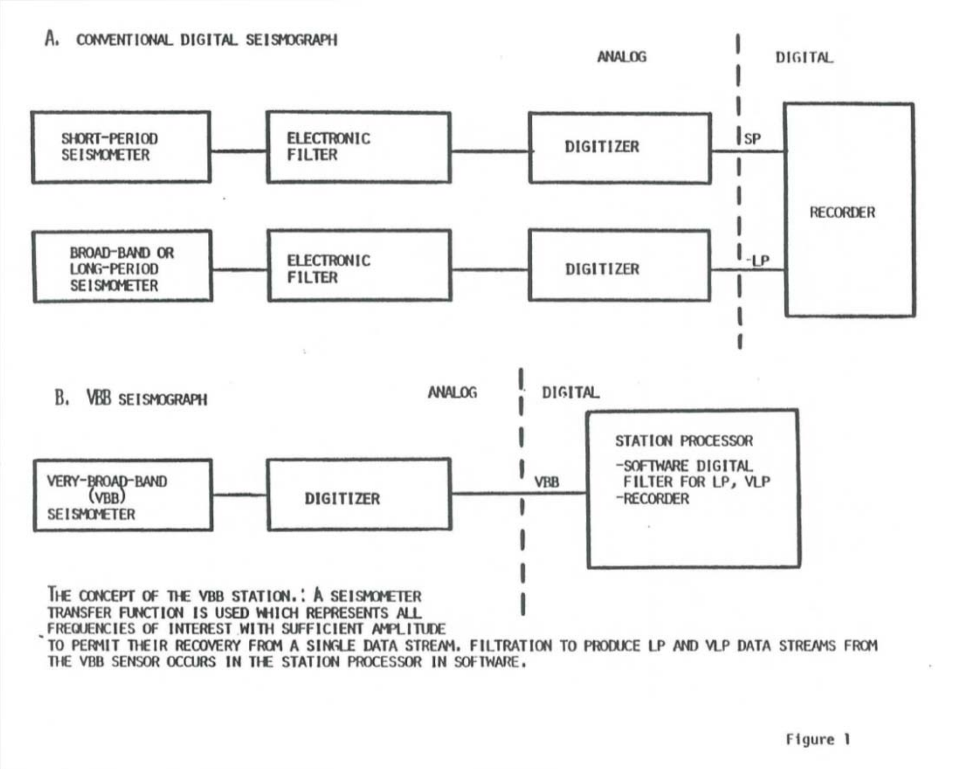
Incorporated Research Institutions for Seismology Arlington, Virginia

[.....................]

In **July 1983**, an *ad hoc* group of **20 scientists** representing 10 academic institutions **met at Harvard** University to discuss a major new initiative in Earth Sciences, whose key element would be the establishment of a **standardized global network of digital telemetered seismographic stations**. Following that meeting, an embryo organization formed to bring these ideas to a wider audience.

Contemporaneous development work on enabling technology

The Concept



World's First Digital Very Broad Band seismogram – 1983 - HRV

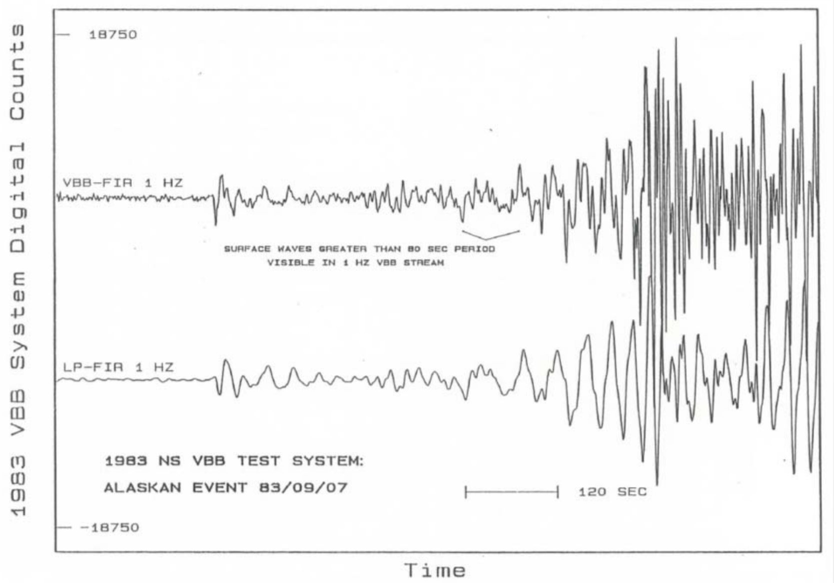
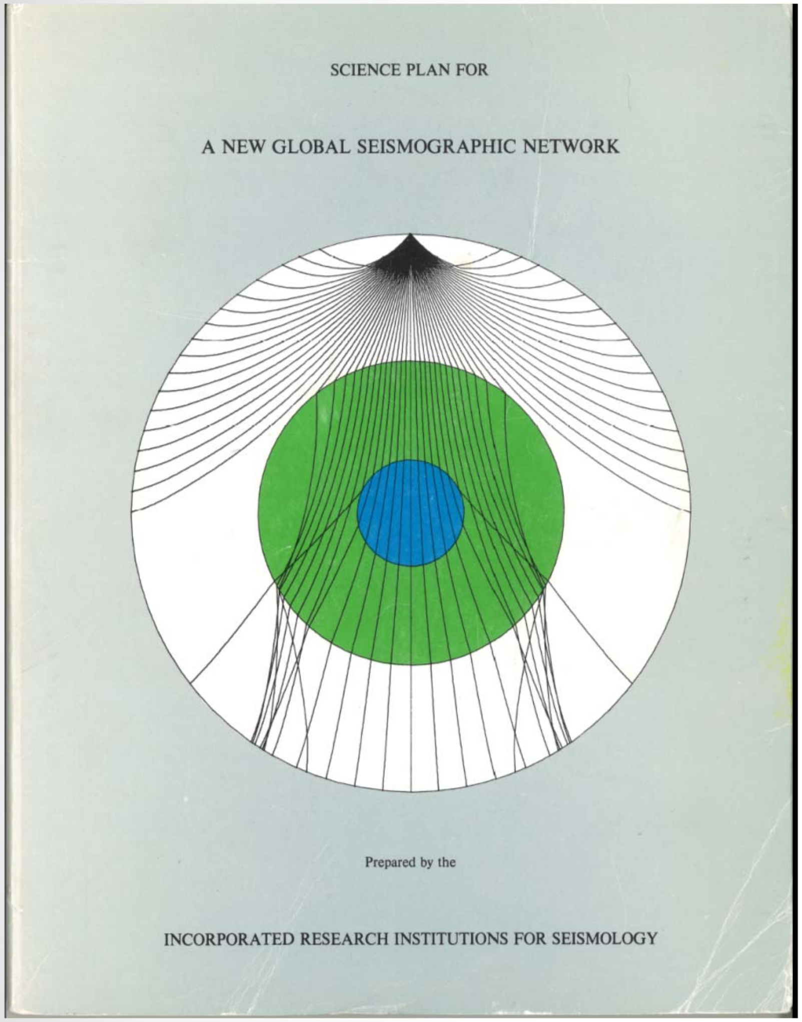


Figure 4.1.3: One of the first events recorded on the 1983 experimental digital VBB seismograph (HRV) compared with a recording from a co-located standard electromagnetic seismometer with electronic filters. The upper trace is from the 1983 VBB seismometer (originally sampled at 20 Hz, and decimated to 1 Hz for plotting); the lower trace is from the electromagnetic LP seismometer. The trace begins about 3 minutes before the P arrival at HRV. Peak ground velocity is about 35 microns/s.



April 1984 first Science Plan

The following scientists contributed to this science plan:

D. C. Agnew,	University of California, San Diego
S. S. Alexander,	Pennsylvania State University
D. L. Anderson,	California Institute of Technology
J. Berger,	University of California, San Diego
R. P. Buland,	United States Geological Survey
R. W. Clayton,	California Institute of Technology
V. F. Cormier,	Massachusetts Institute of Technology
A. M. Dziewonski,	Harvard University
E.R. Engdahl,	United States Geological Survey
F. Gilbert,	University of California, San Diego
B. H. Hager,	California Institute of Technology
T. H. Heaton,	United States Geological Survey
E.T. Herrin,	Southern Methodist University
T. H. Jordan,	University of California, San Diego
H. Kanamori,	California Institute of Technology
C. Kisslinger,	University of Colorado, Boulder
C. R. Langston,	Pennsylvania State University
T. Lay,	University of Michigan, Ann Arbor
B. B. Lusignan,	Stanford University
T. G. Masters,	University of California, San Diego
T. V. McEvilly,	University of California, Berkeley
B. J. Mitchell,	St. Louis University
J. A. Orcutt,	University of California, San Diego
J. Peterson,	United States Geological Survey
J. Rial,	University of California, Santa Cruz
P. G. Richards,	Columbia University
L. J. Ruff,	University of Michigan, Ann Arbor
D. W. Simpson,	Columbia University
S. A. Sipkin,	United States Geological Survey
R. Smith,	University of Utah
J. M. Steim,	Harvard University
T.Tanimoto,	California Institute of Technology
T.-L. Teng,	University of Southern California
J. H. Woodhouse,	Harvard University

The plan envisioned satellite telemetry. No one really believed that…

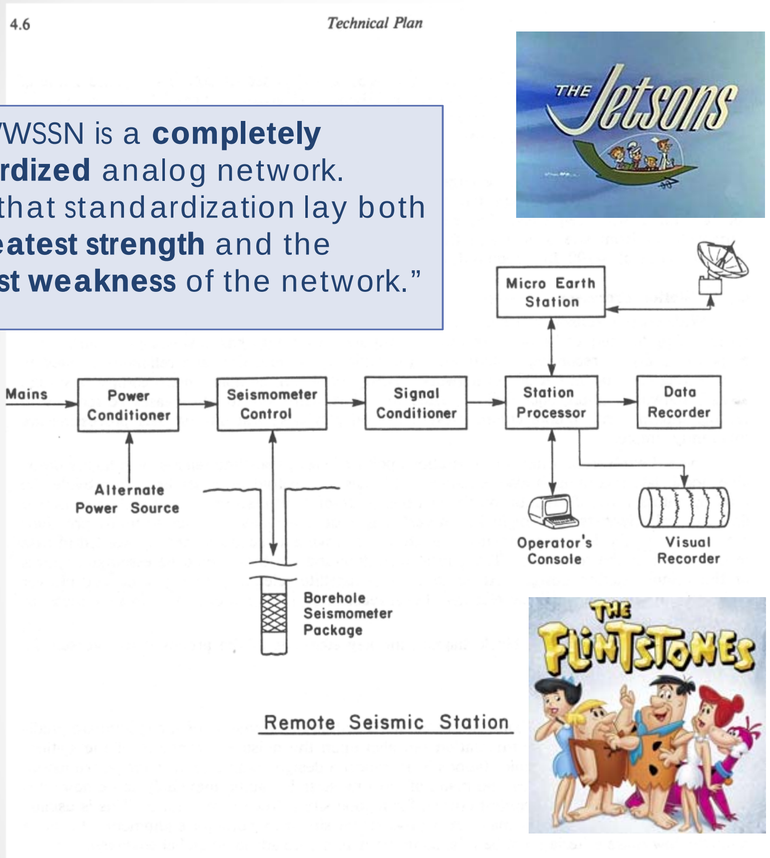


Figure 4.2. Block diagram of the remote seismic stations. Seismometers may be installed on the surface or in boreholes. Data will be recorded locally and telemetered where possible via satellite to central recording facilities. (Berger, with permission)

> "The WWSSN is a **completely standardized** analog network. Within that standardization lay both the **greatest strength** and the **greatest weakness** of the network."

WHY NOW?

- **Technological developments** make deployment of such a network **operationally and economically** feasible.

WHAT TECHNOLOGICAL ADVANCES MAKE THIS PROJECT TIMELY?

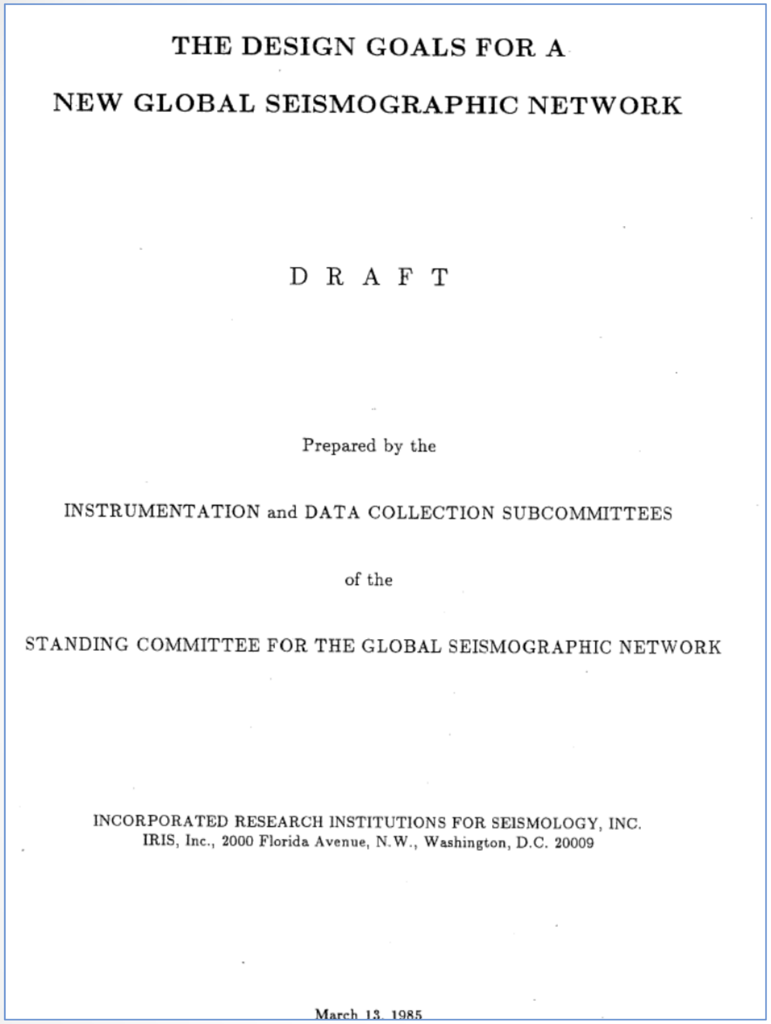
- Application of electronic control methods and digital data acquisition to seismometry
- Developments in digital mass storage methods
- **Advances in satellite communications**
- Availability of large computing facilities

WHAT WILL BE THE CHARACTERISTICS OF THE NETWORK?

- Approximately 100 stations, 3 components each
- **Broadband - 5 Hz**
- High dynamic range - 140 db
- **Real-time telemetry via satellites**

WHAT IS THE PLANNED LIFETIME?

- **30 years**, assuming that the network will be gradually upgraded as new technology develops. In this way, the performance of the network should improve with time.


THE DESIGN GOALS FOR A

NEW GLOBAL SEISMOGRAPHIC NETWORK

D R A F T

Prepared by the

INSTRUMENTATION and DATA COLLECTION SUBCOMMITTEES

of the

STANDING COMMITTEE FOR THE GLOBAL SEISMOGRAPHIC NETWORK

INCORPORATED RESEARCH INSTITUTIONS FOR SEISMOLOGY, INC.
IRIS, Inc., 2000 Florida Avenue, N.W., Washington, D.C. 20009

March 13, 1985

The 1985 Design Goals emerge, based on a few new technical principles

The key technical requirements of the new network identified in the Science Plan that relate to the data acquisition design are:

- Digital data acquisition with real-time or near real-time data **telemetry**
- **Bandwidth** sufficient to record the entire spectrum of **teleseismic** signals
- Dynamic range sufficient to resolve **ground noise** and to record the **largest teleseismic** signals
- Low noise instrumentation and environment
- Linearity
- Standardization of system modules.

That's it!

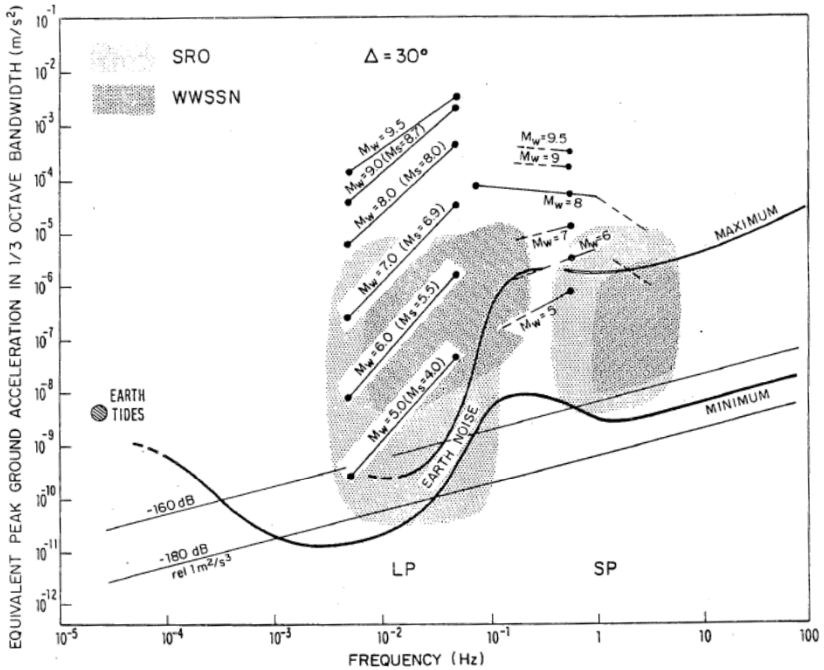


Figure 1.2. Acceleration amplitude as a function of frequency taken as 1.25 times the rms values over a 1/3 octave bandwidth. The heavy lines indicate estimates of the minimum and maximum ambient ground noise. The lines marked −160 dB and −180 dB indicate levels of frequency independent power spectral density relative to $1(ms^{-2})^2/Hz$. The accelerations expected at 30° for a range of magnitude earthquakes are shown. For periods from 200 to 20 s, the estimates are time domain amplitudes of surface waves. For 20 to 1 s, the estimates are for time domain amplitudes of P and S waves. For shorter periods, the estimates are derived from P wave spectra and are subject to large uncertainties. The shaded areas indicate approximately the principal operating ranges of the WWSSN and SRO systems.

The required "operating range" of the new network is first described.

The existing networks (SRO, WWSSN) provided a very limited view of the range of amplitudes and frequencies of teleseismic signals, and could not resolve the lowest observable levels.

UNITED STATES DEPARTMENT OF INTERIOR
GEOLOGICAL SURVEY

IRIS/USGS
Plans for Upgrading
The Global Seismograph Network

Jon Peterson
and
Charles R. Hutt

Open-File Report 89-471

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

Albuquerque, New Mexico

1989

Revised Feb 1992, Jun 1993, Apr 1994, Dec 1994, Sep 1996

TECHNICAL PLAN

FOR A

NEW GLOBAL SEISMOGRAPHIC NETWORK

INCORPORATED RESEARCH INSTITUTIONS FOR SEISMOLOGY

AND THE

UNITED STATES GEOLOGICAL SURVEY

Based on prototype research in the mid-late 80's, detailed requirements were defined for the new GSN in 1989 and 1990

1.	NETWORK CONCEPT
1.1	BASIC GSN DATA SYSTEMS
3.2.1	General
3.2.2	Sensor Subsystems
3.2.3	Digitizer Units
3.2.4	Data Acquisition Processor
3.2.5	Timing Subsystem
3.2.6	Data Processing Processor
3.2.7	Communications Link in Separated Systems
3.2.8	Buffer Memory
3.2.9	Digital Recording Subsystem
3.2.10	Real-Time Data Access
3.2.11	Dial-Up Data Access
3.2.12	Local Data Access
3.2.13	Operator Terminal and Control
3.2.14	Monitor Recorder
3.2.15	Analog Recording Subsystem
3.2.16	Digital Plotter
3.2.17	Station Power Subsystems
3.2.18	Lightning Protection
3.2.19	Mechanical Configuration
3.2.20	Exportability
3.3	REMOTE GSN DATA SYSTEMS

- VBB sensors and optional VSP and LG sensors.
- VBB dynamic range of 140 dB at 20 seconds
- VSP and LG dynamic range of at least 96 dB.
- Low power(< 100 watts); DC powered.
- RAM-based buffer memory of at least 10 MBytes.
- Both real-time and dial-up ports.
- Optional cartridge or disk recording.
- SEED data format.
- Calibration procedures same as basic GSN system.
- Port for portable terminal.
- Switchable DAC for monitoring signals.
- Automatic mass positioning.
- Backup power.
- Lightning protection.
- Sealed, weather-proof enclosures.

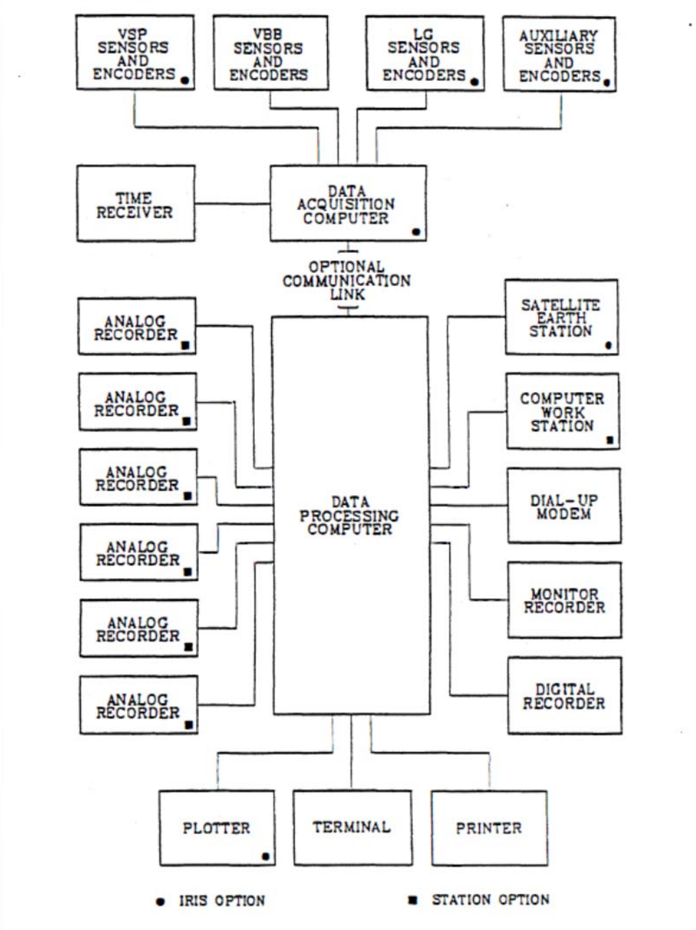


Figure 3.1 Block diagram of IRIS-2 system with separated data acquisition (DA) and data processing (DP) modules.

The GSN design of 1989 anticipated mostly manned observatories as an extension of prior practice. The system design allowed telemetry to evolve in response to technical and funding reality.

TCP/IP: "what would you use that for?"
- anonymous

"Many of the GSN data acquisition systems will be installed **at existing manned observatories** where they will be operated by host organizations. ……. **The configuration of the GSN data system will be tailored to specific site requirements.**

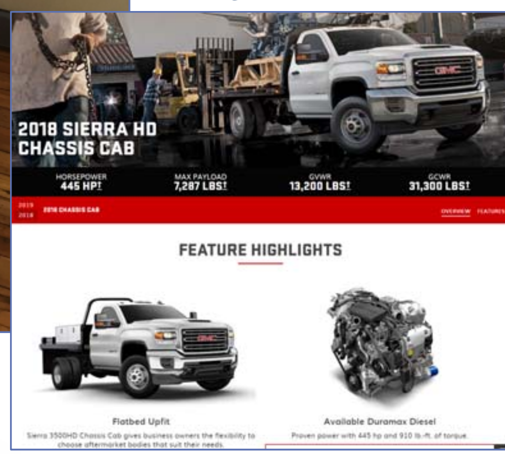
Real-time **satellite** telemetry between the GSN stations and the data collection center continues to be an important program goal, **although it is now apparent that the implementation of satellite telemetry will be delayed except in special cases**.

Data from some stations will be accessible via telephone dial-up. ….. Transmission of messages, computer commands and files between the stations and the data collection center will ease the maintenance of the network. "

Remote access is key to improve data quality and uptime. This was a first for any major network.

Thus began a line of Quanterra "station processors" that evolved synergistically with GSN and regional network requirements.

The newest "Q8", on top samples 20× the data rate, and stores 1000× the data, in a volume 50× smaller, and consumes 100× less power than the GSN "Q680" data system of 1990 (bottom) – a combined factor **100,000,000×** "better" than the systems of 1990. Various intervening Quanterra systems are between, including the **current Q330HR GSN data system** just under the Q8. But, like



the trucks of 2018 and 1942 that have an engine and 4 wheels, the technology is fundamentally unchanged, just more horsepower.

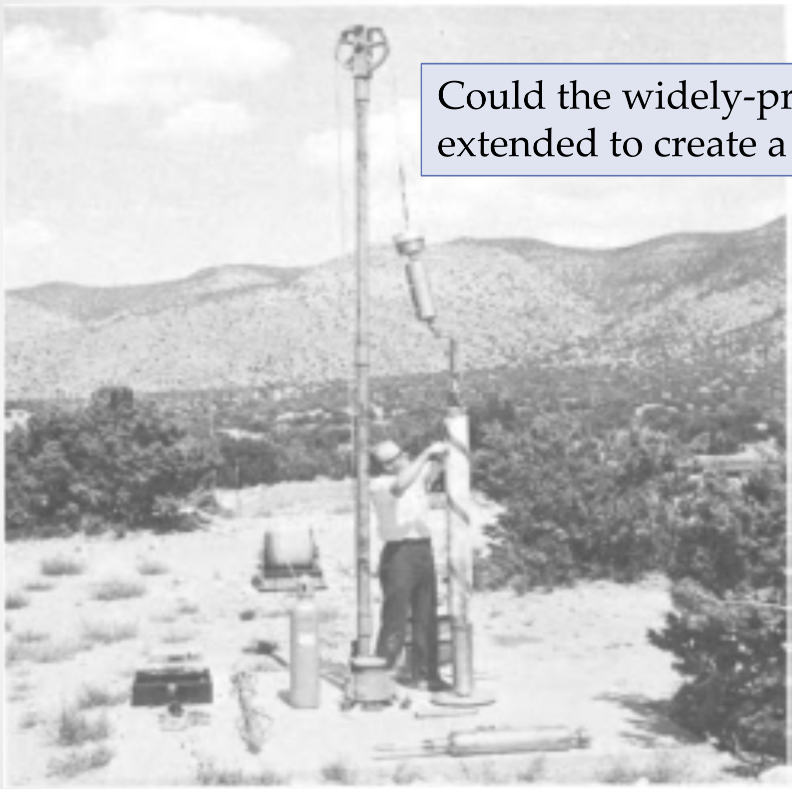
A new paradigm awaits!

Sensors

• • •

~1974 The Call of the Wild Borehole! 2010

Could the widely-produced STS-2.5 technology be extended to create a new borehole VBB sensor?



SRO borehole seismometer being pre pared for installation .
(Photo U.S. Geological Survey , Jon Peterson .

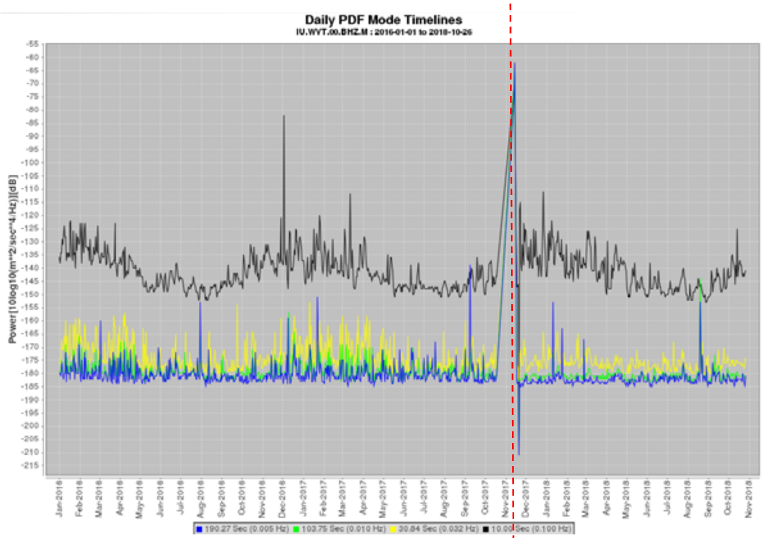
Bob Hutt, Joe Steim, and Erhard Wielandt, in a preliminary test of the STS-2.5 surface sensor in a deep ASL borehole.

Erhard Wielandt and Bob Hutt making delicate broad-band adjustments

New borehole sensors for the GSN

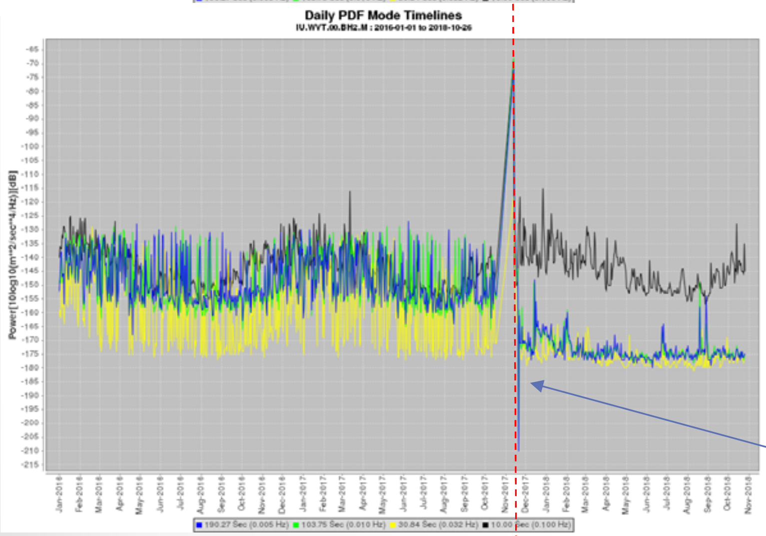
A rigorous development program was launched in 2014 for the development of a new borehole Very Broad Band sensor for the GSN. The program benefited from the preliminary experiments in 2010 with the involvement of noted experts, and called upon the use of special equipment and methods.

Potential improvement moving from surface to borehole – improvement at IU-WVT following STS-6A installation



Vert

IU-WVT



Horiz

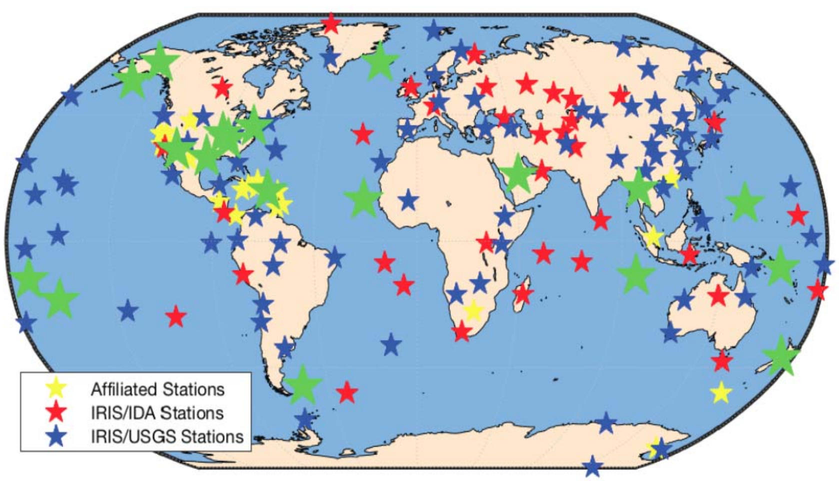
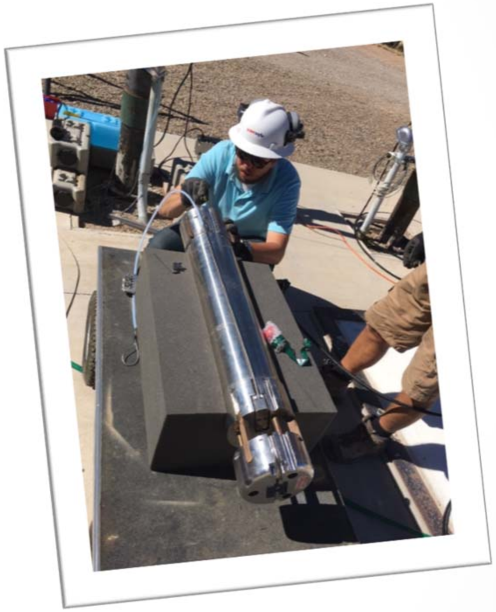


Figure 2. Locations of New VBB Borehole Installations of STS-6A (Bright Green Stars)

Noise is reduced at 30s and longer periods coincident with installation of the STS-6A in late 2017

Installing the STS-6A at ASL

A. T. Ringler photo



As of Jul 11 **ANMO** at ASL is now an **STS-6A**

STS-6 vs 54000

Improvement over the KS-54000

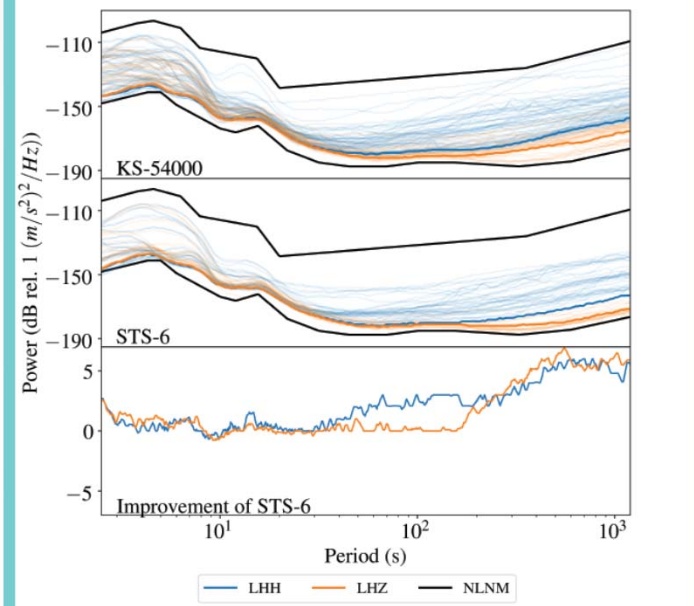


Figure 1: 10th percentile Power Spectral Density (PSD) estimates for 365 days of data for all Global Seismographic Network (GSN) station operatoring GeoTech KS-54000 (top) or a Streckeisen STS-6 (middle) starting September 7, 2018. The horizontals components are denoted in blue (LHH) and the vertical components in orange (LHZ). The 10th percentile differences between the 10th percentile for the KS-54000 and the STS-6 are also shown (bottom). For reference we include the Peterson (1993) NLNM.

1) We can easily get 5 dB improvement at 100+ s period

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A. T. Ringler

3 and 4) LOTS! With just one new sensor we get a NEW NLNM and horizontal hum

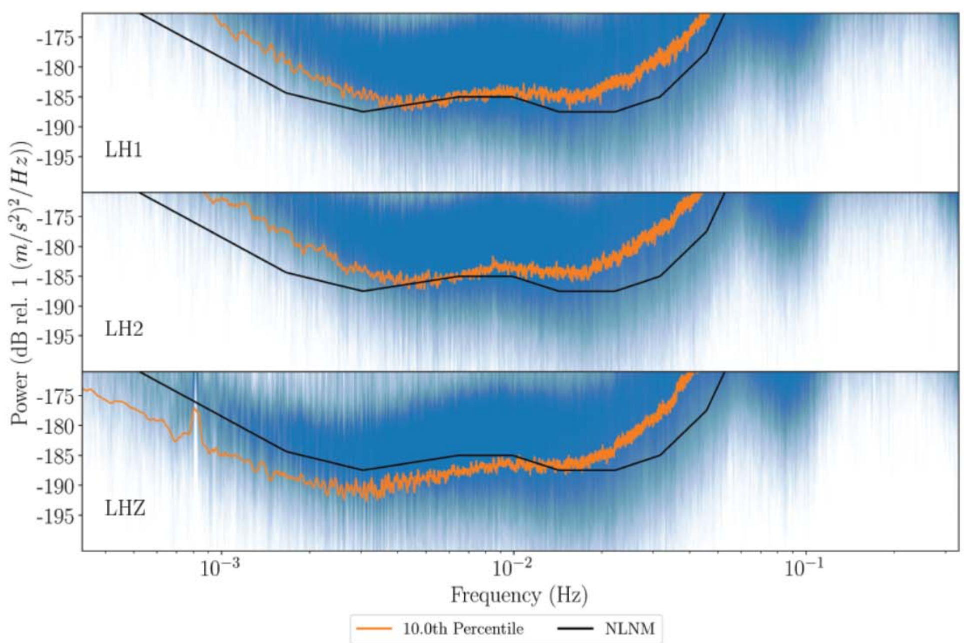

Figure 8: (Top) Stacked PSD estimates for the LH1 component of ANMO from August 18, 2018 to September 27, 2018. The background PSD estimates are shown (blue) along with the 10th percentile (orange). (Middle) Same as top, but for the LH2 component. (Bottom) Same as top, but for the LHZ component. We have included the Peterson (1993) NLNM for reference.

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STS-6 at ANMO

ANMO is showing levels at roughly the 10th percentile well below the NLNM at very low frequencies. This confirms for the first time that the borehole environment and installation methods are compatible with the observation of very low levels at very long periods. Until now, no broad-band instrument existed that was capable of confirming this.

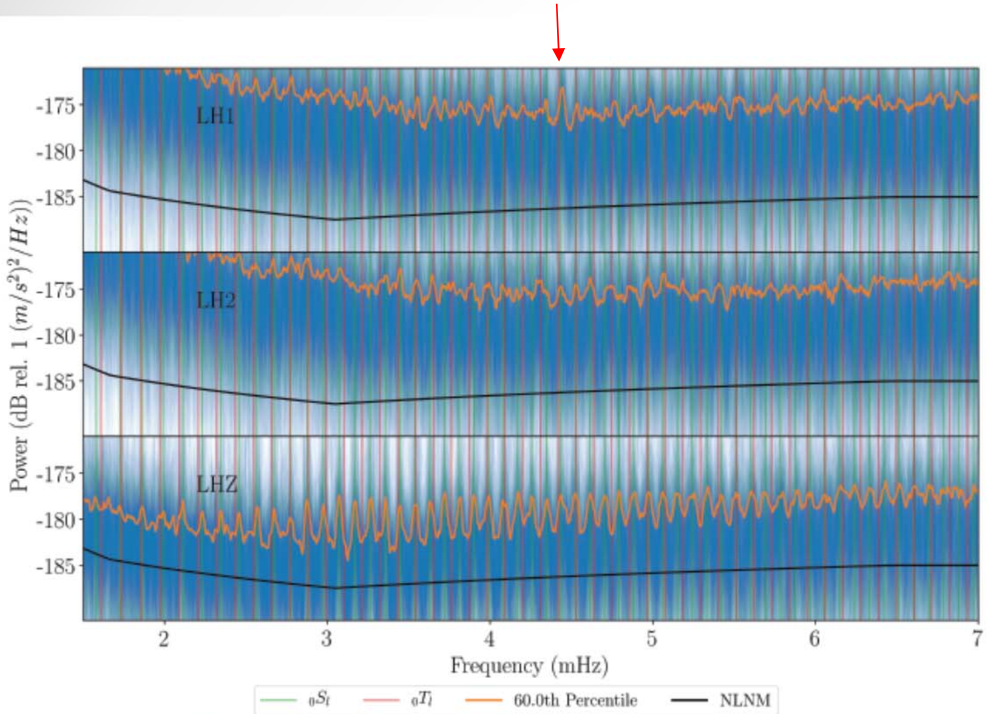


Figure 7: (Top) Stacked PSD estimates for ANMO from July 11, 2018 to September 27, 2018. The background PSD estimates are shown (blue) along with the 60th percentile (orange). We show fundamental mode spherical (green) and torodial (red) modes using PREM (Dziewonski and Anderson, 1981).

A. T. Ringler

Horizontal Hum?

From: Rudolf Widmer-Schnidrig [mailto:widmer@geophys.uni-stuttgart.de]
Sent: Thursday, October 11, 2018 9:07 AM
To: Ringler, Adam <aringler@usgs.gov>; Joe Steim <steim@quanterra.com>
Cc: David Jones <davidjones@usgs.gov>; Robert Anthony <reanthony@usgs.gov>; Thomas Forbriger <thomas.forbriger@kit.edu>; Charles R Hutt <bhutt@usgs.gov>; David C Wilson <dwilson@usgs.gov>; Dieter Kurrle <dkurrle@lennartz-electronic.de>
Subject: Re: [EXTERNAL] RE: Poster for SITS

Dear Adam,

...

there is an. **observational jewel contained in it: With Fig.7 you have convinced me that you see the horizontal hum at ANMO**

The peak at 4.4 mHz in the LH1 PSD is one of the prominent features of the horizontal Hum. You see it clearly at ANMO.

With a surprisingly short time series. **Dieter Kurrle** (I add him in the CC) **used 10 years. You see it in 2.5 months of data!**

After BFO, TTO, MAJO and BJT we now have a 5th stations that sees the horizontal hum: ANMO.

Congratulations.

"I want you to find a bold and innovative way to do everything exactly the same way it's been done for 25 years."

Right…

- Very Broad Band GSN. Now 0.1 mHz – 50Hz. Simple, widely applicable.
- Continuous recording. Data compression (early) and storage growth.
- Quantitative goals, and technical plan.
- FDSN
- Standardization on efficient, open data formats for exchange. (fork?)
- Boreholes are mostly better (1980’s instruments could not confirm that)
- Data return and data quality metrics. Adoption of standards, e.g. LNM
- Telemetry + onsite archival data return greater than either alone

Not quite….

- Staffed observatories and local technical support (1984 Science Plan).
- *tailoring to specific site requirements*. WWSSN, TA were pedantically standardized.
- 90% return is acceptable (1990 Technical Plan). 99+% is a better goal.
- Reliance on surface sensors (they are "cheaper") – lost years.
- The "Great STS-1 Panic of 2004"
- Understanding measurement physics (temperature, ~~measuring cal sensitivity~~)
- PI-driven projects can be a missed opportunity in terms of rigor and development and propagation of best practices.
- Recurring emphasis on satellites (GSN, TA), thought to be important.
- Missed: ubiquitous reach of internet and cellular.
- Seismological data volume "important". Facebook: 4PB/*day*; IRIS: 4PB/*30 years*!

Transportable Array

$$\sum_{i=1}^{N} P > N \cdot P$$

Common, proven ingredients

- Low-power equipment
- Cellular radios
- Solar panels
- Batteries
- Backhoe

- REQUIREMENTS ANALYSIS
- CAPABILITY ANALYSIS
- SYSTEMS ENGINEERING
- PROCEDURAL DISCIPLINE
- FEEDBACK/IMPROVEMENT
- NOVEL THINKING

Alaska TA: re-imagined TA with key improvements: borehole sensors, drilling methods, battery technology, rapid deployment of pre-assembled station equipment. Wow!

Uncommon Results, thousands of installations

- Science-driven remote siting
- 99.74% data return/1.3×10^6 station-days
- 98.4% of stations: 100% availability
- Real Time: < 3s latency, a decade before EEW
- Atmospheric sensors rolled into operations
- Near-real-time operations monitoring
- Oriented, calibrated, consistent low noise
- Field data is archive quality
- Low equipment attrition – parts reused in ATA

“opportunities”

- The cost and time to develop a *reliable, reproducible, consistent, and hence **useful***, scientific instrument can be justified (for both user and developer) only if amortized over a sufficient market.
- Teaching best practices and instrumentation physics. Are young scientists and students learning to be careful *experimentalists, thinkers, and creators? Or users?*
- Diminishing role of academic technical guidance and engagement. Academic leaders increasingly distant from instrumentation science and engineering.
- Will instrumentation-driven discovery, and furtherance of a better global and regional observation system be advanced by a return to narrow-band instrumentation, and consequent selection of the data audience?
- Will anybody pay any attention 10 years from now about how successful programs are conceived and executed? 10 minutes from now? How is *technical and operational competence transferred and propagated?*
- “flattening” the data archive (stripping all but seismic waveforms). (Peeve alert!) Underestimates resourcefulness of future researchers to mine information.
- Instrumentation for very low frequencies is still by no means entirely deterministic. There is work to do!

⚠ Rant

The 1977 Panel used the word "scientists" to describe the designers of the HGLP project. Instrumentation development is both *science* and *engineering*.

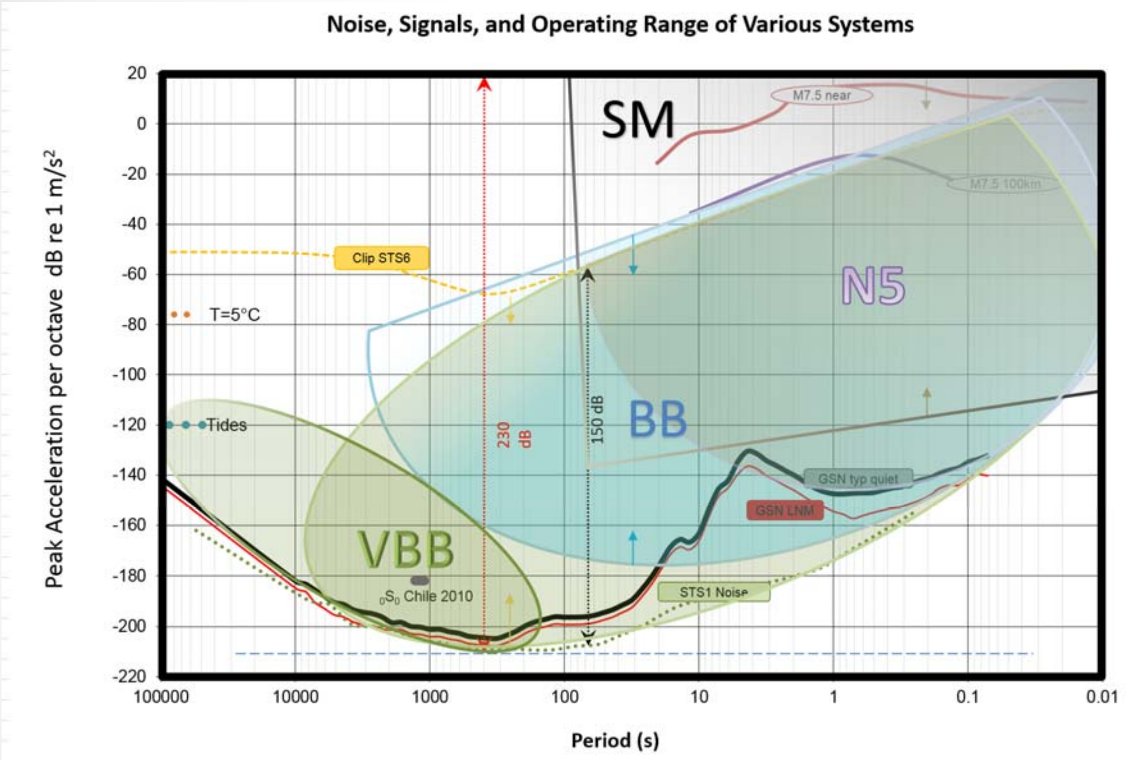
Seismological observation is hardware-intensive. A **reproducible**, **deployable and therefore useful** tool is an essential, if not *the* essential, physical element enabling a grand vision like IRIS. This is a collaboration. **Increasingly, reduction of the development of tools for science to a lowest-cost commodity procurement threatens the scientific soul of seismological investigations world-wide**. Stop this trend if you can!

IRIS is able to do what it does in part because instrument developers strive to reduce the design and construction of the essential tools to "a science". Thank an instrumentation scientist of the past 60 years who sweat the details to make possible what you do!

Maximize chance of Success

- Seismological network not a one-off "telescope." copies of equipment are deployed many times.
- Scaling up successful programs has leveraged proven, deployable technologies. Campaign instrumentation, e.g., is now returning to decades-proven approaches in the exploration industry.
- Lowest power consistent with the objective. Drives siting, size, weight, reliability…etc.
- Autonomous, rugged, small, self-contained footprint with limited, or no physical "grid" interactions.
- Archival and telemetry storage together optimize data return
- Understand the instrumentation physics (noise, clip, frequency range, environmental sensitivity…).
- Seek out, use, and contribute to Best Practices
- Disciplined systems engineering, deployment, and operations. ~~Ad hoc~~
- Flexible *capabilities*; uniform *deployment*.
- Active management! every detail!
- Timely, near-real-time performance analysis and corrective action.
- Continuous improvement. Don't accumulate needed procedural or equipment improvements.
- Instrumentation scientists design equipment that *can* do remarkable things. It's up to *you* to *invest in understanding the data collection problem* to apply those capabilities effectively.

Operating ranges of various instrumentation systems as of 2018



Recognize: Goals will converge on what is available until viable economics allow what is available to evolve to attain new goals.

Global and Regional instrumentation of 2018 can now be implemented with **2 sensors** (VBB and SM), not 3. A dedicated sensor for high frequencies is no longer needed, as the borehole STS-6 incorporates frequency coverage exceeding the original GSN Design Goal. The clip level now also exceeds STS-1 **clip level by a factor of 2**.

The "Intermediate BB" class of instrument overlaps with VBB, without low-noise long-periods. The range of a 5Hz "Node" covers a short periods subset.

The VBB or BB vs. N5 split begins to resemble a higher dynamic range version of the LP/SP split of 1980.