From Past to NOW and Beyond

Technology Developments used to Support EarthScope USArray/TA & PBO Projects and Beyond

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QUG and AUG Meeting
March 22-24, 2010
Abu Dhabi, UAE

QUANTERRA

Presentation Outline

- Introduction
- Early days
- System evolution – changing requirements
- Requirements for a new data exchange system
- Introduction to US NSF Funded EarthScope Project & Transportable Array (TA)
- What have we learned? – issues relevant to this meeting
- Future

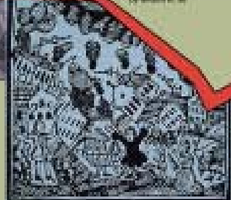
QUANTERRA

KINEMETRICS

THE HISTORY OF SEISMOLOGY

Robert Hooke, CEIIOSSOTTUU

In 1678 the English Physicist published a treatise entitled the **True Theory of Elasticity or Springiness** with the anagram above on the title page. The solution to the puzzle is Ut Tensio, Sic Vis, or "as the extension so the force". Today we state this as "stress is proportional to strain" and call this Hooke's Law. This is the first fundamental mathematical formulation in modern Seismology.



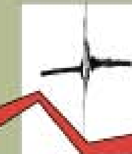
November 1, 1755 Lisbon, with a population of more than a quarter of a million was one of the largest cities in Europe. About 9:30 a.m. a great earthquake occurred 200 km to the southwest beneath the Atlantic ocean. The city shook for nearly 10 minutes and ~30 minutes after the event, a tsunami swamped the Tagus river which runs through the center of the city. The Lisbon Earthquake was the first event to be studied scientifically. J. Michell proposed the shaking was caused by wave propagation from a distant source, and that the waves were very similar to those produced by sound in air.

1830 Discovery of P and S waves The early part of the nineteenth century was an extraordinary time for mathematics. French mathematicians Navier and Cauchy developed equations for elasticity. Then, in 1830 Poisson published a paper showing that there were two fundamental elastic waves, P and S waves. Poisson's Ratio, which is a measure of the S to P velocity, is widely used in seismology today.

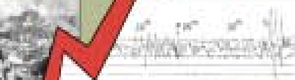
Robert Mallet Not only the inventor of the word seismology, Robert Mallet was considered the "first" seismologist. Born in Ireland, he was an engineer of considerable skill and his contributions to seismology mark the birth of the science. He constructed the first comprehensive earthquake catalog and world seismicity map. In the late 1840s, Mallet used explosives to produce seismic waves and investigate the idea that seismic waves travel at different speeds in different rock types. Following the 1857 Neapolitan earthquake, Mallet traveled to Italy and using the orientation of cracks and fallen masonry produced an isoseismal map for the event. The map identified areas of similar intensities of shaking.

John Milne In 1875 a 25 year old mining engineer named John Milne was invited to become a professor of geology at the Imperial University of Tokyo. Milne organized a seismic survey of Japan and soon recognized the importance of recording the seismograms. Milne was a great promoter of establishing a world wide seismic network, designed several types of seismometers, and made the first accurate global travel time curve.

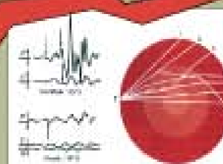
1889, The First Teleseism The first time a seismogram was correlated with a distant earthquake was in 1889. The record shows a great Japanese earthquake as recorded in Potsdam, Germany.



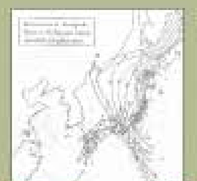
April 18, 1906 At the turn of the century San Francisco was a bustling port city with a population of 400,000. Early on the morning of April 18 a major earthquake occurred on the San Andreas Fault, and the "City by the Bay" was devastated. A nearly 400 km long section of the fault slipped with offsets as great as 6 meters. Many of the structures in the city were destroyed, but much of the damage was caused by the ensuing fires that burned out of control for days. The state of California set up a commission, headed by H.F. Reid and G.K. Gilbert, to study the earthquake and the resulting report laid out the theory of "elastic rebound" which forms the core of understanding earthquake cycles today.



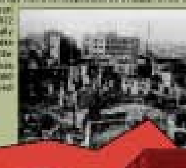
Lehmann: The Inner Core Inge Lehmann discovered the inner core, a zone of solid material at a depth of 5150 km in the early 1930s. Lehmann worked at the Copenhagen Observatory and carefully measured the arrival times of seismic phases from distant earthquakes. She noted that the only way to explain the core phases was to have a boundary within the core with an increase in velocity. She hypothesized that the inner core was solid, which was later proved on the basis of free oscillations.



1935: The Richter Scale In the early 1930s Charles Richter was assessing a catalog of California earthquakes. Richter wanted to publish the catalog with the "size" of the earthquakes instead of the intensity. He developed a measure of earthquakes size based on two fundamental principles: the level of shaking experienced at a distant site will depend on the size of the earthquake, and the level of shaking will decrease the farther the distance traveled by the seismic waves. Richter used these principles to develop a logarithmic scale (each unit of the scale corresponds to a 10 fold increase in shaking) which became known as the "Richter Scale". Although Richter's early work was only applicable to southern California, it served as the basis for modern magnitude scales.



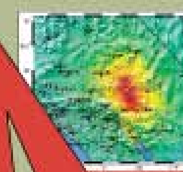
September 1, 1923: Tokyo One of the deadliest earthquakes of this century struck the densely populated Kwanto province in east-central Japan. The death toll in Tokyo exceeded 100,000, and nearly 2 million people were left homeless. Seismology was a developed science in Japan in the first part of the 20th century. Professor Fusakichi Omori had studied earthquakes in Japan and in 1922 concluded the region around Tokyo was "seismically quiet" and predicted that no earthquake would strike the region in the future. After the 1923 earthquake the Imperial Earthquake Investigation Committee was formed and produced fine volumes of scientific and engineering studies, which dramatically improved building practice in Japan.

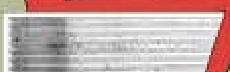


Wadati: The Discovery of Deep Earthquakes Kiyoo Wadati noted that earthquakes with the same epicenter had very different patterns of P and S wave arrival times. Wadati suggested that this phenomenon was due to different focal depths (depth below the surface of the Earth) for the earthquakes. Wadati proved conclusively that deep focus earthquakes occurred, and showed that the depths of these events formed an inclined zone beneath Japan, which we now recognize as subduction zones. Wadati's observations had a profound effect on tectonic theories, which in turn, produced the first 3-D pattern that suggested plate tectonics in 1932.

1965: J. Tuzo Wilson and Transform Faults The spatial distribution of earthquakes was a fundamental in developing the theory of plate tectonics. J. Tuzo Wilson made a major contribution with the discovery of Transform Faults, which are shear faults with significant motion that are roughly terminated by ridges or subduction zones.

Shake Map Realtime collection of seismic data allows for the construction of maps depicting shaking intensity within seconds of an Earthquake occurrence. Shake Maps can highlight areas of expected damage and help provide rapid emergency response as is shown on the left. for the Hector Mine earthquake.

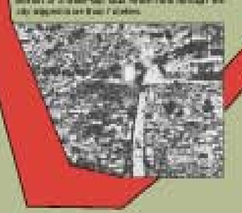


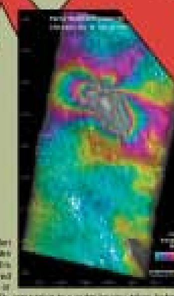


July 16, 1945 At 5:30 a.m. the USA detonated the first nuclear weapon in central New Mexico. The test, code-named TRINITY, had an explosive yield of approximately 15 kt (equivalent to 15 thousand tons of TNT). The closest seismic station was in Tucson, and the seismologist Beno Gutenberg used the record to determine the origin time of the explosion. The ability to seismically record this and other explosions gave rise the the field of "Forensic Seismology".

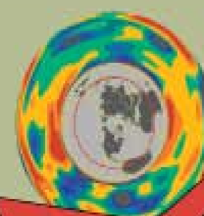
May 22, 1960 The largest earthquake in recorded history occurred in southern Chile in 1960. The earthquake, which had a magnitude of 9.5, ruptured a 1000 km section of the subduction zone where the Nazca plate descends beneath Chile. The event triggered a tsunami that not only devastated the coast of Chile, but killed 61 people in Hilo, Hawaii. The tidal tsunami height was measured to be over 10 meters. The Chilean earthquake was the first event to produce free oscillations of the Earth. Free oscillations are vibrations of the entire planet, and can be used to detail the structure of the Earth's deep interior.

July 28, 1976 The deadliest earthquake of the 20th century struck the city of Tangshan, China on July 28, 1976. The death toll has been in excess of 500,000. The industrial city was totally destroyed when a 150 km section of a strike-slip fault which runs through the city ruptured in less than 7 minutes.





Earth Velocity Structure Using a very large number of earthquakes it is possible to map changes in velocity throughout the interior of the Earth, known as tomographic slices. These slices can show descending slabs and the upwelling of hot material.



Seismology from Space The sudden slip along a fault during an earthquake causes permanent deformation of the Earth's crust. This deformation can be measured from space by a technique called INSAR, or Interferometric Synthetic Aperture Radar. By comparing two radar images taken before and after the earthquake, it is possible to measure changes in the ground surface. This technique was used to produce a map (right) of crustal deformation following the October 16, 1999 Hector Mine earthquake, a magnitude 7.1 event in the Mojave Desert of California.

sAso IRIS

T. Wallace, A. Paquette, and M. Hall-Wallace
University of Arizona

Modern Digital Seismology — Instrumentation, and Small Amplitude Studies in the Engineering World

John F. Clinton

Doctor of Philosophy

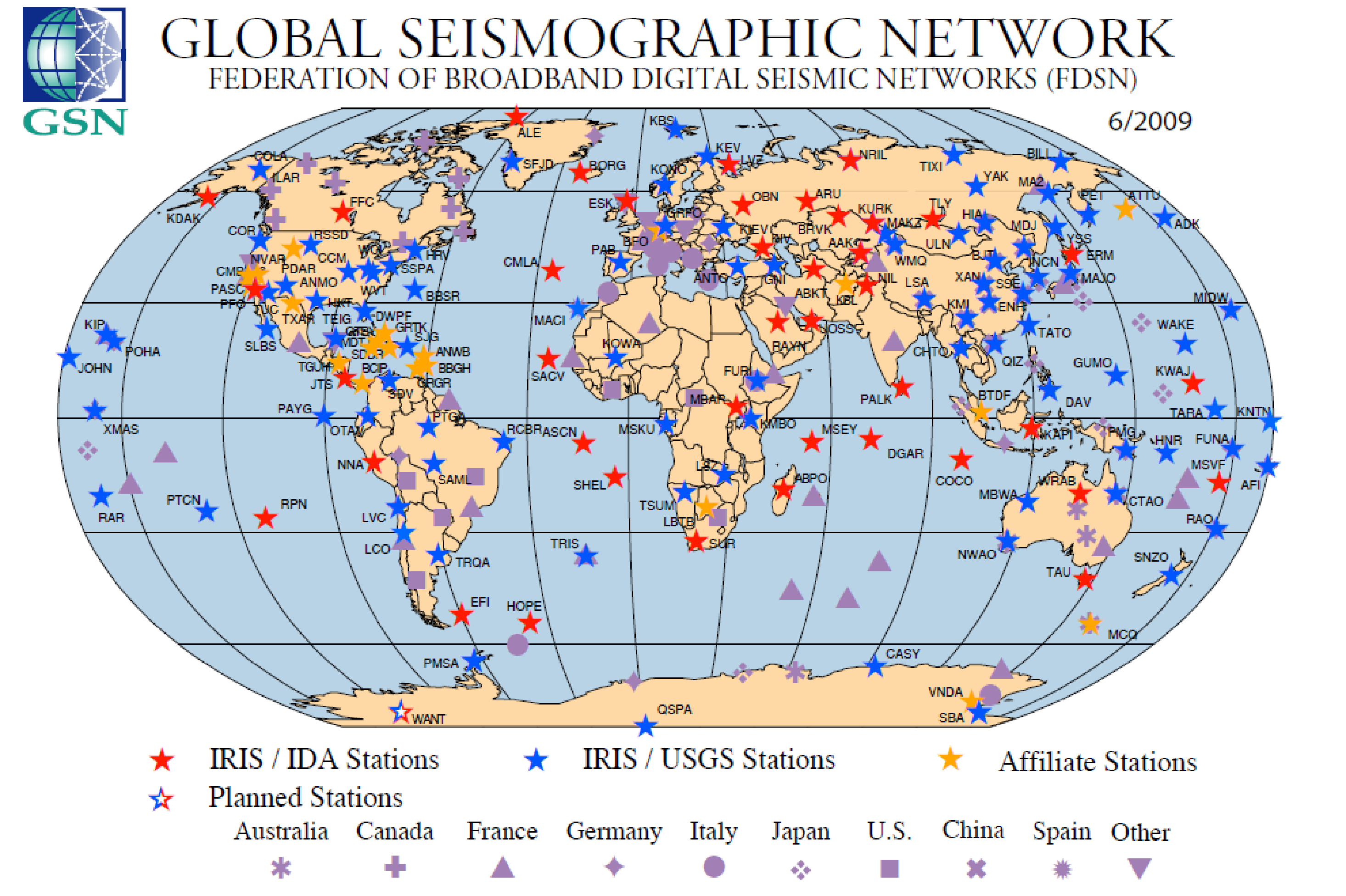
California Institute of Technology

2004

Chapter 1 Introduction

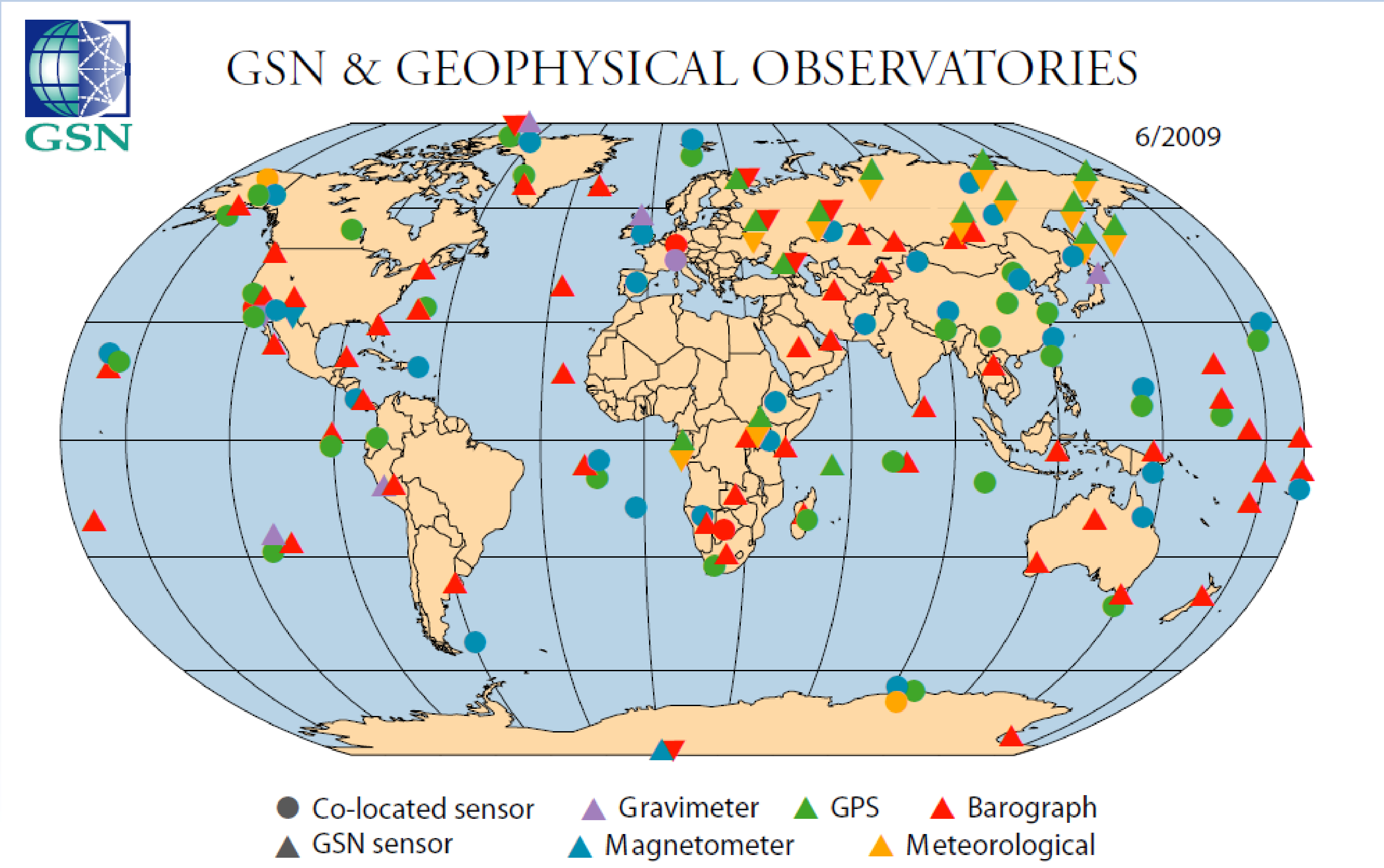
The last few years have seen the beginning of a new era in high dynamic range seismic instrumentation. 24-bit resolution (which translates to ~ 7 orders of magnitude) is now commonplace and becoming readily affordable. It is the standard for many seismic networks, and is increasingly common in engineering networks. Instruments are now designed to record over a wide frequency range to take advantage of this new resolution. It is also increasingly possible for networks to store large volumes of high sample rate continuous data at reasonable cost with relative ease. This thesis examines new research that has only become possible with the wealth of data that has recently become available to the community.

Global Networks 2009

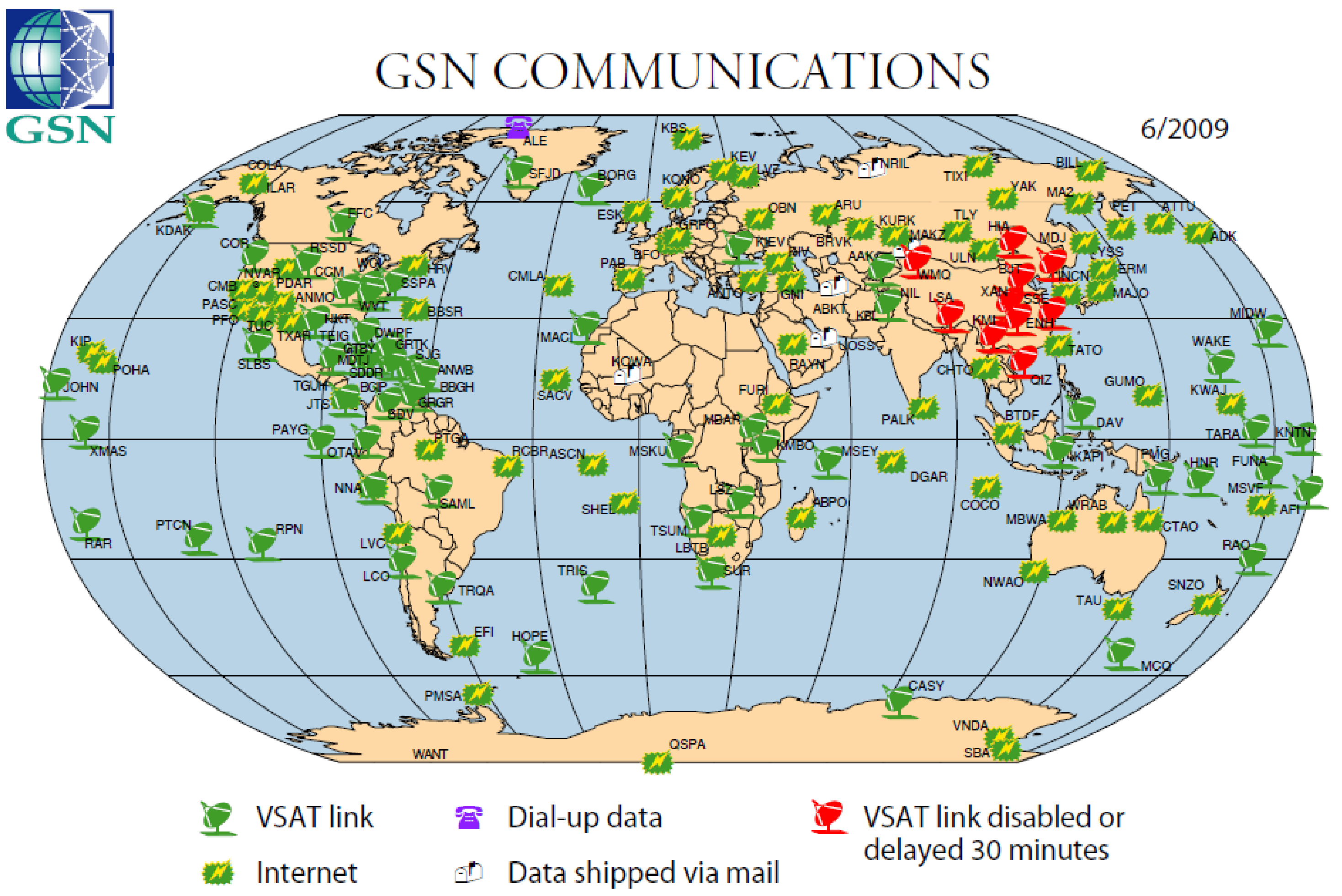


Global Seismic Network & Other Sensors 2009

Defacto: Station is Geophysical Observatory



GSN and Real-time 2009



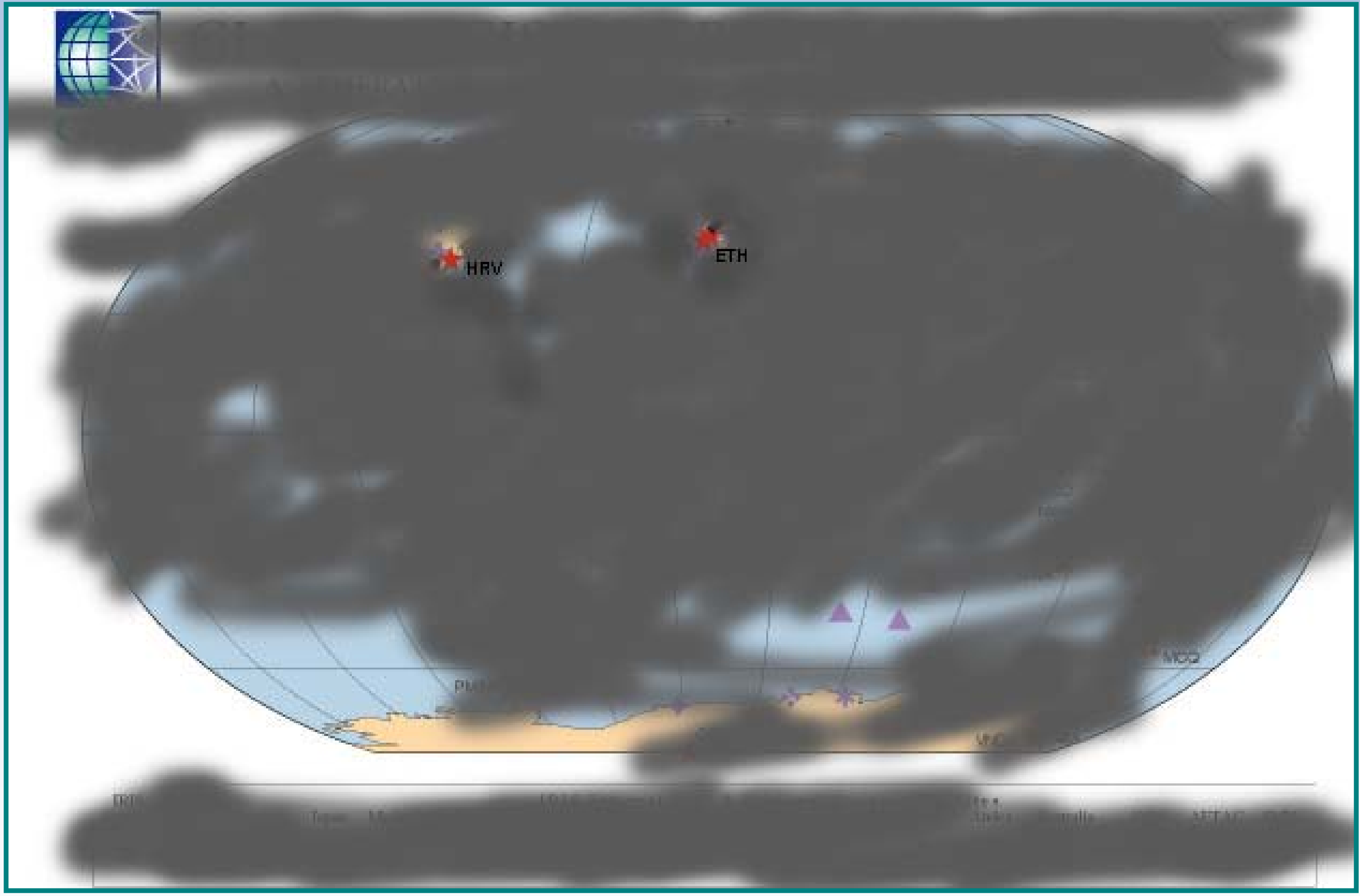
~20 -Year Rough Estimate
5,000-7,000
World Wide, High-Performance Broad Band Systems

Great Community Accomplishment

But Wait a Minute!

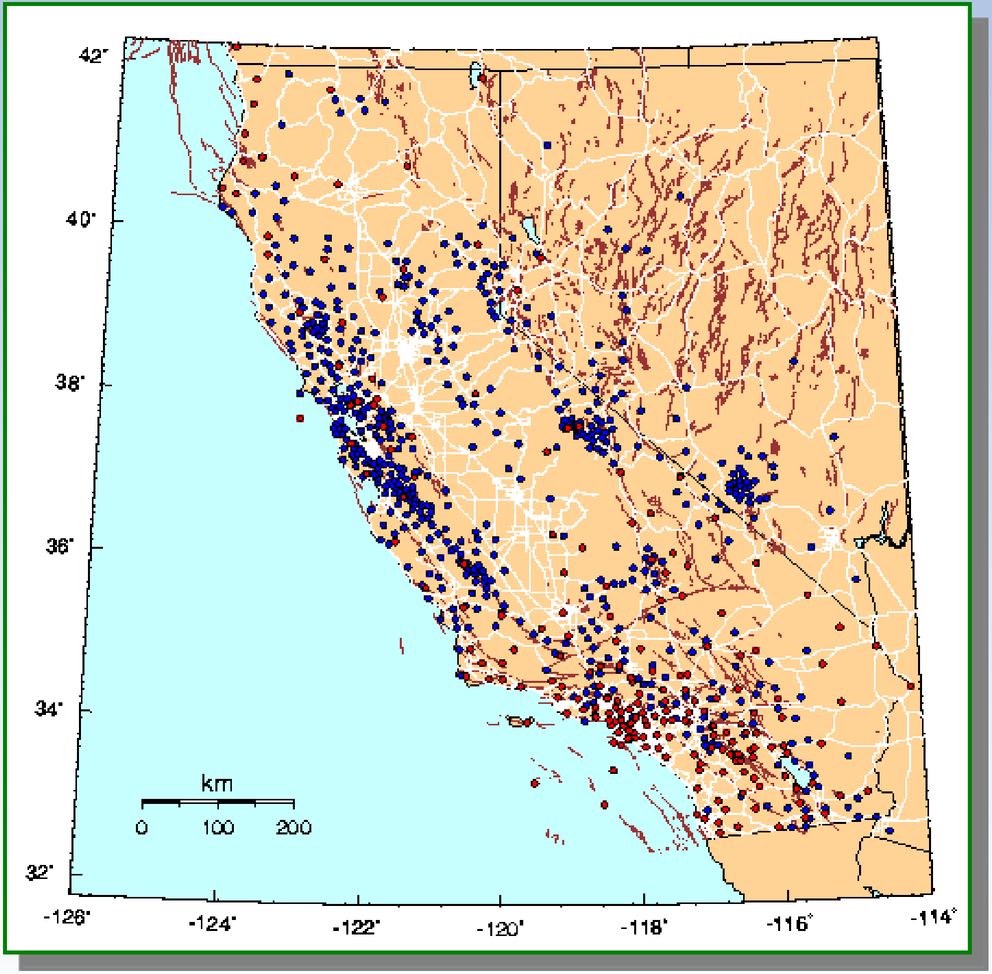
High-Performance Broad Band seismic monitoring was quite different several years looking back…..

Global VBB stations 1984



Proliferation

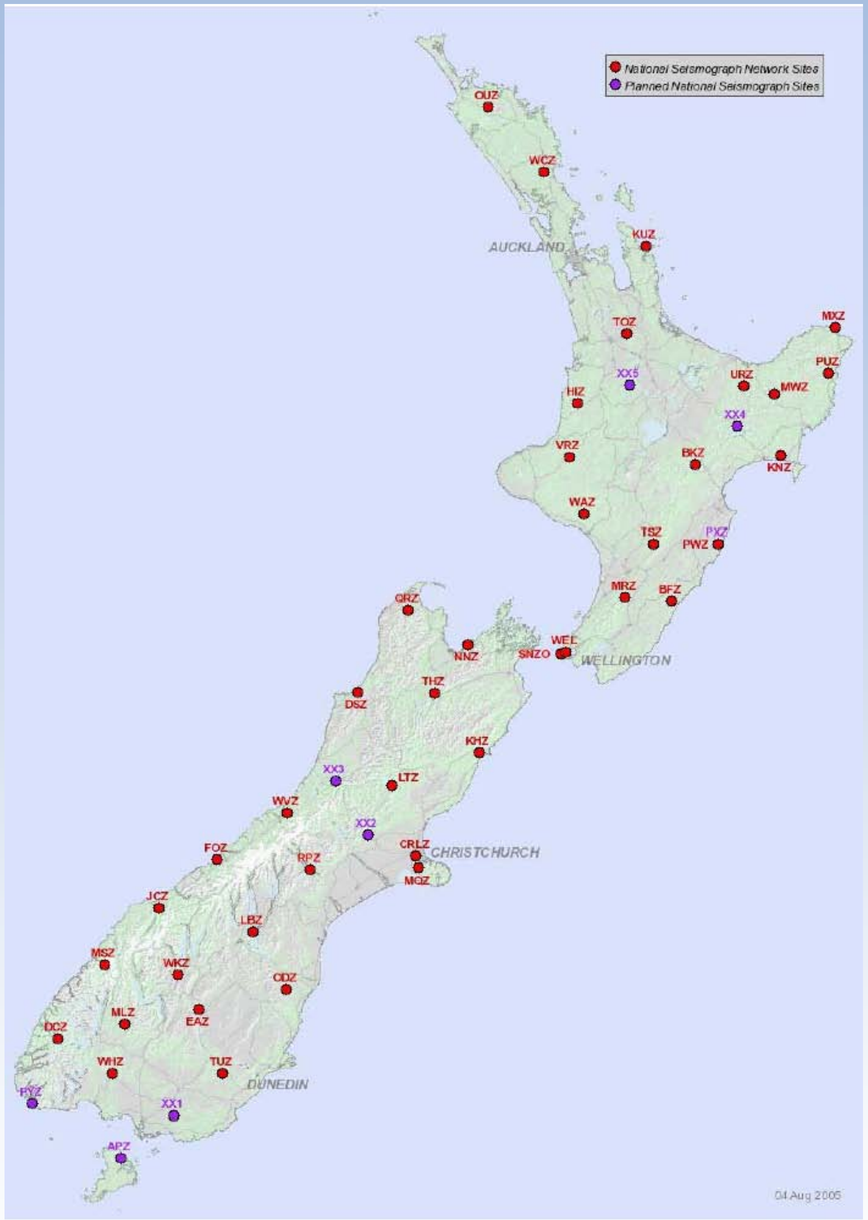
California Integrated Seismic Network



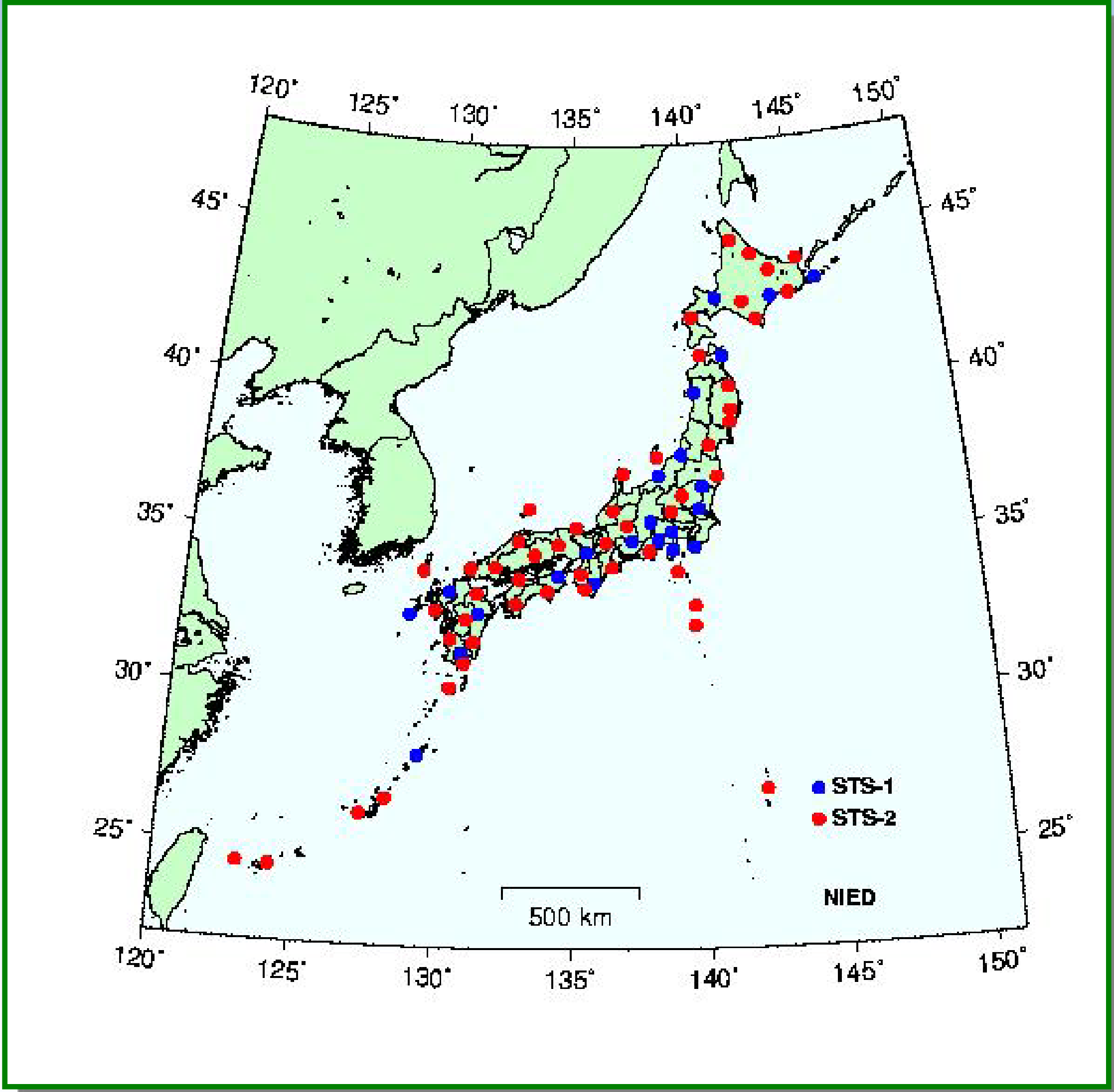
- *95+% of Digital Broad-Band and Strong Motions are Quanterra and Kinemetrics based*

New Zealand National Network

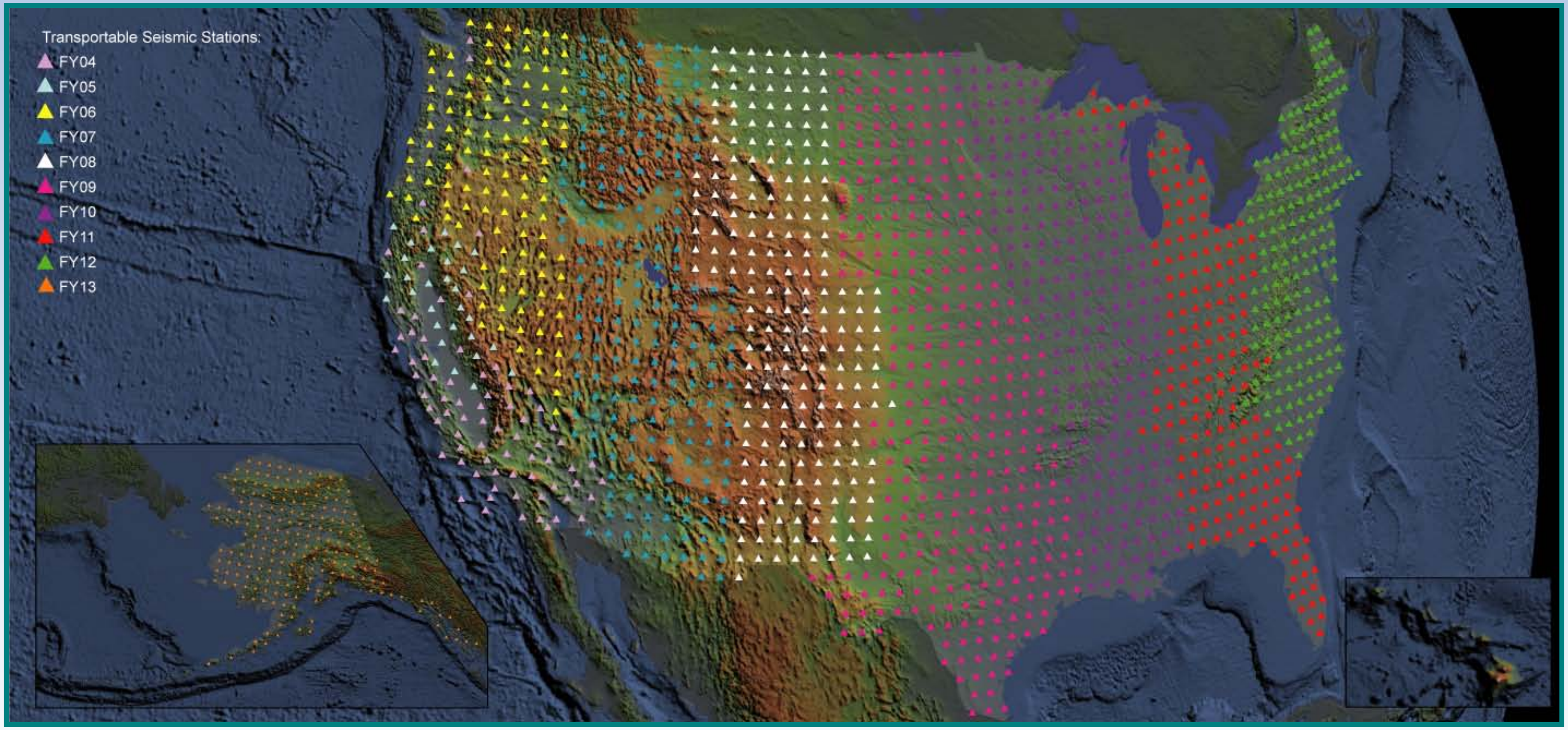
Q330, Q4120



Japan: F-net



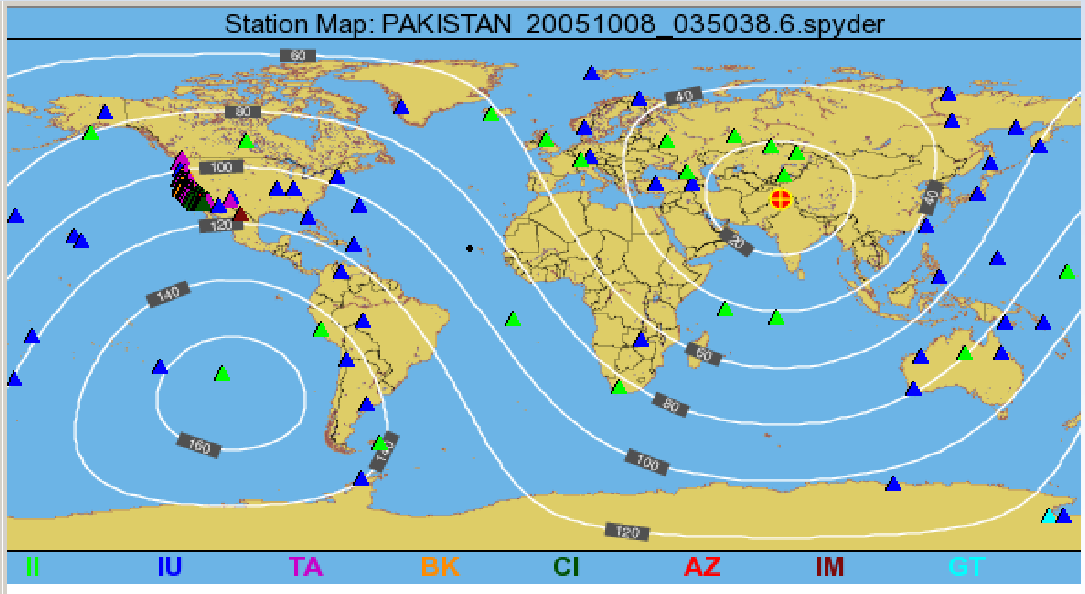
USArray, or "Seismometers in every Congressional District"

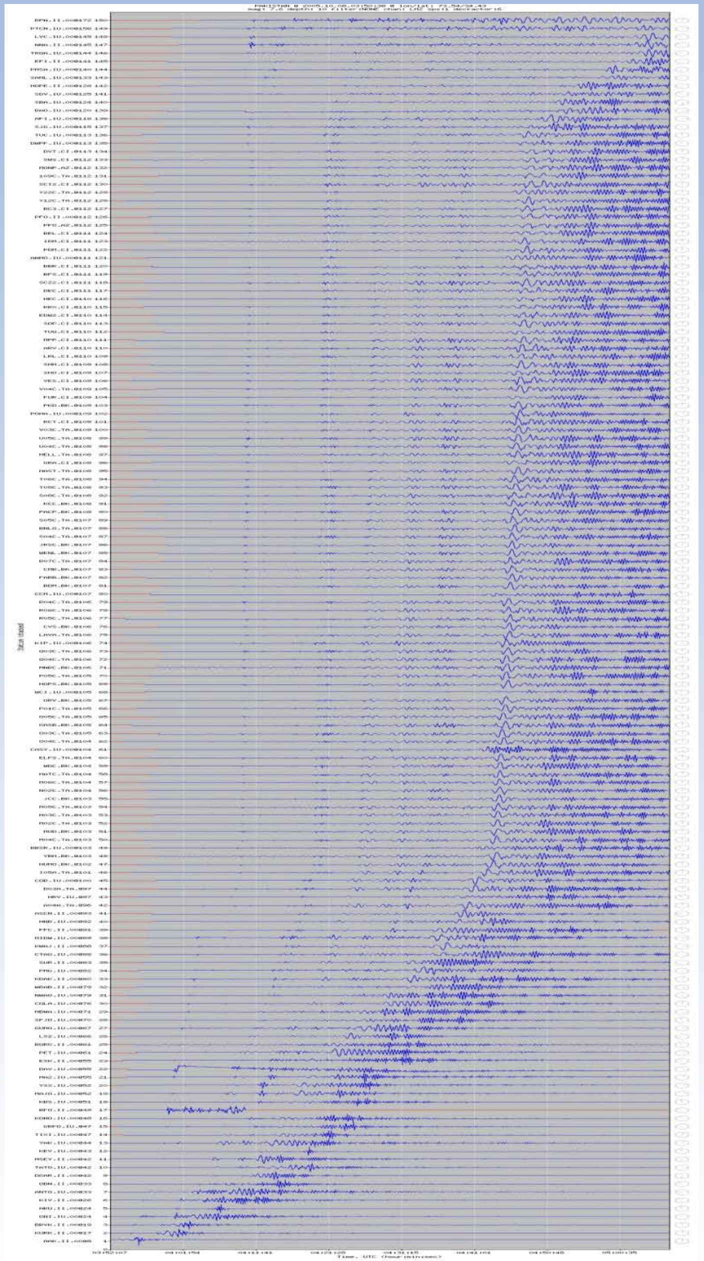


Real Time: USArray and PBO station digitizer is Q330

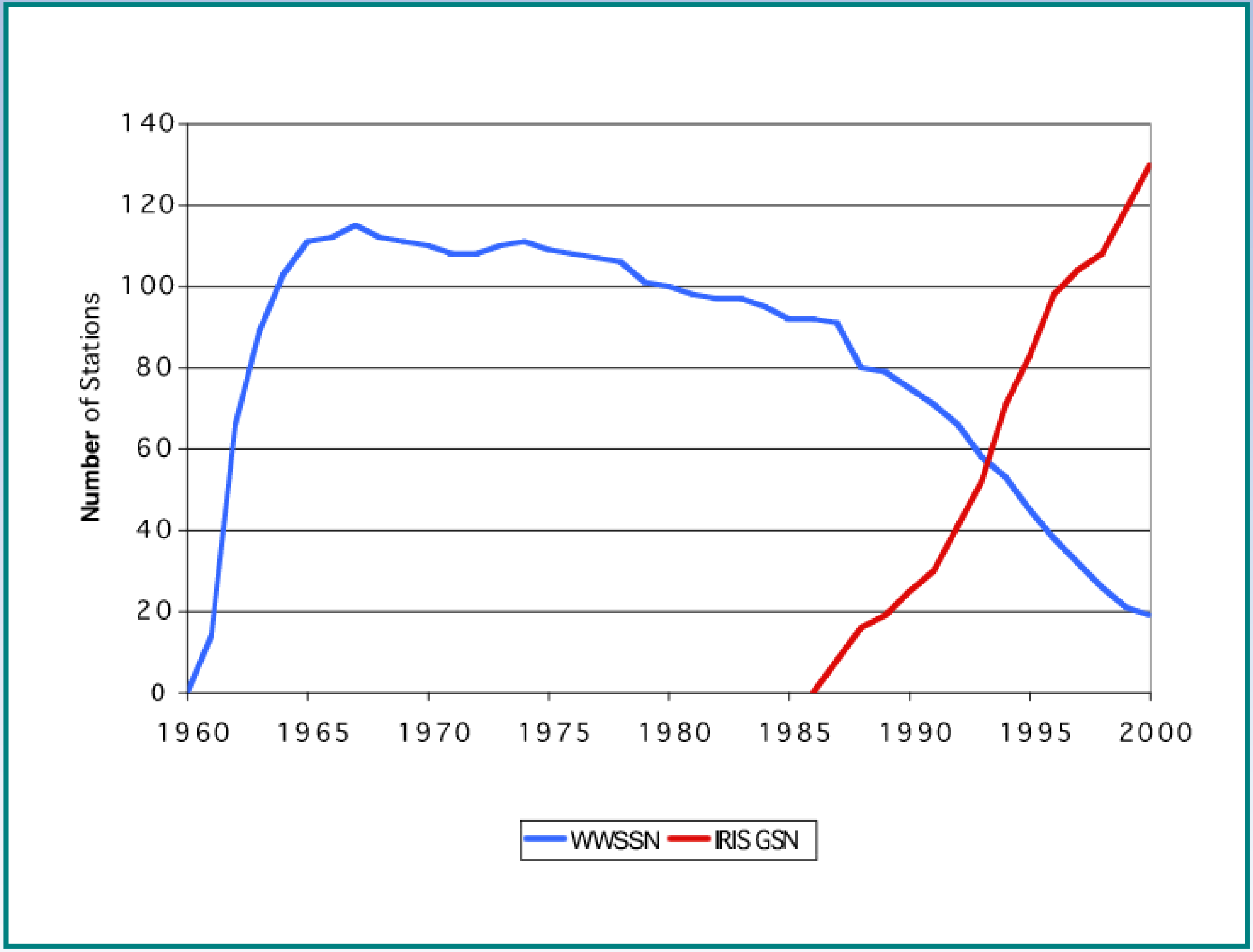
GSN & USArray Transportable Array: IDA & Q680, Q4120, Q330HR

Pakistan earthquake
2005/10/08
Mb7.6





Growth of the Networks – Value to Science!



~20 -Year Rough Estimate 5000-7000
World Wide, High-Performance Broad Band Systems

How did all this happen?

What was missing?

Prior seismological networks existed, such as the WWSSN, SRO, HGLP, RTSN, IDA, GRF, and many other regional and national programs. Some networks provided digital data. International cooperation existed within some of these networks and, e.g. ISC.

But NO suitable broad-band, high-dynamic range instrumentation existed to fuel the dramatic revolution that has taken place since 1985. A new instrumentation technology was the essential enabling ingredient.

"It's the bandwidth."
"Too much gain."
"The problem is 1/f noise."
"Can you produce it?"

"Let's just make one"

- Dr. Erhard Wielandt

Wielandt & Streckeisen

– early 1970's – STS-1

Pfungen, Switzerland

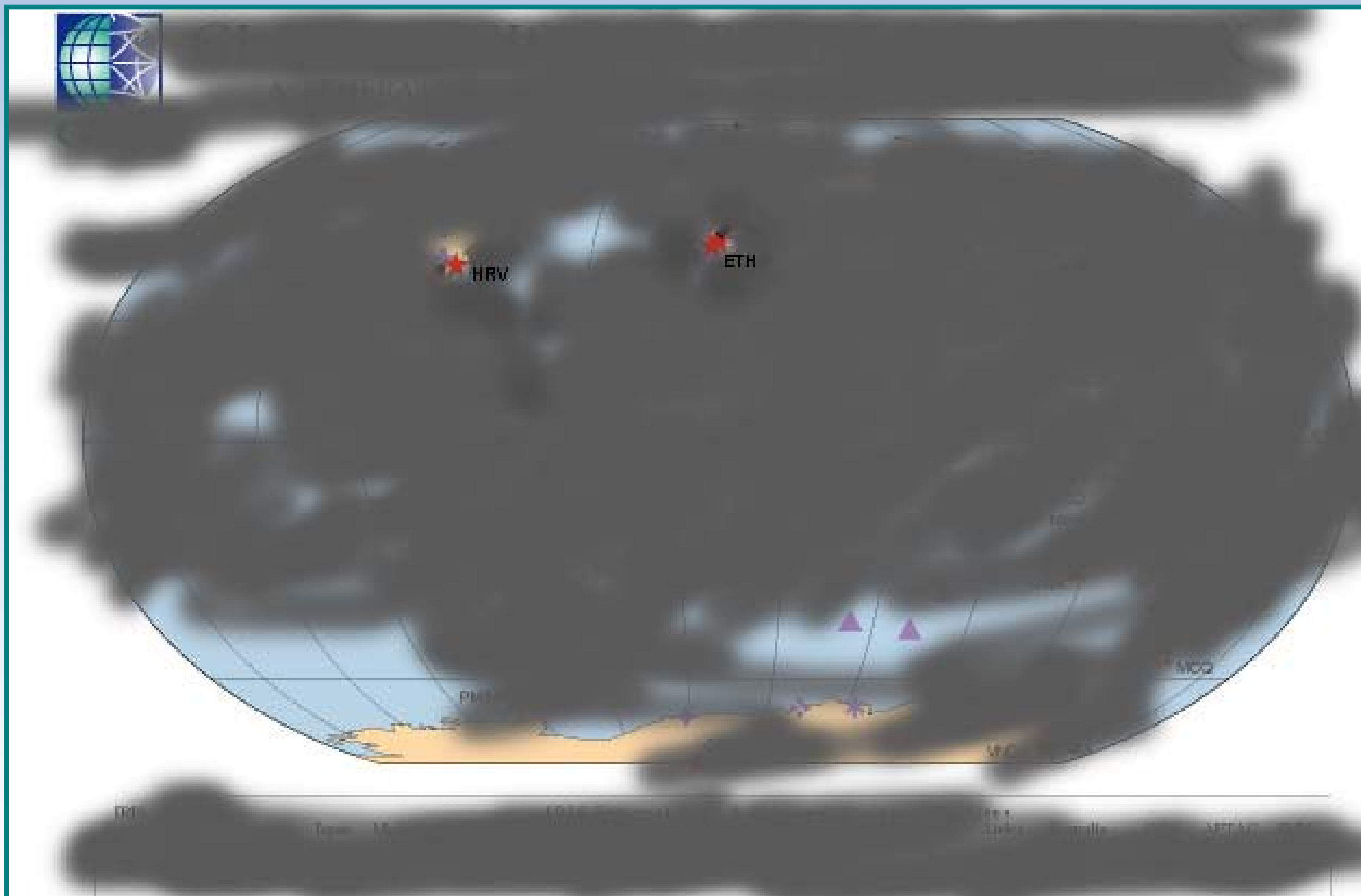
STS-2: A VBB seismometer for everyone

STS-2 - High-Performance Portable Very-Broad-Band Triaxial Seismometer

world-standard, field-proven - 145 dB dynamic range - mutually-aligned 3-components - robust locking - low power - wide temperature range without adjustment

Wielandt & Steim - *1979*

First Digital VBB stations 1984



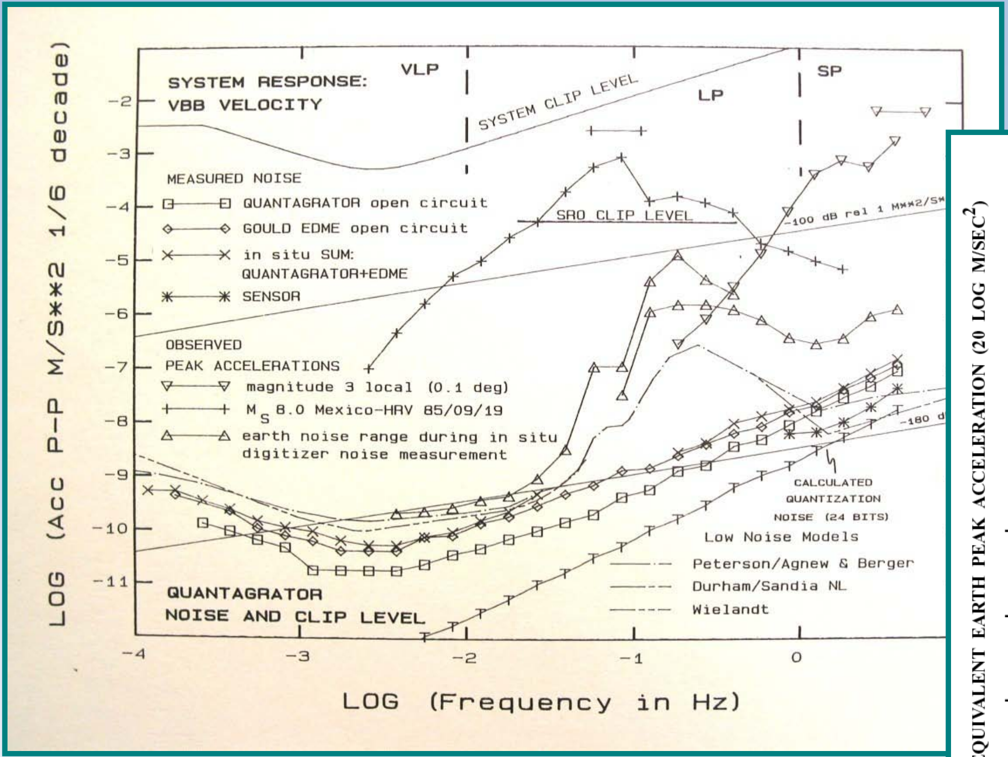
World's First Digital VBB stations 1984

Work of:

- **Harvard University, USA**
  - ***Joseph Steim, Principal Investigator, (Later founder of Quanterra Inc.)***

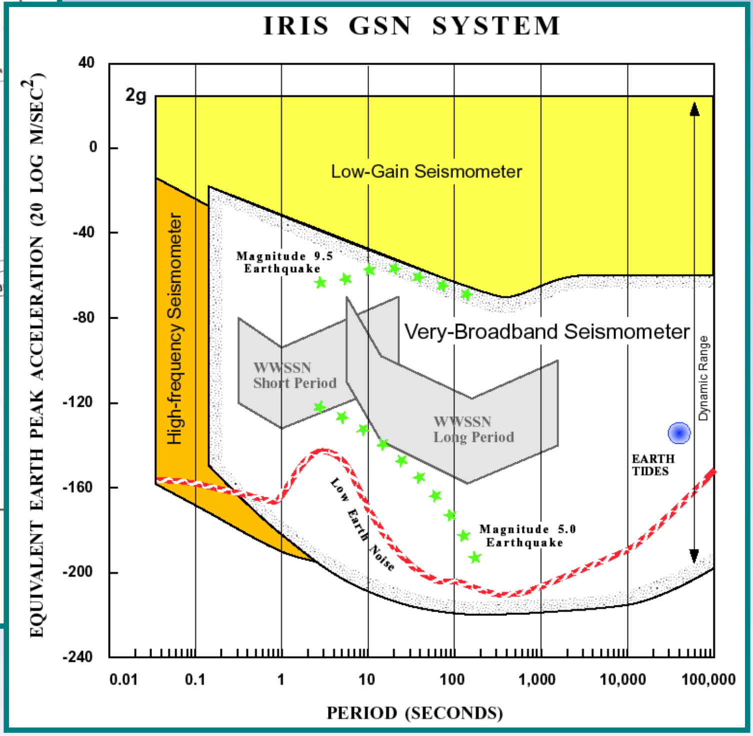
- **ETH, Switzerland**
  - ***Work of Gunar Streckeisen, Principal Investigator, (Later founder of Streckeisen AG.)***

Signals, Noise, and Dynamic Range: VBB



VBB Operating Range defined, 1985

IRIS New Generation GSN Proposal 2002.



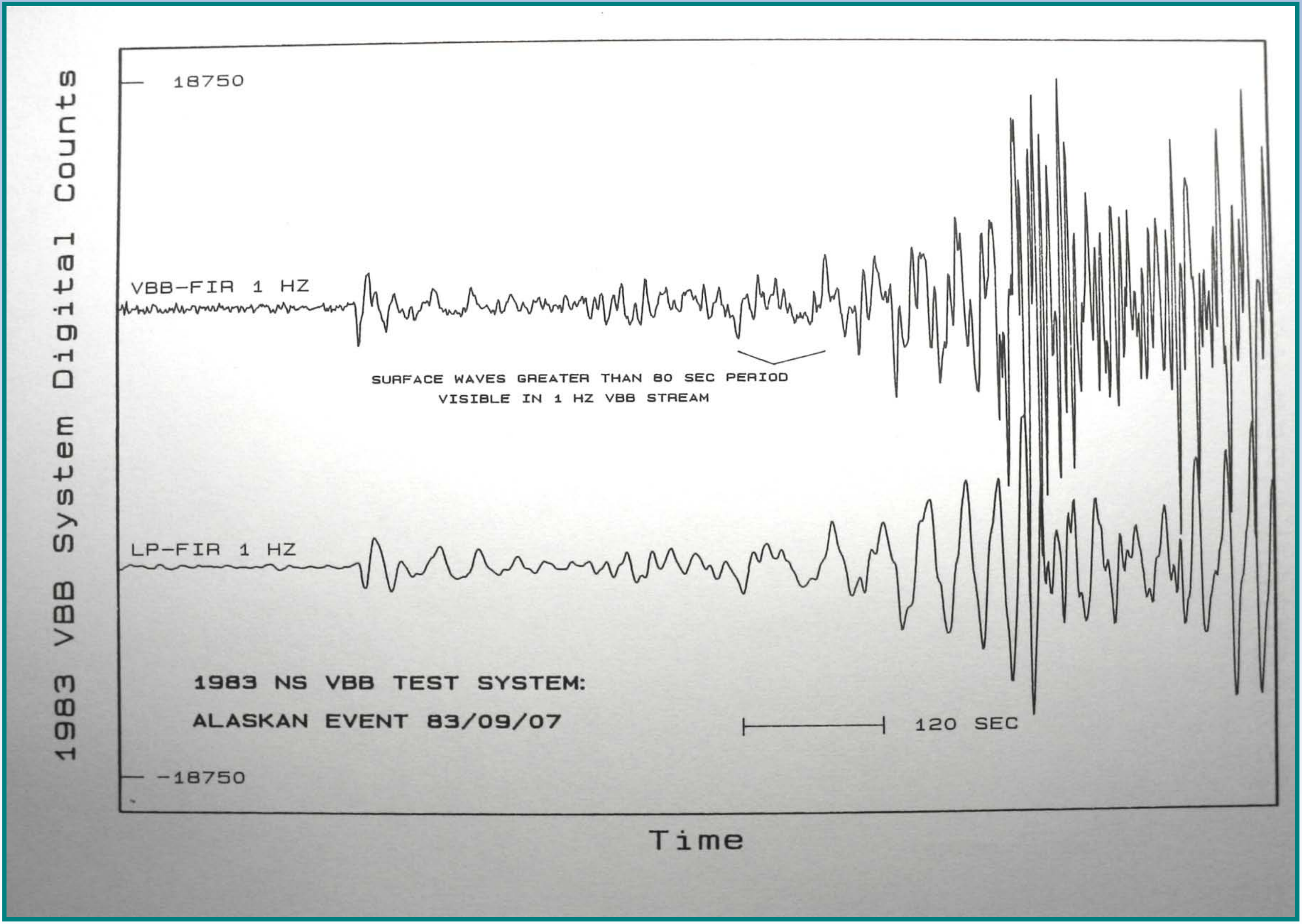
Q330HR: exceeds IRIS New Generation GSN Requirements and is selected in 2006 for GSN Upgrade

QUANTERRA®

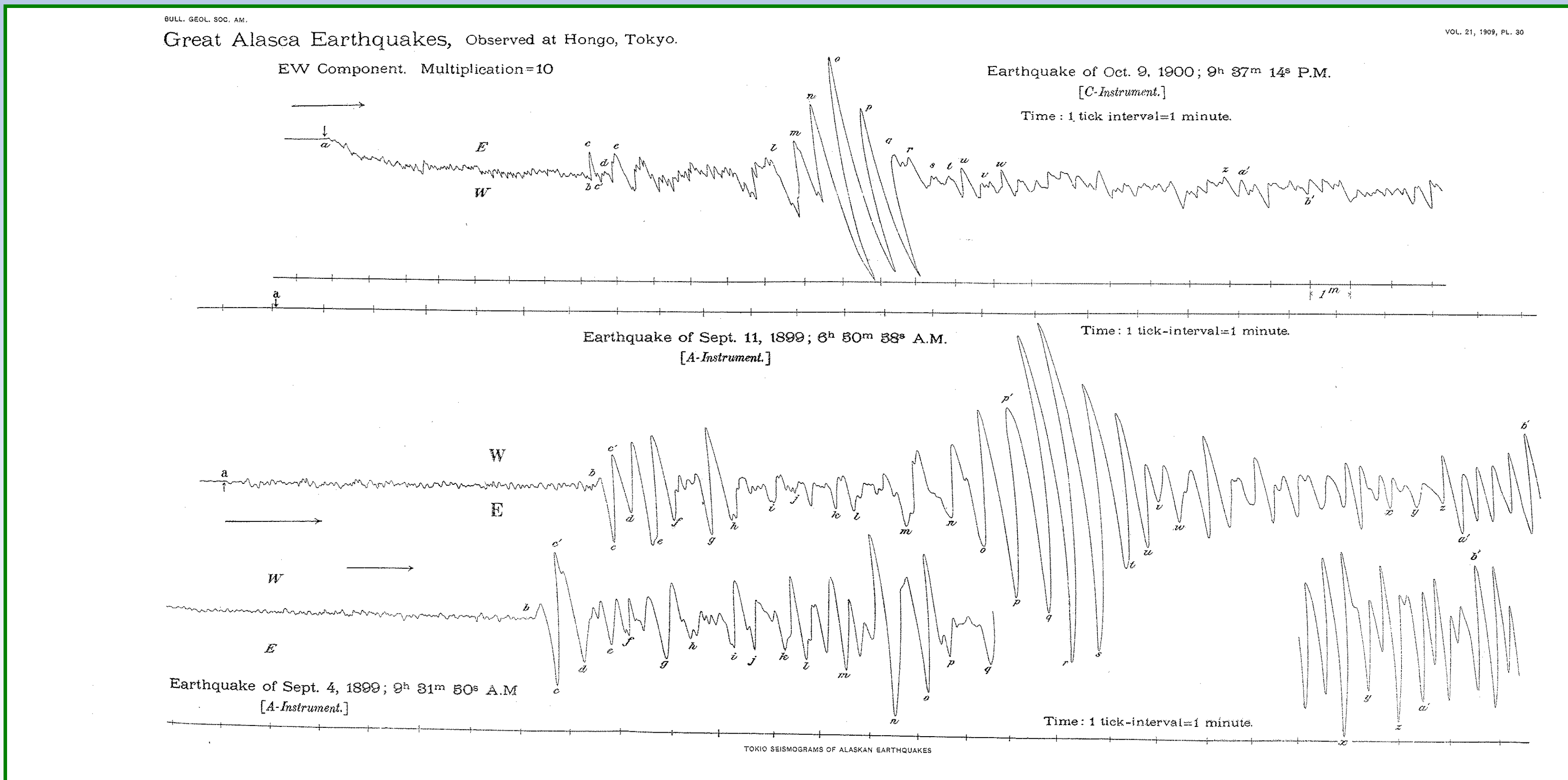
US 4866442
Japan 2787445
EPO 0293780
Germany P3883081.7-08
France 0,293,780
UK 0 293 780
Singapore P9790690

First Commercial Seismological High Resolution A/D 1987

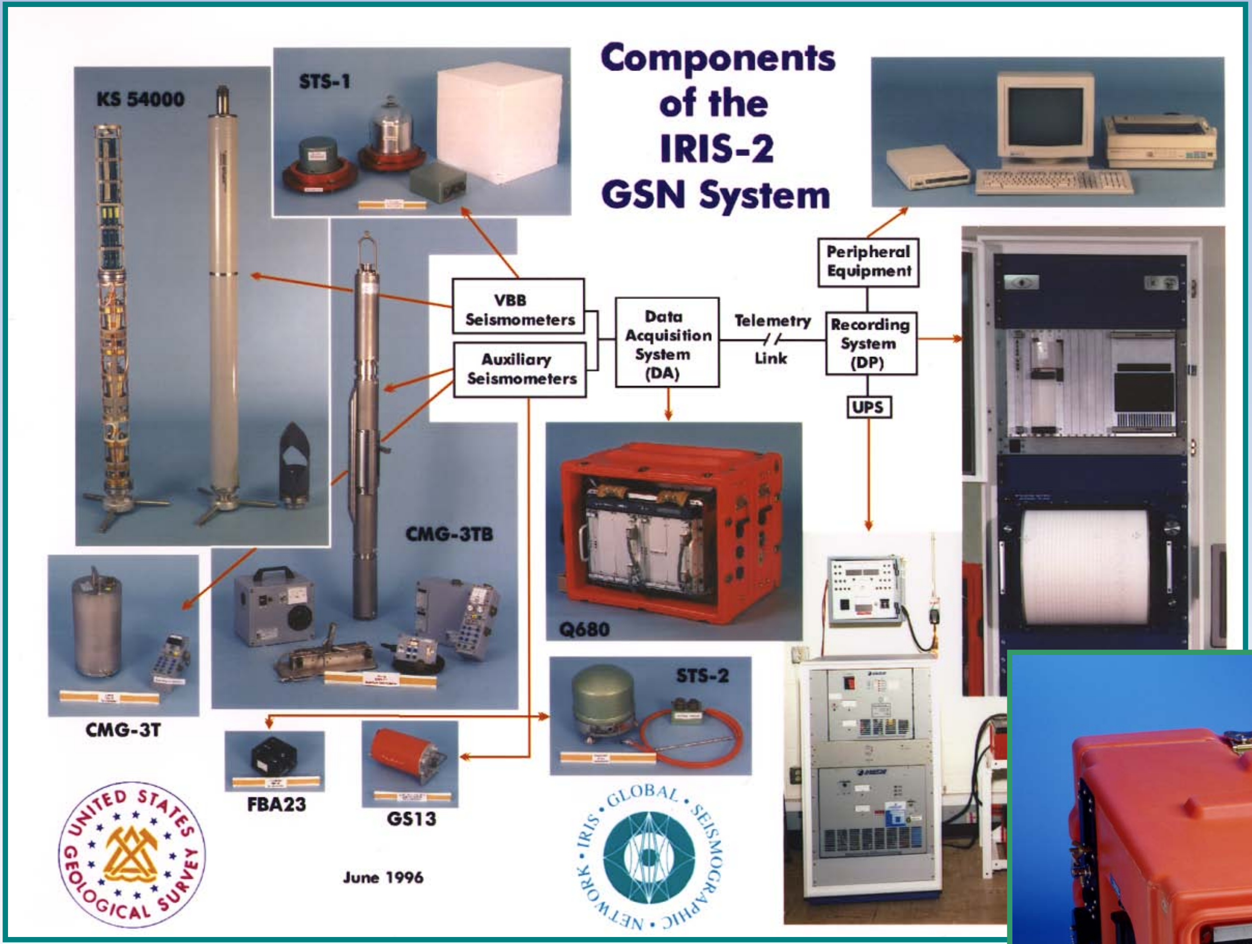
World's first digital VBB seismogram



Omori VBB Seismogram 1899

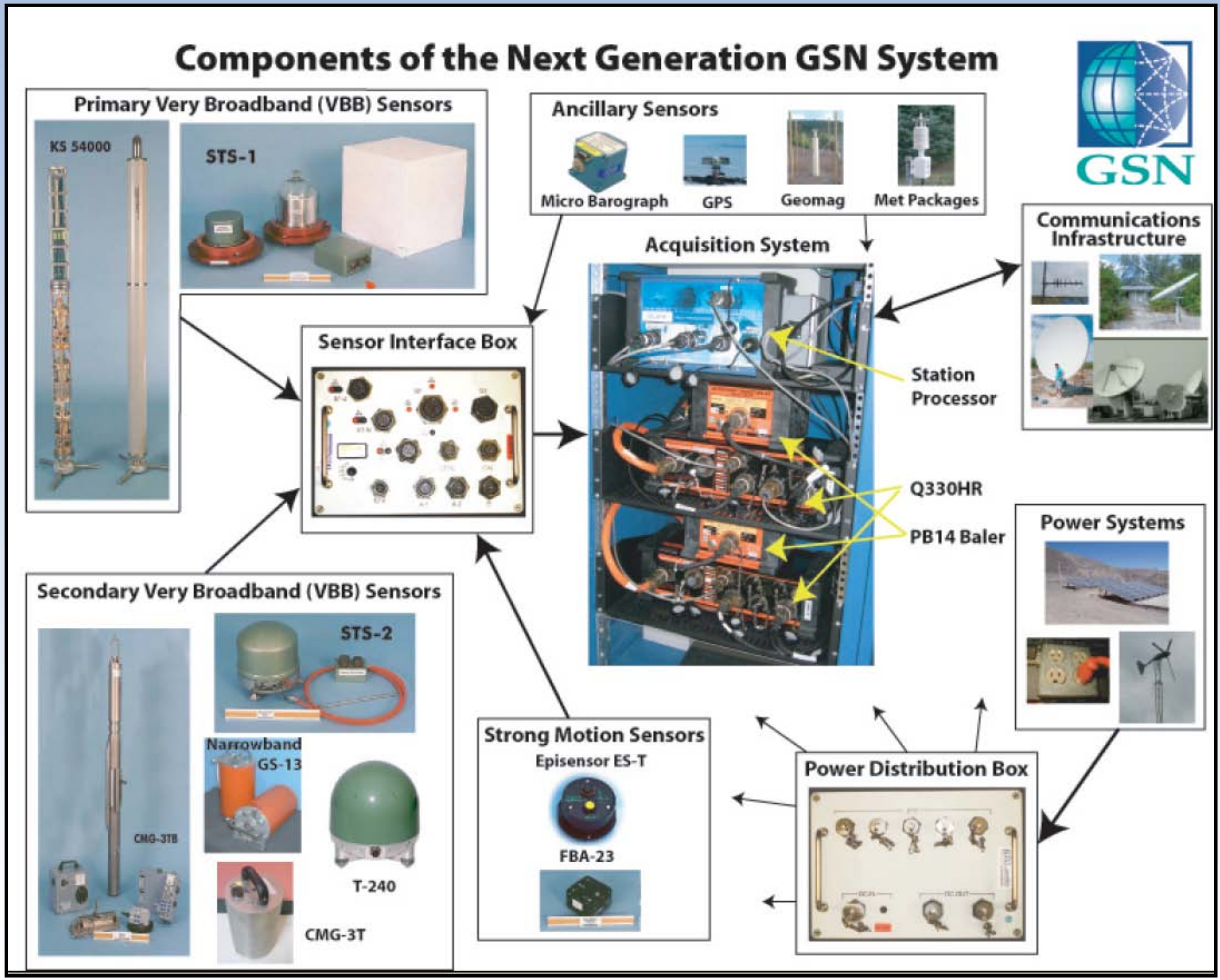


GSN 1990

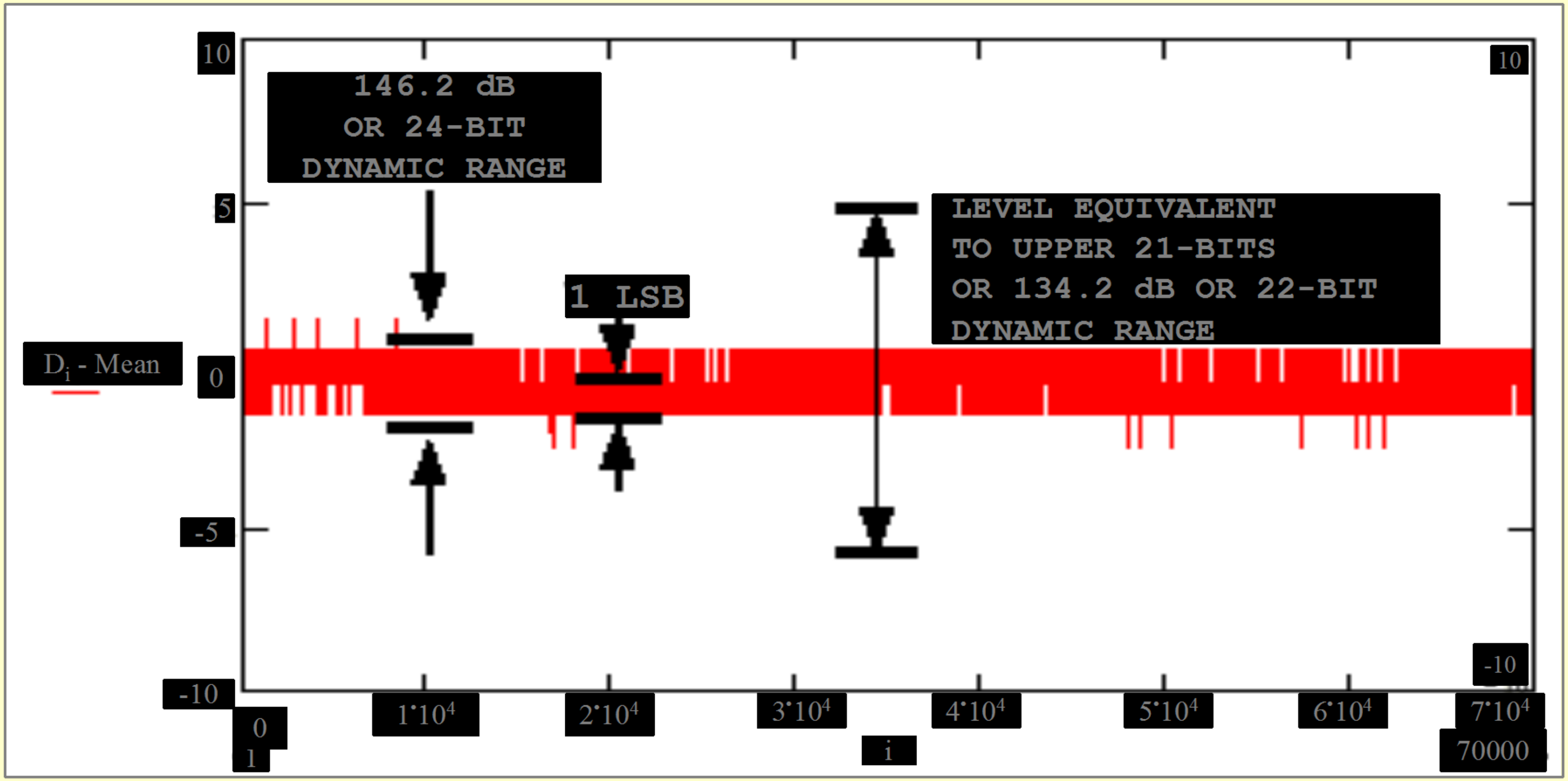


1995

GSN Upgrade 2009



Recorder: 26 bits – What's That ?



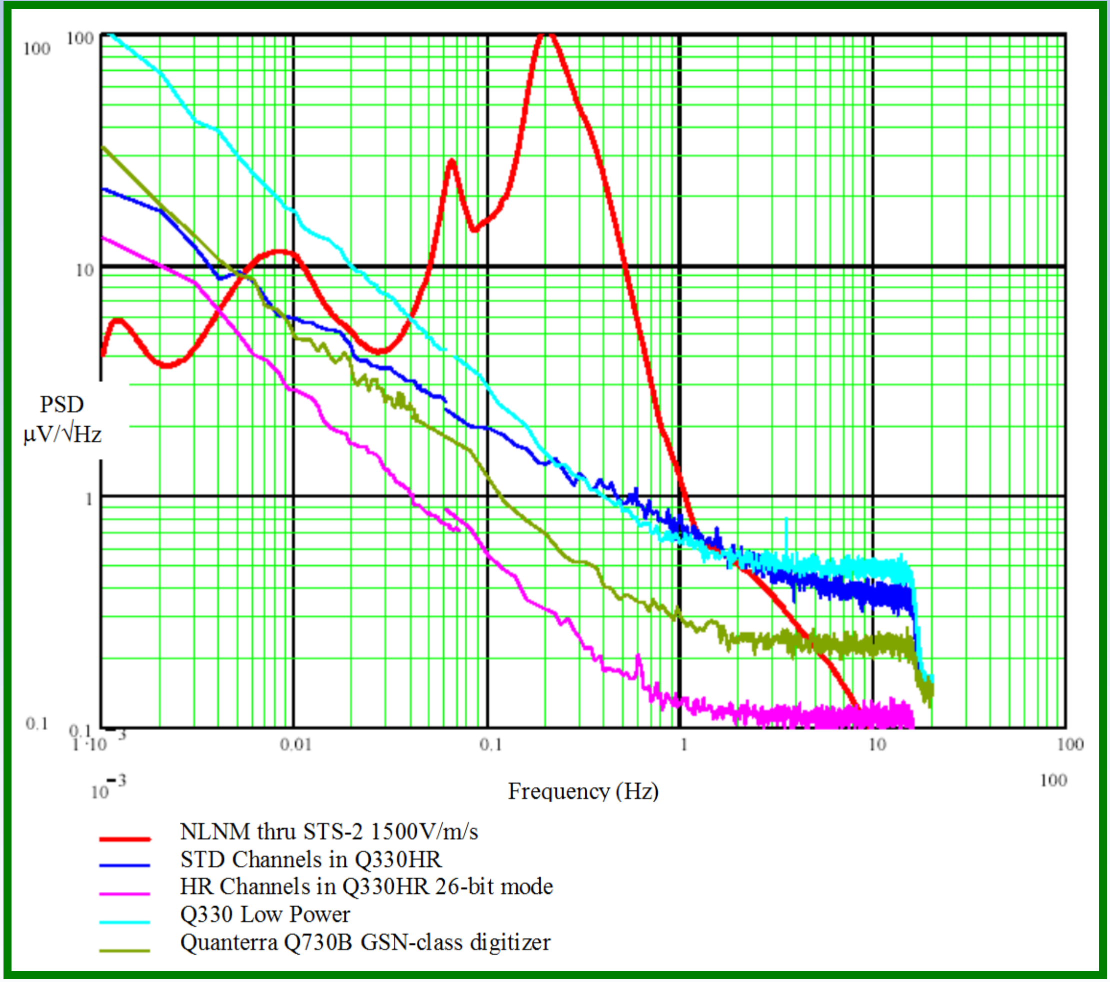
26 bits	67 108 864 counts	0.60 µV/count	0.4 nm/s
24 bits	16 777 216 counts	2.38 µV/count	1.5 nm/s
22 bits	4 194 304 counts	9.52 µV/count	6.0 nm/s

BRTT QUANTERRA Streckeisen KINEMETRICS

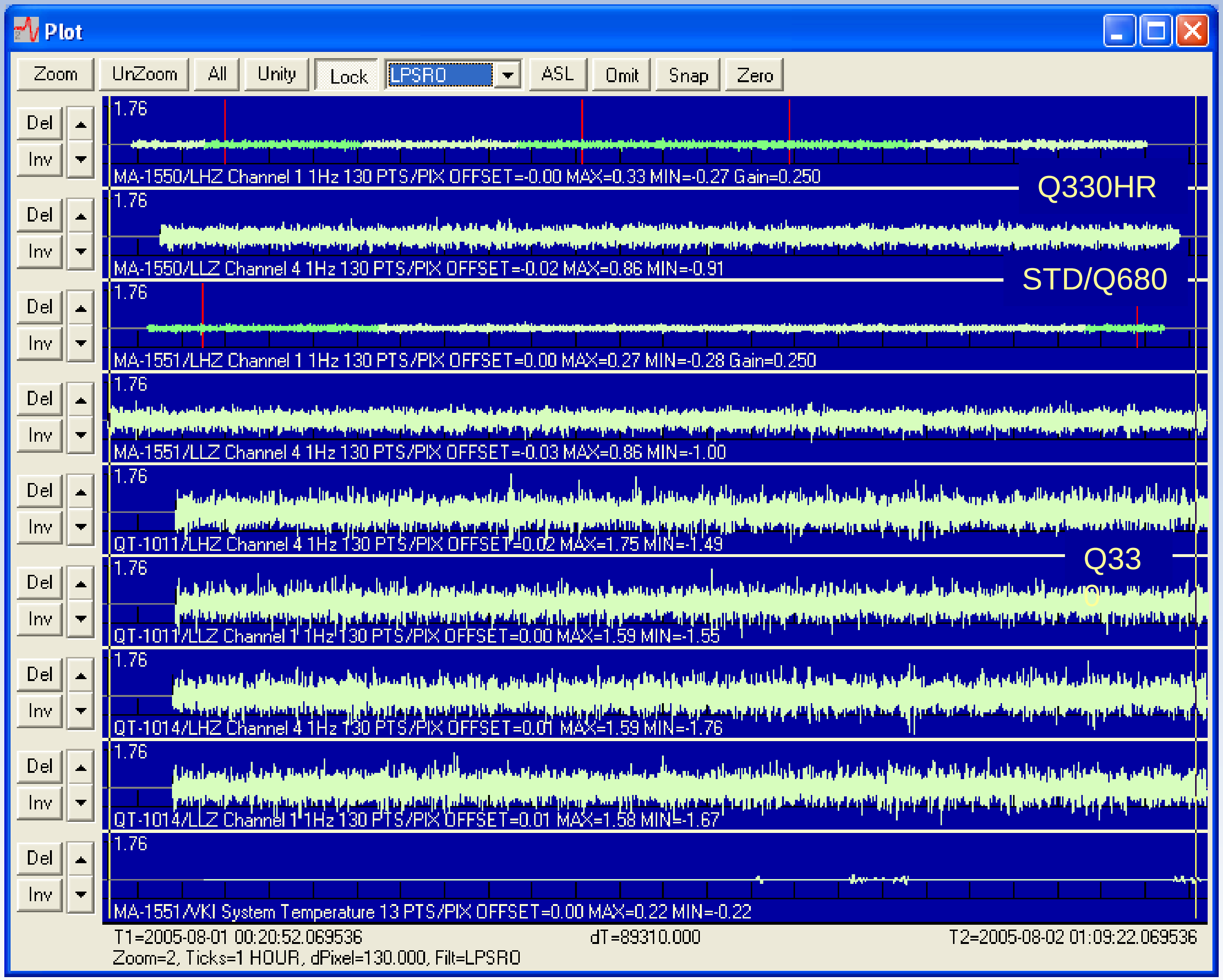
Q330HR

World's first 26-bit Broad-band Data Acquisition System

Q330HR Typical Performance



Q330HR Noise Level



Narrow-band (LPSRO) filtered long-period noise of Q330HR's "HR" channels, and "standard" channels, and a low-power Q330 compared at room temperature. The "standard" channels are equivalent to a Q680

Selected Quanterra Milestones

- First 24-Bits Broadband Data Acq. – early ’80s
- First TCP/IP Implementation – early ‘90s
- First Ultra - Low Power – less 0.5 W – ‘00
- Q330HR - First 26-Bits Broadband Data Acq. – ‘05
- Q330HR - 153 dB Broadband Data Acq. – 2010
- Q3000 - 130 dB @ 250 sps – 2010
- With sister companies 45+ registered patents

Seismic Real-time Evolution:

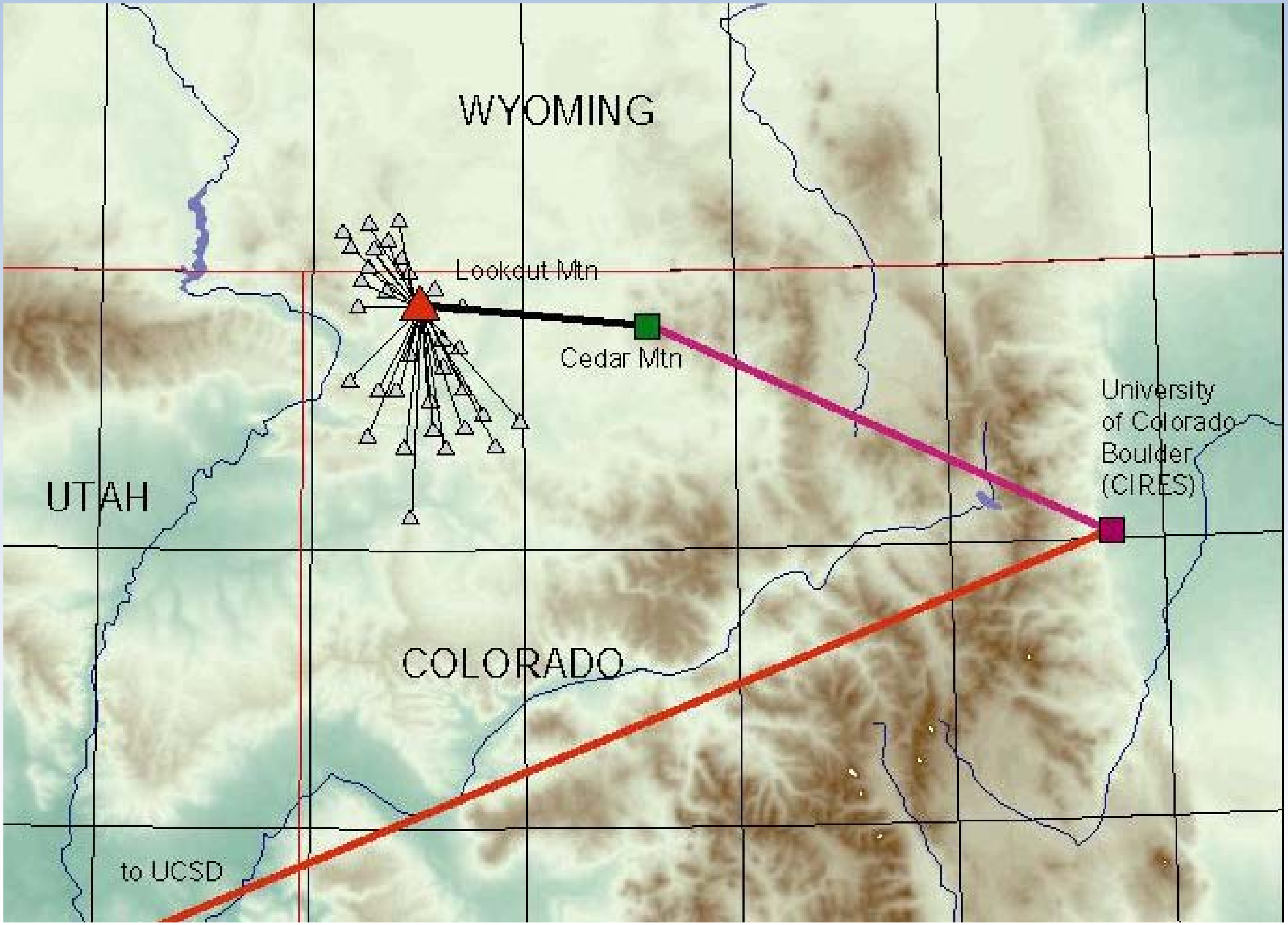
From Telemetry to Networking

- From Analog Modulation to IP World -

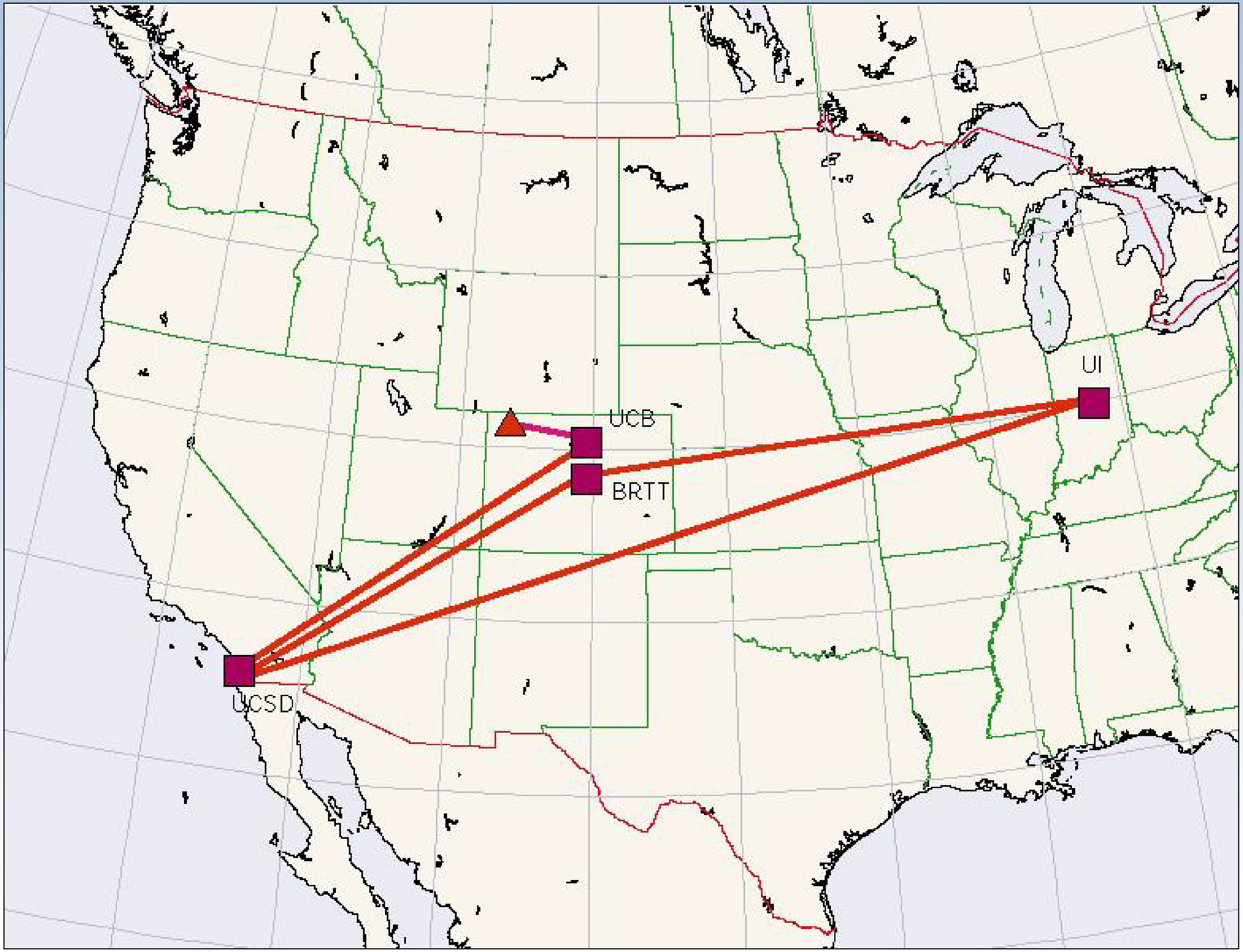
“Seismic Network Is Computer”

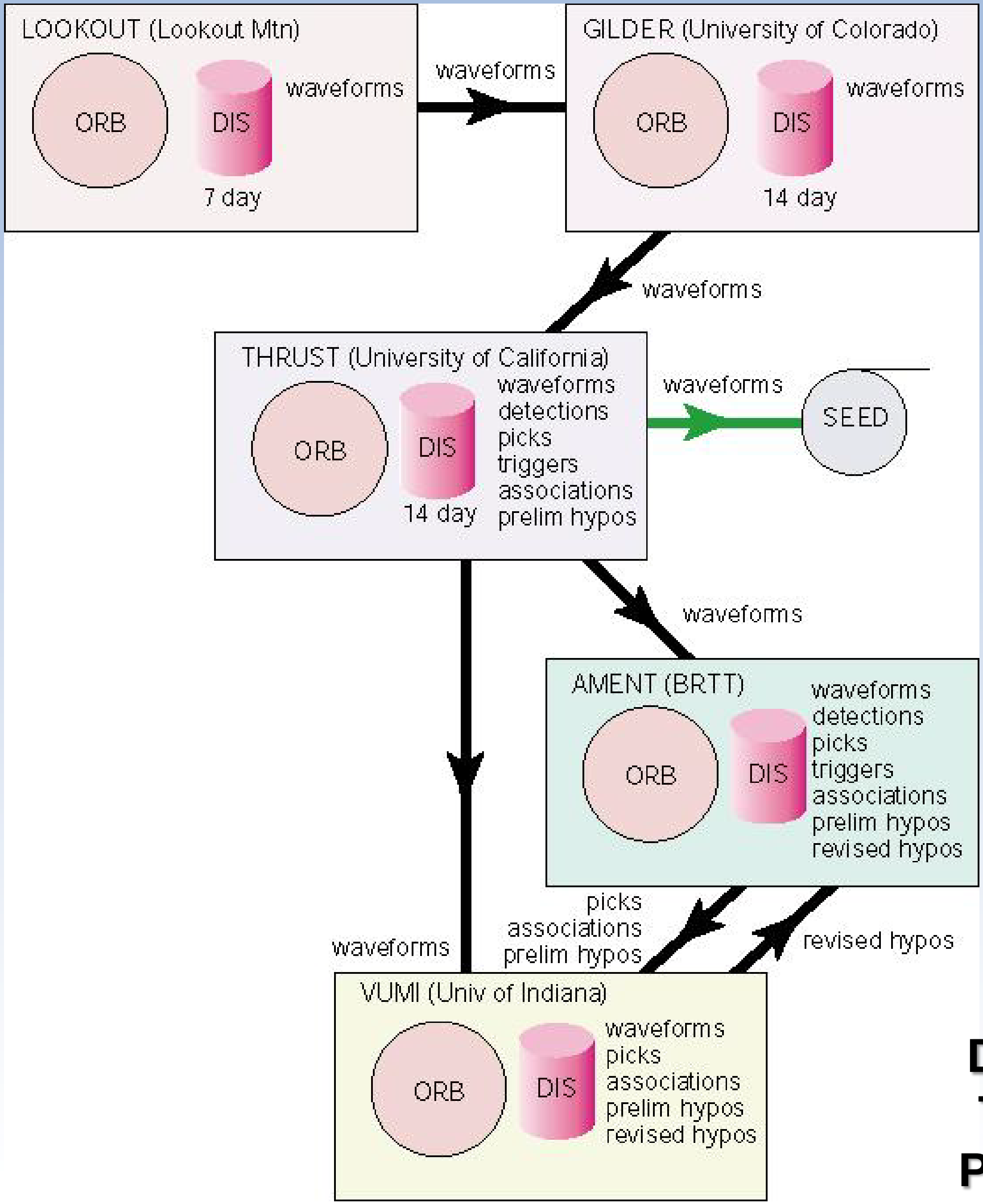
From Computer to Web Server

All New Concepts Started: IRIS "Lodore" Broadband Array ~1995



IRIS "Lodore" Broadband Array (c. 1995)

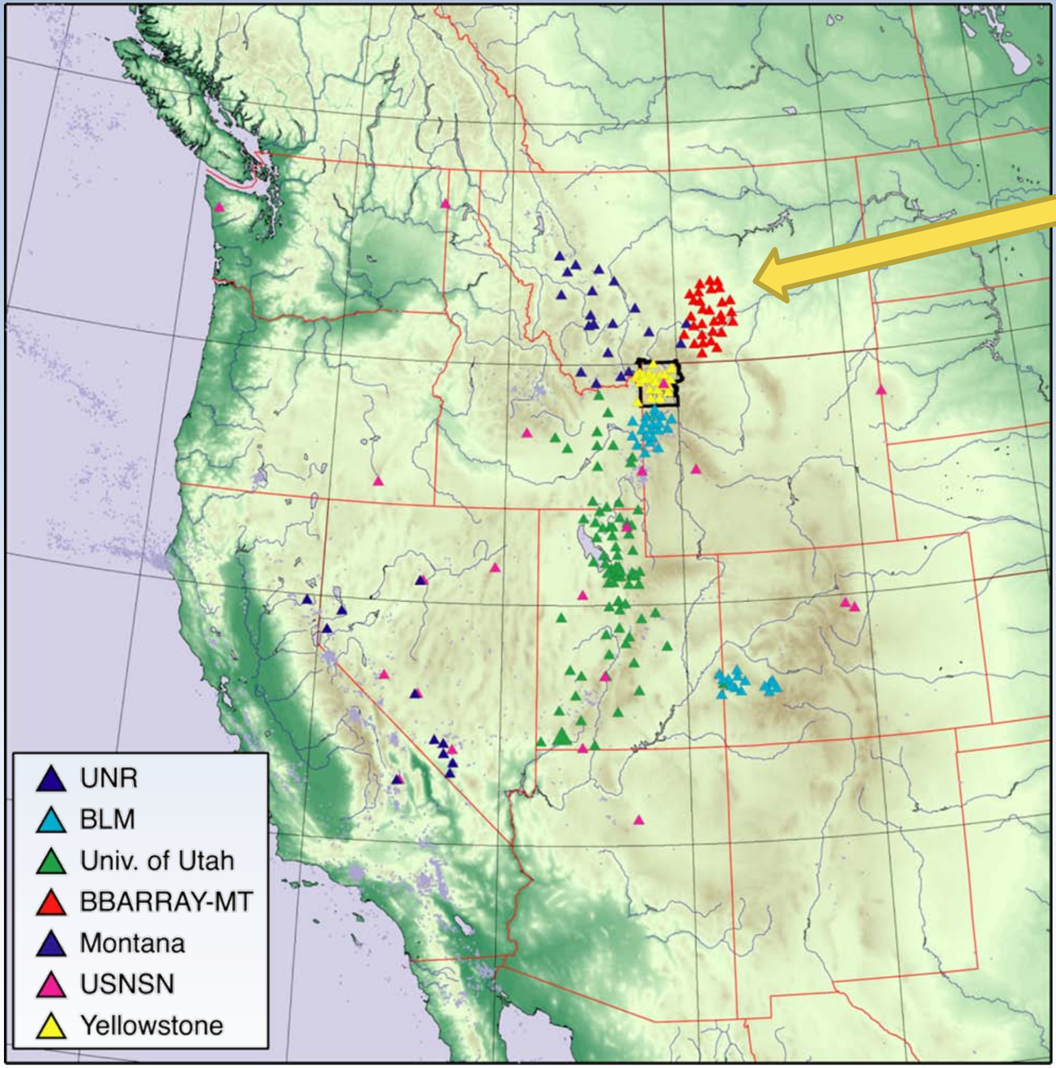




IRIS "Lodore" *Broadband Array (c. 1995)*

IRIS Development Real time Technology to support Portable Array BBArray

Intermountain Seismic Networks



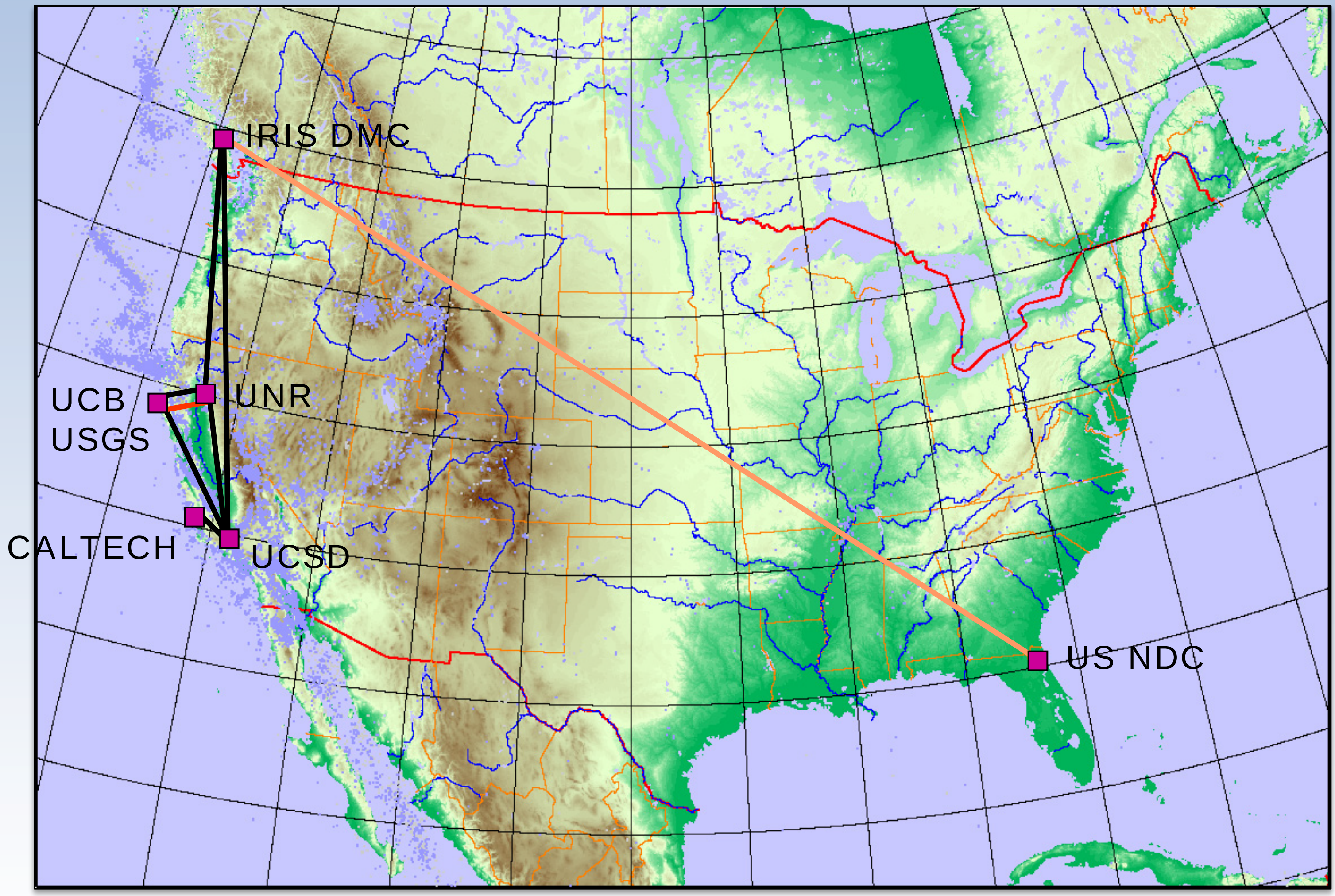
IRIS Development Real time Technology to support Portable Array BBArray-MT

Intermountain Seismic Networks and IRIS Real-Time BB Portable Array

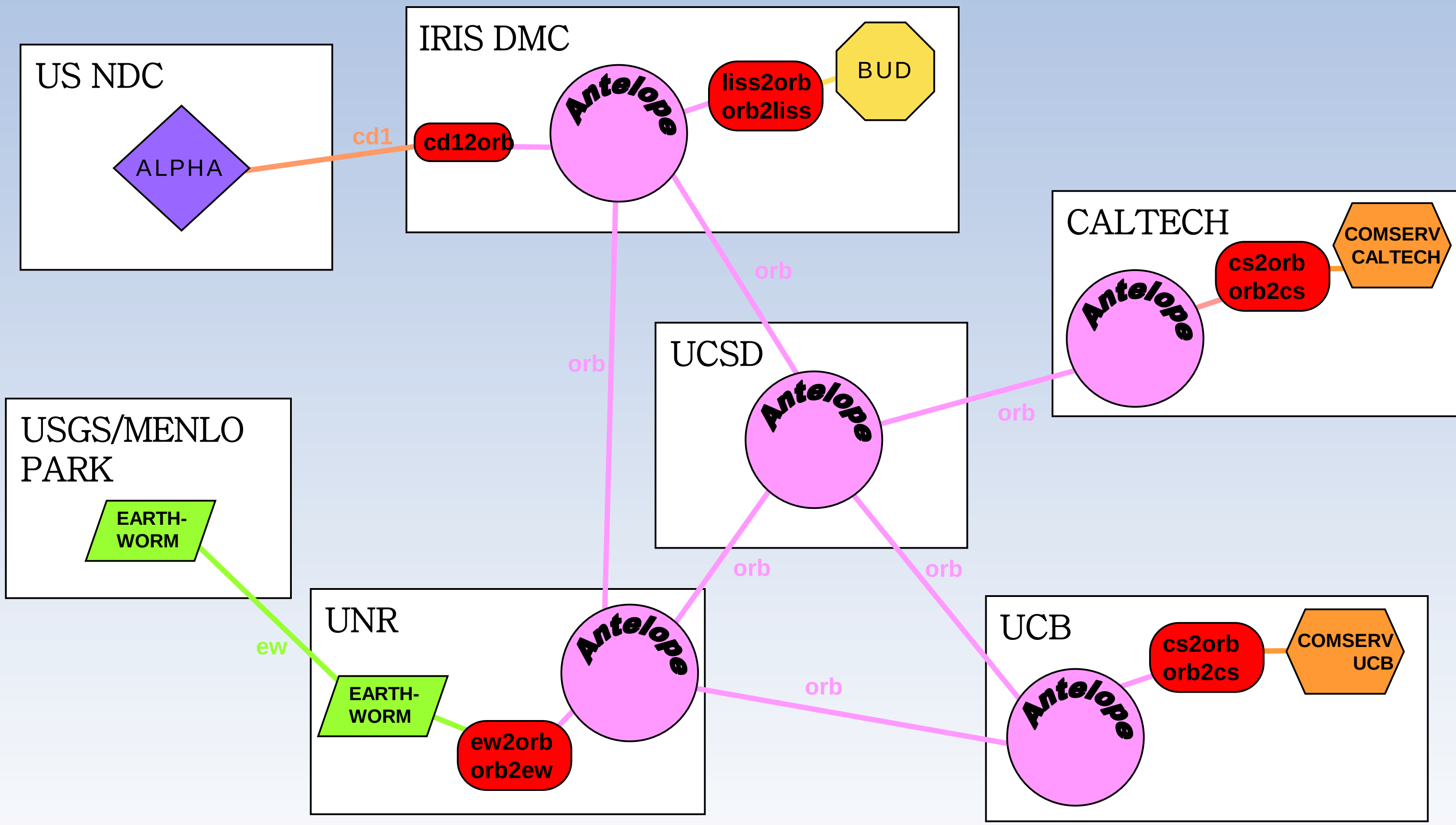
Circa 1996

First Virtual Seismic Network @ UCSD

IRIS Interoperability and Real-time Data Exchange ~1996



Iris: Interoperability ~1996



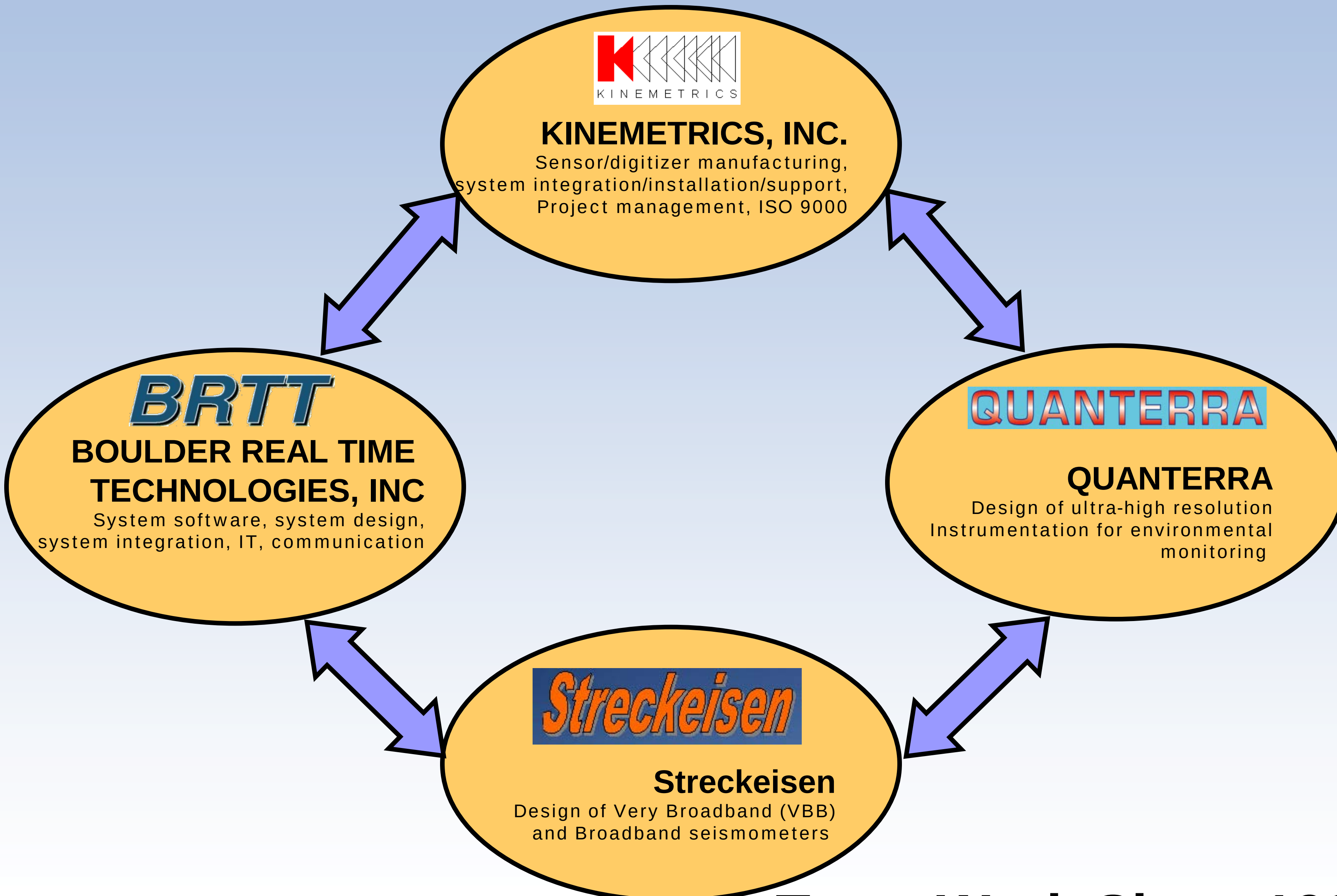
UCSD Virtual Seismic Network and Antelope

Stress test: ~ 1000 stations

Great Ideas Developed at University Labs finds its Commercial Success!

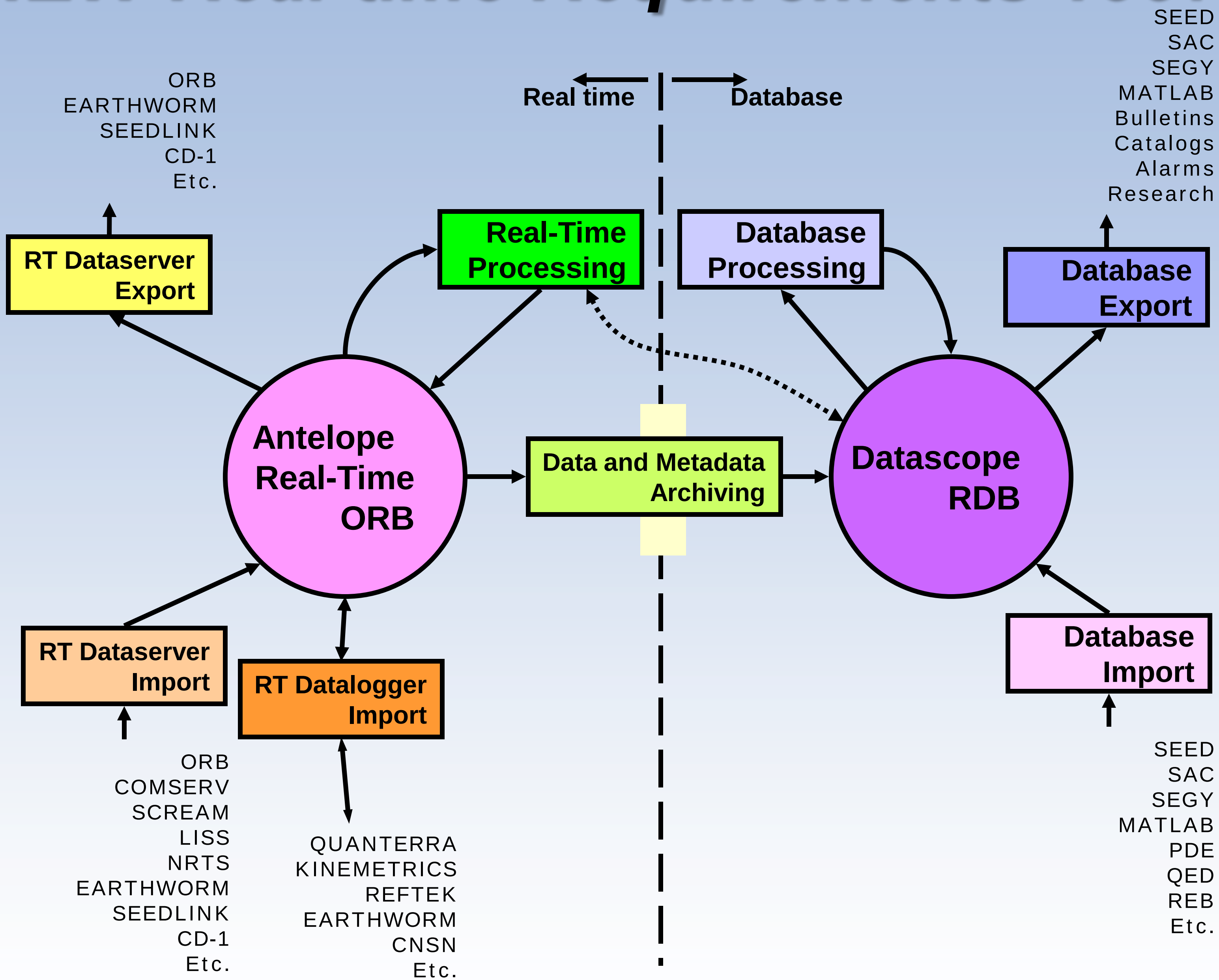
- Stanford ⟹ Google
- Stanford ⟹ SUN Microsystems Inc.
- UCSD ⟹ QUALCOMM Inc.
- Harvard ⟹ Quanterra Inc.
- ETH ⟹ Streckeisen A.G.
- IRIS Consortium ⟹ BRTT Inc.

Kinemetrics-BRTT-Quanterra-Streckeisen

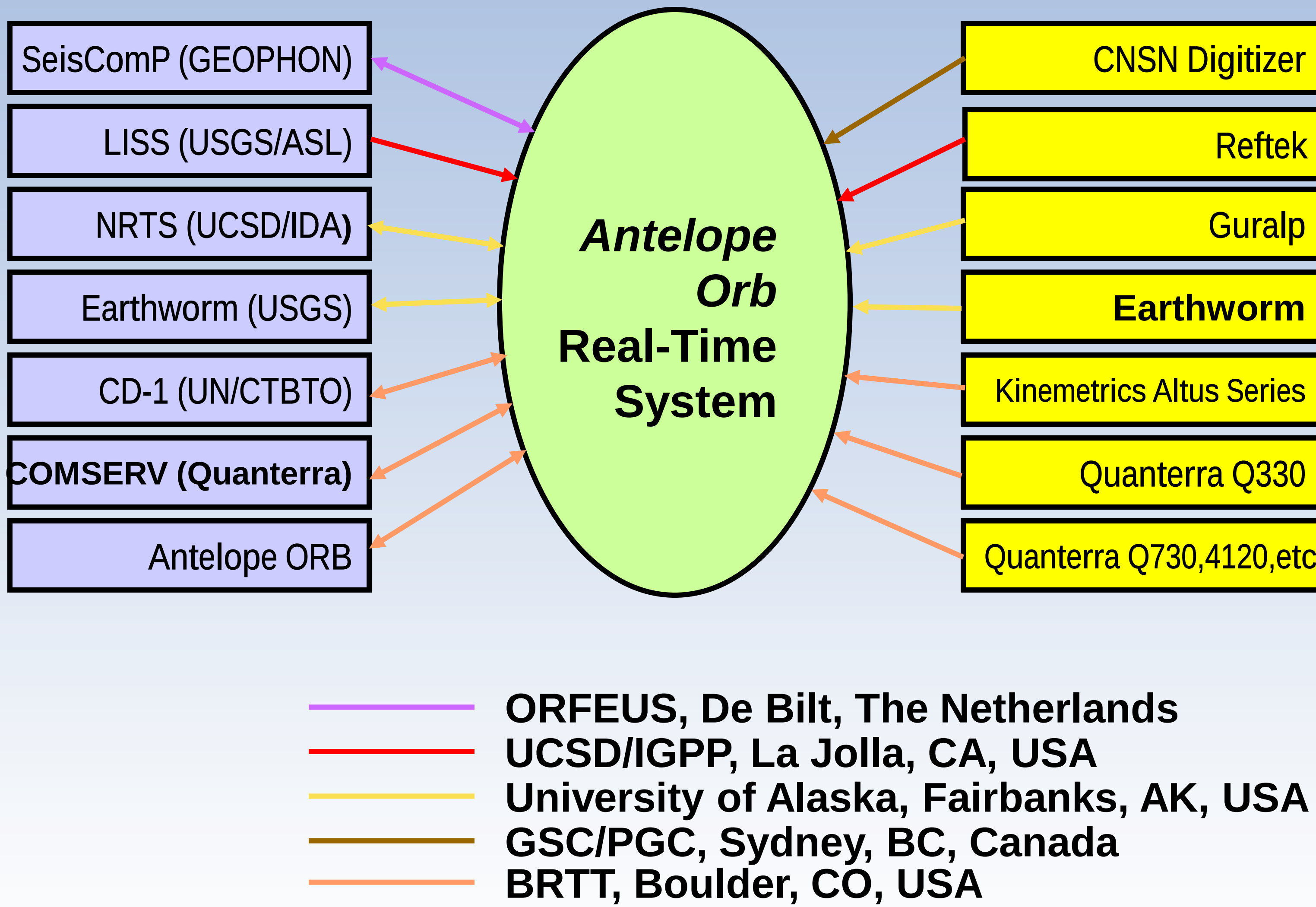


Team Work Since 1997

NEW Real-time Requirements 1997



Interoperability



Continued Improving Software and Hardware 1997- 2005

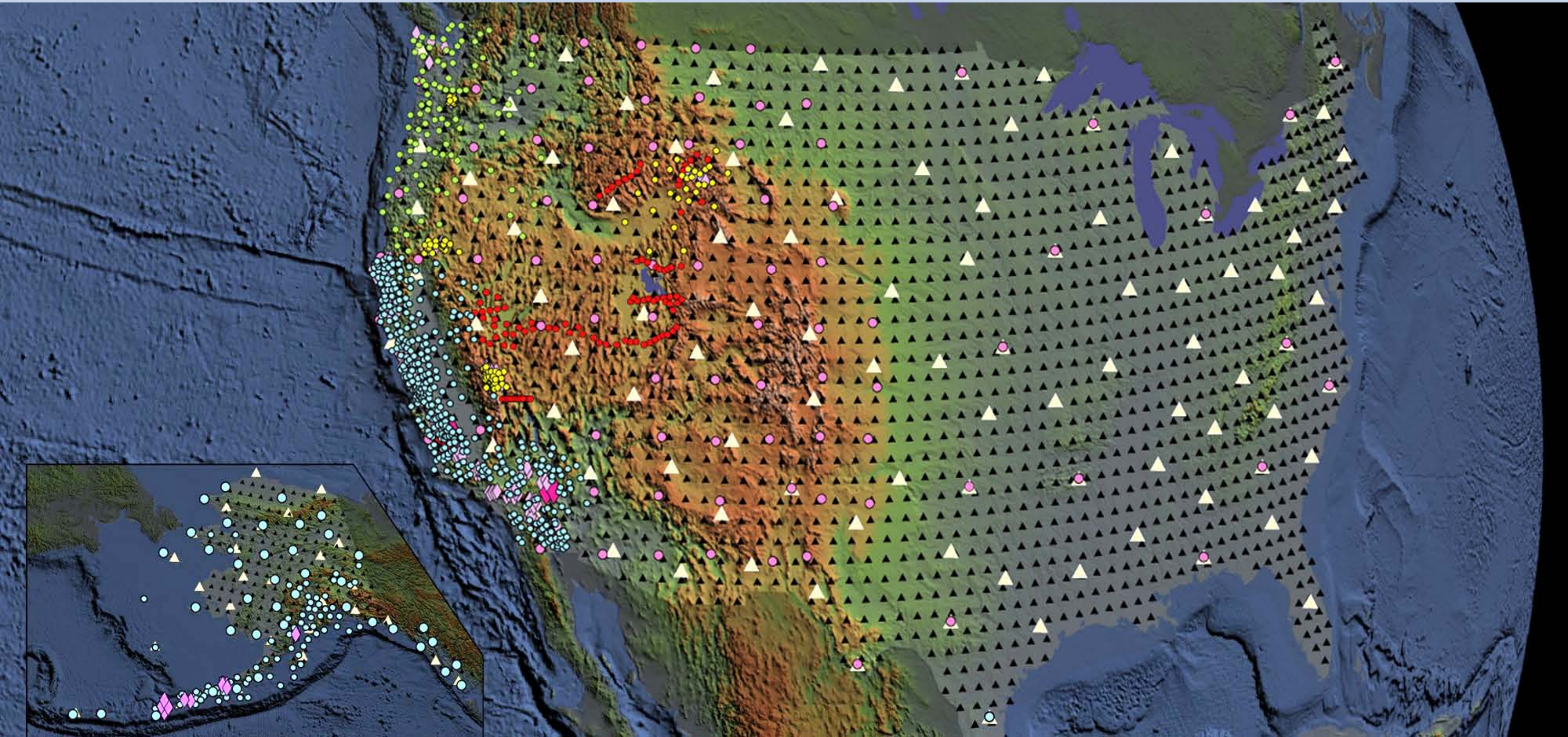
Year 2005

Ready for NEW challenges!

EarthScope Project

Study the three dimensional structure and evolution of the North American Continent

- 3.2 km borehole into the San Andreas Fault
- 875 permanent GPS stations
- 175 borehole strainmeters
- 5 laser strainmeters
- 39 Permanent seismic stations
- 400 transportable seismic stations occupying 2000 sites
- 30 magneto-telluric systems
- 100 campaign GPS stations
- 2400 campaign seismic stations



EarthScope Project

EarthScope Project Components

www.earthscope.org

Plate Boundary Observatory — UNAVCO

SAFOD — USGS science for a changing world

USArray — IRIS

Not the focus of this presentation but use of same technology

USArray Observatory Components

The focus of this presentation

Transportable Array — 400 seismic stations, 70km grid

Flexible Array — 355 portable instruments, 1200 single component for PI driven experiments

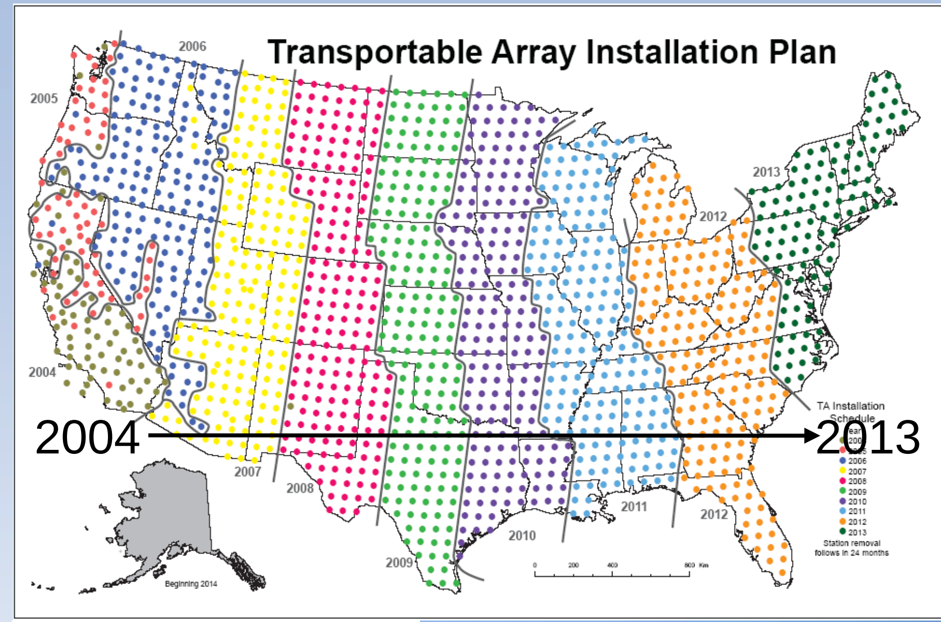
Reference Network — about 100 permanent seismic stations

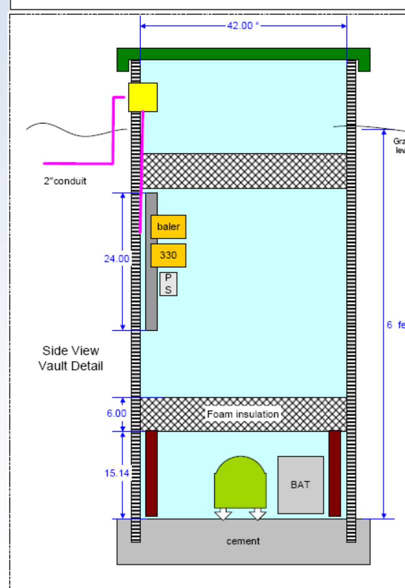
Magnetotelluric — 7 backbone stations and 20 portable instruments

Transportable Array Concept

- 400 broadband seismic stations
  - ~70 km spacing between stations
  - ~1500 x 800 km “footprint”
  - ~2 year deployments at each site, 1623 sites
  - Migrate across the country in 10 years
  - $8M / year budget

- Operational Goals
  - High-quality broadband data
    - On par with permanent network stations
  - Maximize data return (>85%)
  - Data to the scientific and regional network community in near real time
    - 40 and 1 sps continuous
  - Equipment redeployed five times



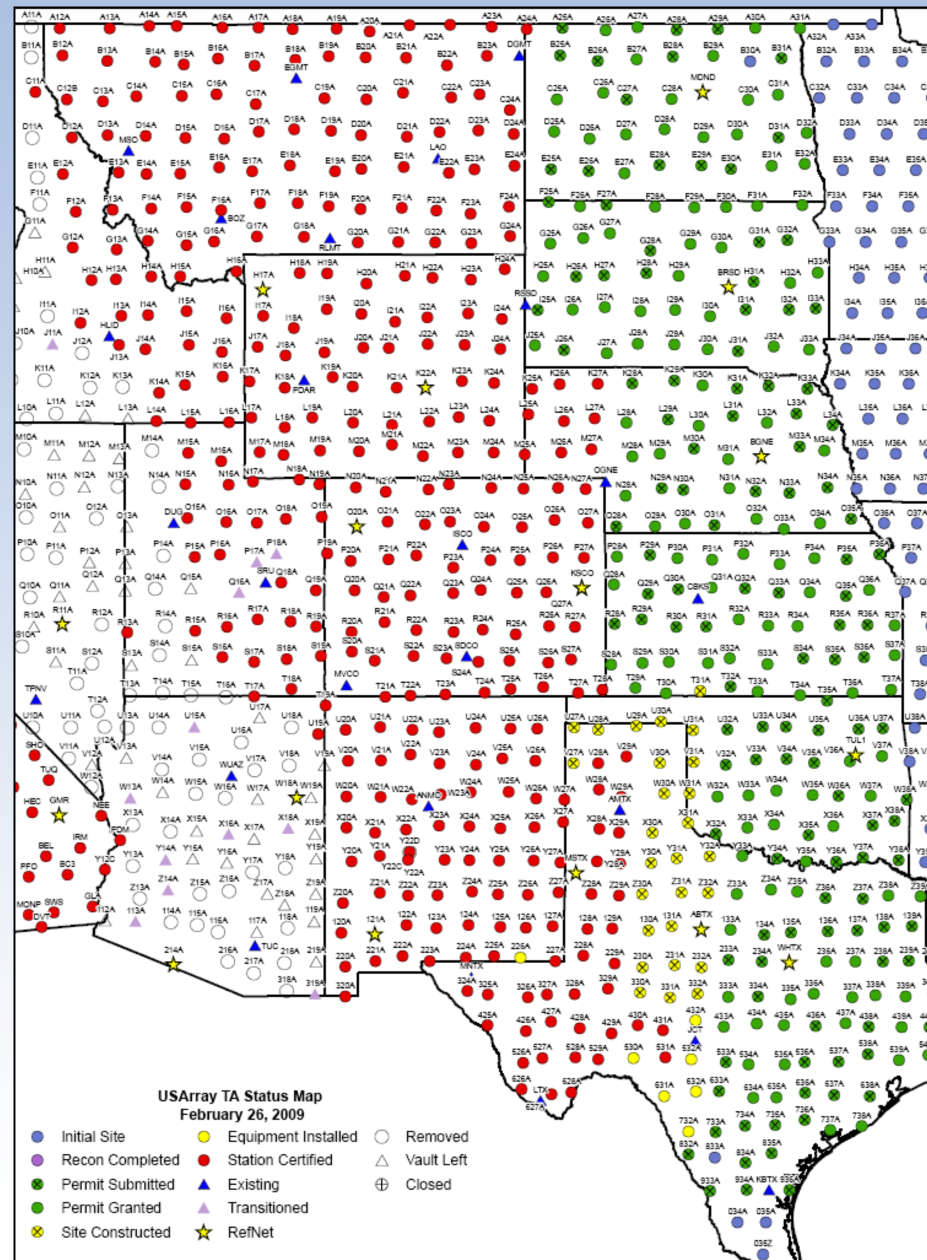


Status: Deployment

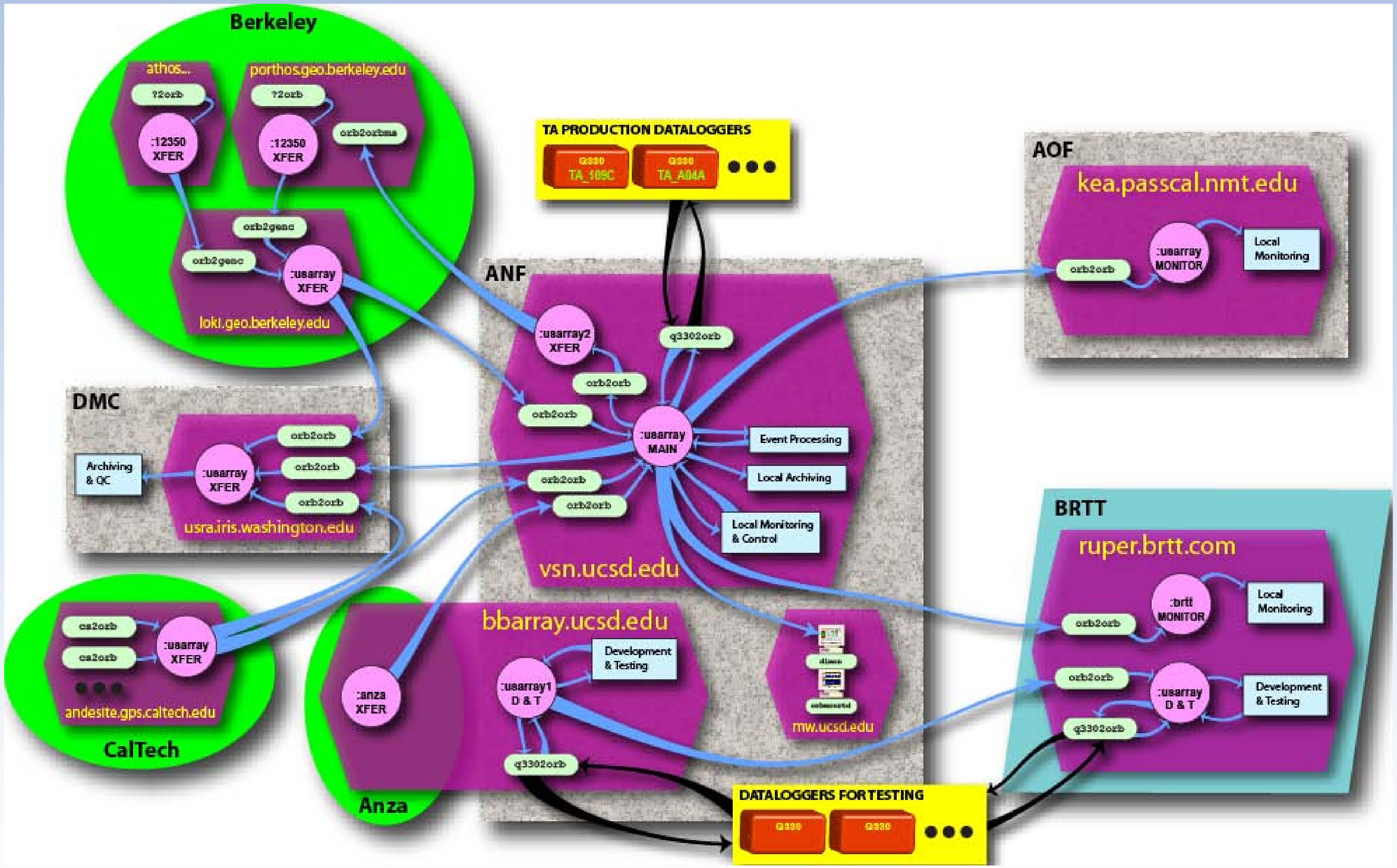
- On Schedule
  - 734 commissioned Stations
  - **~ 442 operating Stations**
  - 292 removed Stations
- **Rolling eastward at a rate of about 400 km /year, 18 station/month**
- North-south deployment strategy permits year-round operations

Stations going in . . .

. . . and coming out

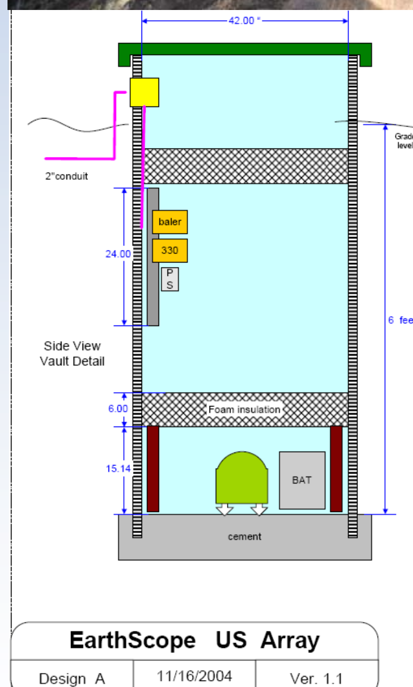


Circa 2005: World's Largest Real-time Portable Research Network – USArray (TA)



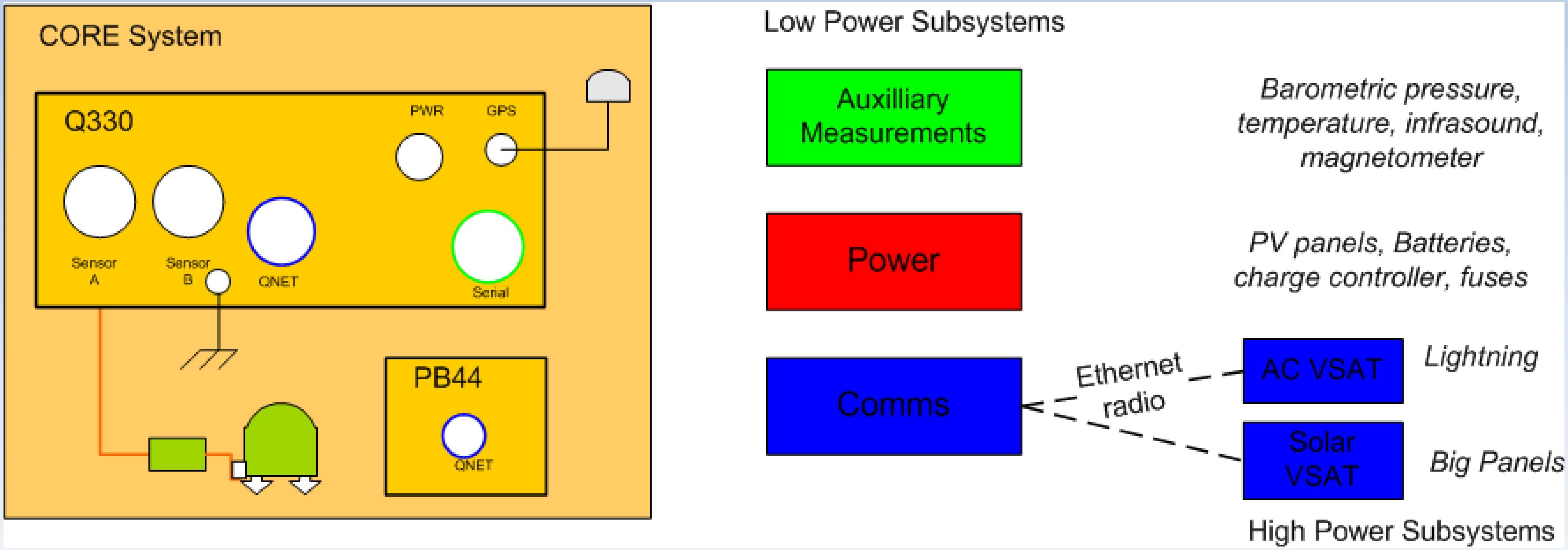
Station Design

- Very Low power to avoid cultural noise sources and to maximize siting opportunities. 3-5W solar powered.
- Fast construction, material adapts to conditions, from ready sources.
- high quality LP data requires thermal isolation.
- High power communications separated from station power.
- Local recording, minimum complexity in uplink



Design Principles of Station

- Modularity in subsystems



Other Design Considerations

Global Networks:

- Long term stable operation
- Integration of numerous sensors
- International shipping

National Networks:

- Earthquake monitoring for hazard, low latency.
- Public information, emergency response

Q330: Data Engine – Ultra- Low power, small size

Provides three essential functions;

Digitizer, sensor controls, telemetry integration

Q330 Operation in TA

Q330 notable advances for TA

- 32Mb memory
  - about 28 hours real-time buffering
- Integration and development of Antelope support
  - Q330util, webdlmon, SOH RRD
  - POC receiver (no need for Static IP)
  - In-situ Calibrations
- Configuration management
  - Configserver
  - Garfield firmware bulk loader
  - XML file templates
- Q330 auxilliary data channels
  - add low rate information into standardize processing flow

Construction

… No Student Involvement

On-site 3 hours

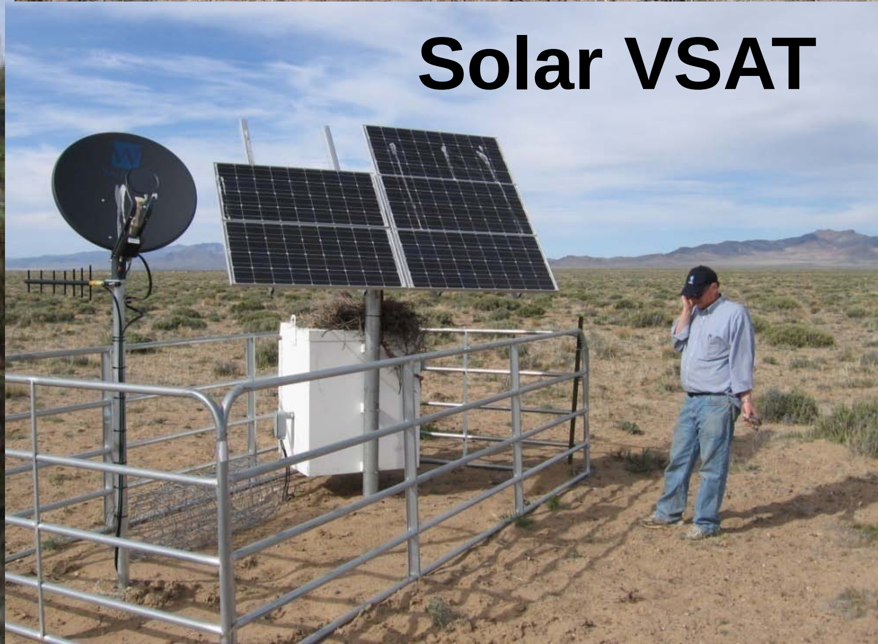
Construction Complete

Modularity in Communications

71% Cellular

20% AC VSAT

8% Solar VSAT

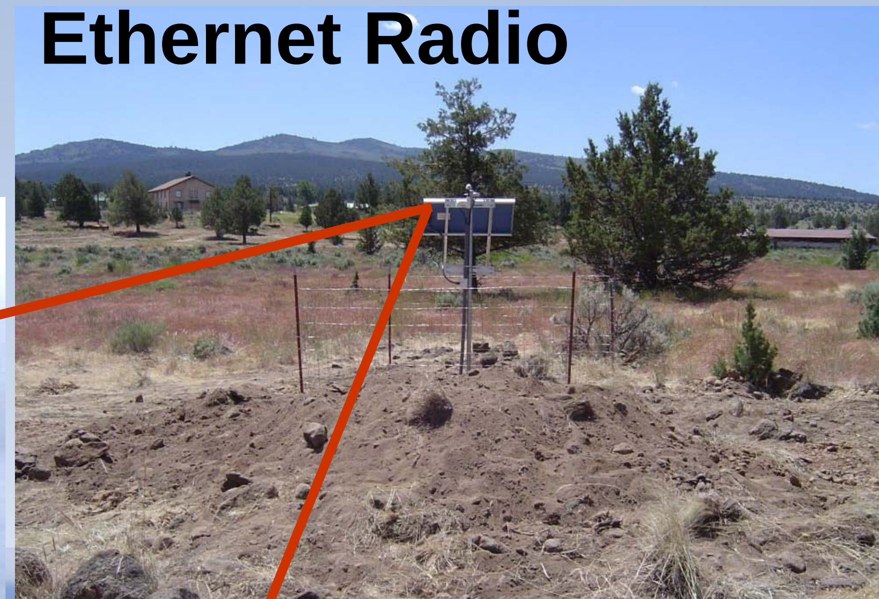


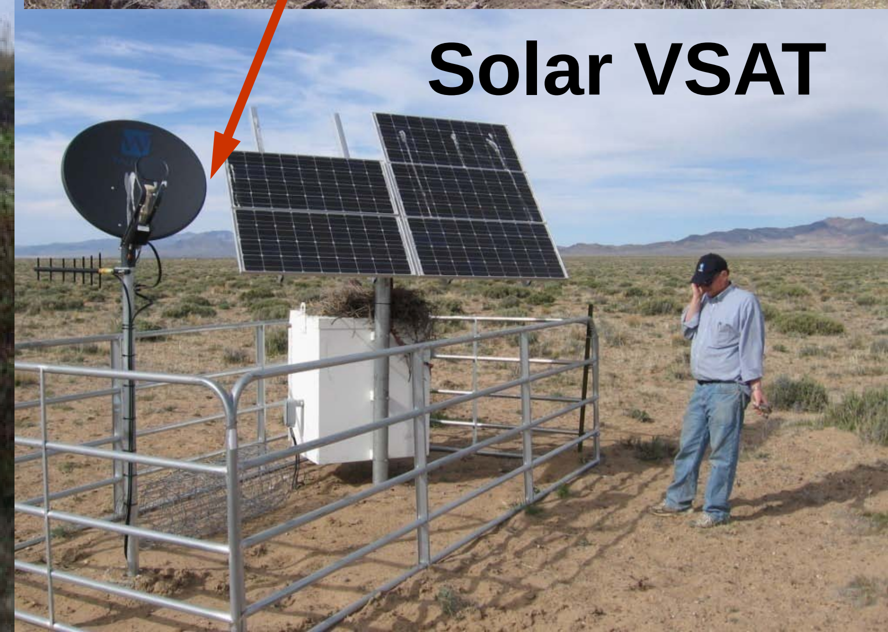
Communication Variety

- Cell modems ---71%
  - 191 Verizon CDMA ($720/year)
  - 20 Alltel CDMA ($830/yr)
  - 57 AT&T GSM ($850/year)
- VSAT systems -- 28%
  - 103 Wild Blue Enterprise ($1079/year)
  - ~20 of these Solar powered, 8 Cycled
  - Abandoned Hughes, SpaceNet
- Broadband providors
  - (4) DSL, (1) Cable, (2) WiFi
- Internet via Host --1%
  - Research Campus, schools, city (3)

Modularity in Communications

External Communication Module linked by Ethernet Radio to Station





Cell Service Providers

Verizon

- CDMA 1X, EVDO rev a.
- 70/70 150/450 kbps respectively
- Static IP address
- Excellent account management
- 5 Gbyte/mo, continuous connection
- Roaming issue at international borders

AT&T

- GSM, EDGE, HSDPA
- 40/40 kbps
- Static IP address, SIM cards
- Complex account setup, create APN
- 5 Gbyte/mo, continuous connection
- Roaming issue depending on carrier agreement

Cell Modem Choices

Airlink Raven

- Serial Interface
- Grounding issues
- unsealed
- PPP connection to Q330 serial 1.
- PPP connection to network.
- Modem manages NAT, simplifies Q330 config.
- 2 Watts, timed watchdogs

Sierrawireless Raven X

- Ethernet Interface
- Signals transformer coupled
- unsealed
- Single address forwarding
- DHCP server
- 2.5 Watts, less inclined to get stuck.
- 3G protocols

Proxicast, Digi, Multitech, etc

Cell Modem Operation

AceNet - [TA_VZW_jan2008.acn]

File Edit View Modem Window Tools Help

Name	Address	Modem Type	RSSI	Result	Date and Time	Phone Number	Modem EID/IMEI	ALEOS Software Version	Modem Soft
TA_I14A	166.161.119.226	Raven CDMA	-86	Success	11/15/2007 05:59:08	7742832041	F60E05A0	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_L20A	166.241.252.250	Raven X EV...	-98	Success	11/15/2007 06:00:59	5085051720	603CD6AD	V4221_3.1.3.059 Mar 29 2007	p2005700,5(
TA_I03A	166.159.115.121	Raven CDMA	-87	Failure: Can't reach m...	11/15/2007 06:20:15	3397888025	09900956799	C3210_3.1.5.064 Oct 17 2007	R2_1_0_6SE
TA_R19A	166.161.112.9	Raven CDMA	-91	Success	09/16/2007 15:17:13	3397888624	F60D8AC1	WCR200603B05 Apr 17 2006	S/W VER: V
TA_M20A	166.139.17.237	Raven CDMA	-82	Success	11/15/2007 05:43:27	3397887644	09900911511	C3210_3.1.5.064 Oct 17 2007	R2_1_0_6SE
TA_Z18A	166.161.106.228	Raven CDMA	-78	Success	11/15/2007 05:48:34	3397888413	F60D1A53	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_G15A	166.161.98.231	Raven CDMA	-78	Success	11/15/2007 06:11:29	3397888467	F60D0F78	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_X15A	166.139.136.17	Raven CDMA	-91	Success	11/15/2007 06:34:11	3397887725	09900911718	C3210_3.1.5.064 Oct 17 2007	R2_1_0_6SE
TA_T18A	166.161.112.28	Raven CDMA	-90	Success	11/15/2007 05:58:03	3397888628	F60D78CD	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_319A	166.159.101.7	Raven CDMA	-75	Success	11/15/2007 05:54:58	3397888288	F60CC0DF	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_J17A	166.161.119.253	Raven CDMA	-84	Success	11/15/2007 06:00:59	3397882221	F60E389E	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_A16A	166.161.229.204	Raven CDMA	-75	Success	11/15/2007 06:02:08	3397881670	F60D19F7	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_S14A	166.161.113.32	Raven CDMA	-79	Success	11/15/2007 06:06:48	5084680659	F60DAEF4	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_G18A	166.241.252.215	Raven X EV...	-93	Success	11/15/2007 06:12:53	5085051685	603C996A	V4221_3.1.5.064 Oct 17 2007	p2005700,5(
TA_H11A	70.203.103.133	Raven CDMA	-80	Failure: Can't reach m...	11/15/2007 06:14:41	3397888631	F60D89D5	WCR200603B05 Apr 17 2006	S/W VER: V
TA_S13A	166.161.113.25	Raven CDMA	-105	Success	11/15/2007 06:10:09	5082089793	F60DB3AE	WCR200603B05 Apr 17 2006	S/W VER: V
TA_H04A	166.159.115.115	Raven CDMA	-82	Success	11/15/2007 06:04:11	3397888018	09900956792	C3210_3.1.5.064 Oct 17 2007	R2_1_0_6SE
TA_M14A	166.161.113.26	Raven CDMA	-83	Success	11/15/2007 05:54:11	5084680436	F60DAEF7	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_C12B	166.161.119.225	Raven CDMA	-103	Success	11/15/2007 06:01:34	7742832040	F60E2956	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_X14A	166.159.101.8	Raven CDMA	-101	Success	11/15/2007 06:13:04	3397888289	F60CC13B	WCR200603B05 Apr 17 2006	S/W VER: V
TA_117A	166.139.17.240	Raven CDMA	-81	Success	07/23/2004 20:48:39	3397887647	09900911702	C3210_3.1.5.064 Oct 17 2007	R2_1_0_6SE
TA_Q18A	166.161.113.21	Raven CDMA	-89	Success	11/15/2007 05:54:11	5082088781	F60DB3C6	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_I17A	166.161.119.247	Raven CDMA	-86	Success	11/15/2007 05:55:18	3397882215	F60E38AE	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_N10A	166.159.101.10	Raven CDMA	-92	Success	11/15/2007 06:16:02	3397888291	F60CC6A8	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_T14A	166.161.113.30	Raven CDMA	-77	Success	11/15/2007 06:14:19	5084680656	F60DB3AA	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_B15A	166.161.119.250	Raven CDMA	-93	Success	11/15/2007 05:55:19	3397882218	F60E38B1	C3211_3.1.5.064 Oct 17 2007	S/W VER: V
TA_D08A	166.161.106.237	Raven CDMA	-80	Success	11/15/2007 05:57:49	3397888422	F60D1A40	WCR200603B05 Apr 17 2006	S/W VER: V

Commercial-Of-The-Shelf (COTS) VSAT Operation

Wild Blue

- Ka band spot beams
- Small (0.6m) dish size, eases transport and wind load
- modems are single DC level (30VDC)
- Can be provisioned at remote site without contacting VSAT Network Operations Center.
- Shared Master station-data delivered via internet
- Online technical portal for service history

Provisioning Details -

- 2 year service agreement, annual fee $1070/yr
- Enterprise level: static IP, 5Gbyte/mo upload
- Throughput rarely surpasses 50kbps.

KINEMETRICS

Communication Power Modules

- **AC based system for housing Wild Blue VSAT, Cable Modem or DSL modem**
  - Must be located within line of sight to vault and near power. Prefer pole mounts near out buildings.
  - Has heater / cooling fan for electronics.
- **Solar Powered module designed for 30W load.**
  - Commercial design is Robust, Large and expensive; 300-800W PV, 600-900AH battery
  - Sometimes duty cycled: 2 hour on / 6 hour off
  - Simpler systems do not use active heating / cooling.

VSAT Operation

Station Installation tricks

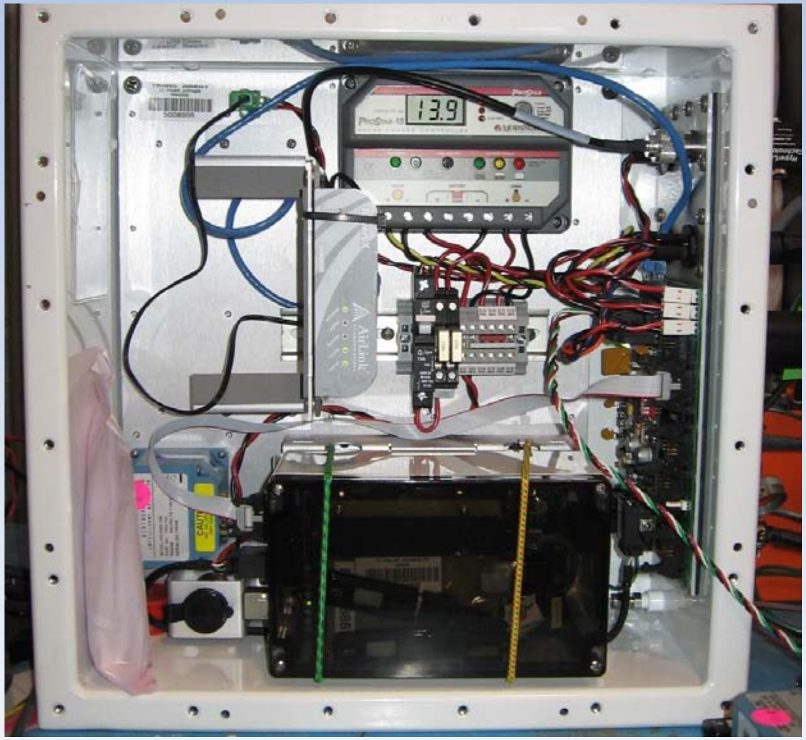
- Power cycle system 5 minutes once a day
- Compact Router handles DHCP/port forwarding
- Rotate arm to reduce snowbanks

Equipment Refinements

- Vault Interface Enclosure (VIE)
  - Protect equipment from humidity, increase reliability of comms equipment
  - Standardize connections
- Cell modem replacements as networks upgrade
- Baler44 phased into stations, replacing Baler14
- Add meteorlogical measurements

Vault Interface Enclosure (VIE, Ibox)

- 16x16x8” Enclosure, hangs inside vault.
  - IP68, 0.5” Lexan Clear lid, bulletproof!
- Q330 interfaces converted to industrial standard connections;
  - IDC flat ribbon, RJ45.
- Custom power regulation circuit
  - Faultfree switchover to alkaline backup battery
  - Signalling via existing data channels for power SOH
  - Sensor power regulation, filtered power for Q330 and Baler
  - High efficiency regulation, load shedding/mode switch on backup power
  - Independent fault isolation of powered devices.
- Station Integration
  - Integration of new Baler44CT, Environmental sensor
  - Simplified Data collection via new Baler44
  - Reset power cycle for comms equipment
  - Remotely controlled power interrupt for sensor
  - Monitor and signalling of pump operation
- Protected housing for electronics and auxiliary equipment-allowing better flexibility and increased reliability.
  - Allows economical packaging choices for small ancillary devices
  - Protects commercial modems, charge controllers and circuit boards.
  - Simplifies troubleshooting, acts as a field replacable unit.
- Uniform cabling for installation
  - MS style connectors, molded termination
- Commercial production in large runs; Enclosure, cables, PCB, testing, etc
  - Custom cable fabrication, custom metal, factory assembly and testing.



the IRIS CONSORTIUM

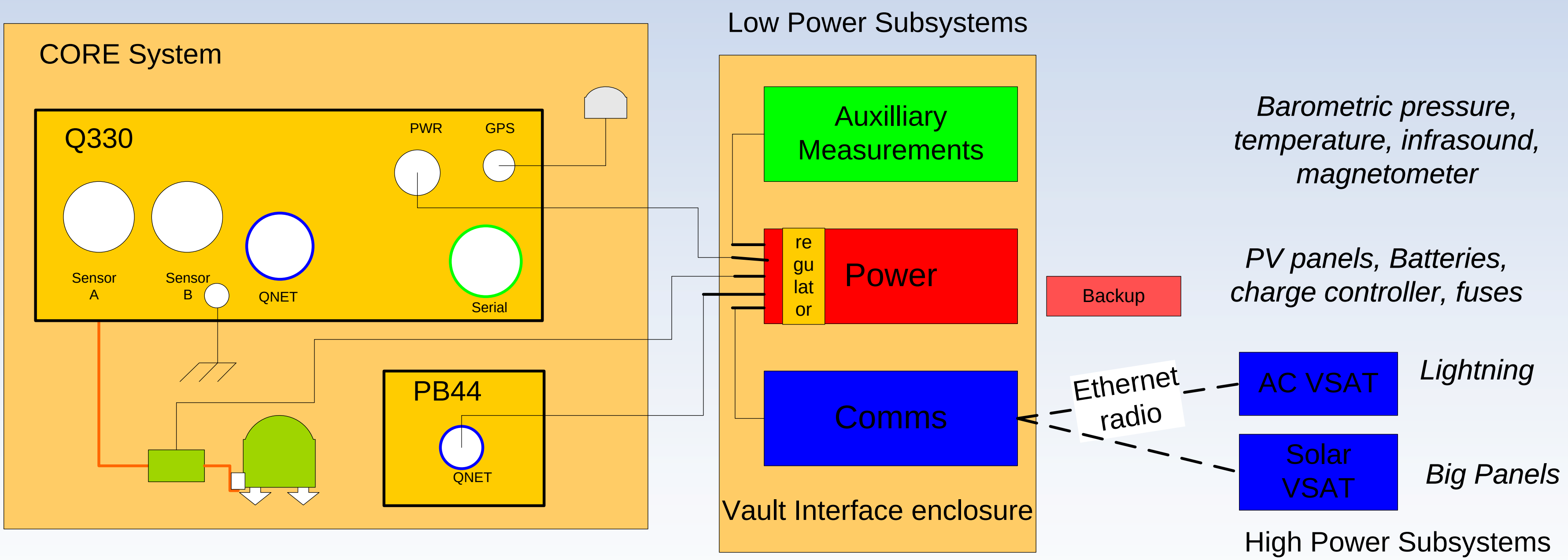
SOLARCRAFT POWER PRODUCTS

QUANTERRA, INC.

KINEMETRICS

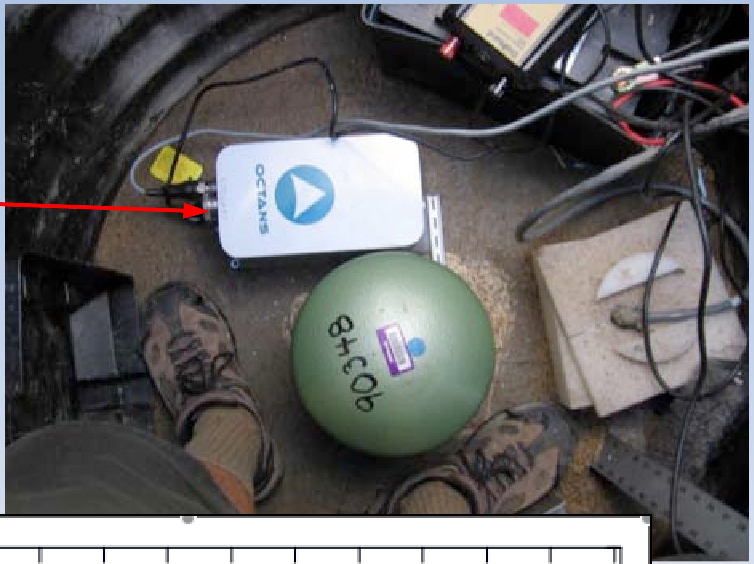
Station Regulator

- Independent regulation / distribution
- Power control of comms device
- Switching of backup power

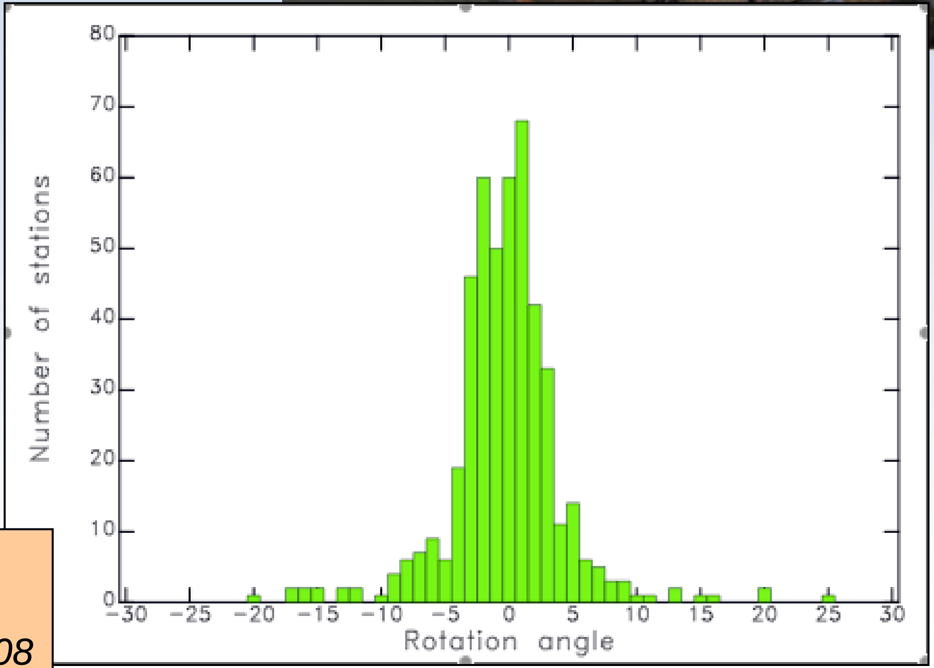


Procedures: Orientation

- **Direct measurement of orientation of all stations**
  - Using fiber-optic gyroscope IXSEA Octans IV, *Nonmagnetic orientation accurate to < 0.2 degrees*
  - Used at all new station installations
  - Used when existing TA stations are removed



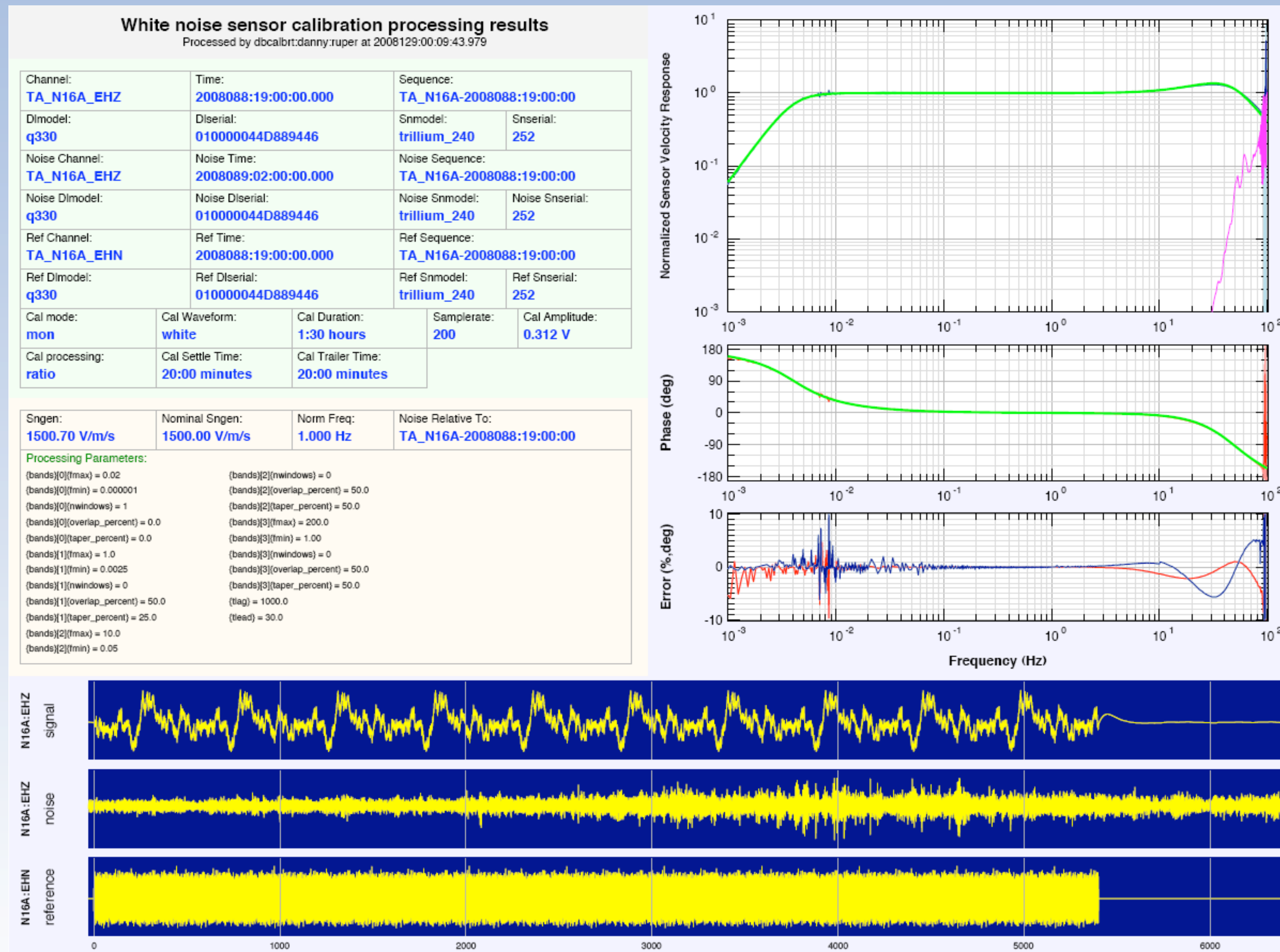
- **Validation of empirical orientation determinations**
  - Empirical estimates from surface and mantle wave polarization techniques



TA station orientation, relative to north, from empirical analysis
Results from Ekström and Busby, SRL, 2008

Procedures: Calibration

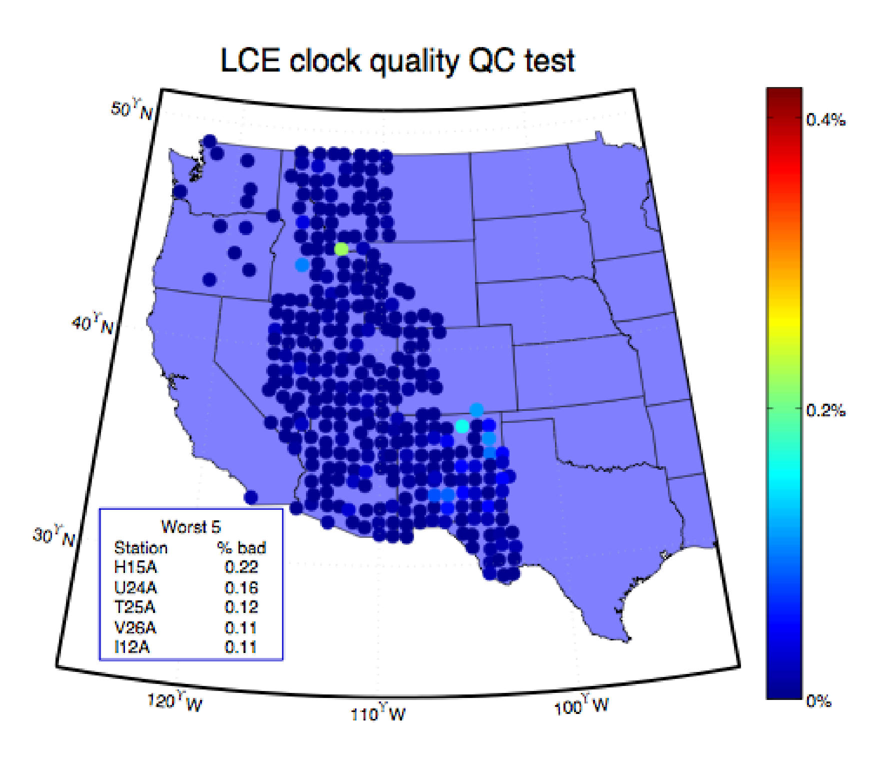
- Automated process for command, capture, and analysis of cal signals
- Analysis of calibration signals to verify amplitude and phase response
- Will apply to all TA stations at beginning and end of deployment
- Network-wide calibration for sensor statistics

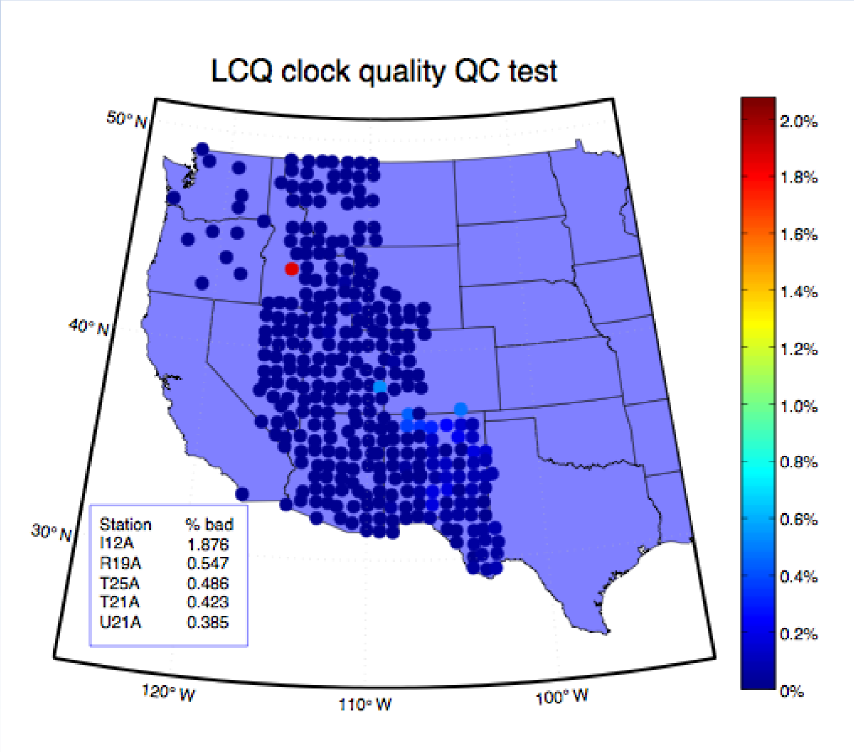


Results from BRTT Antelope software

Clock Quality

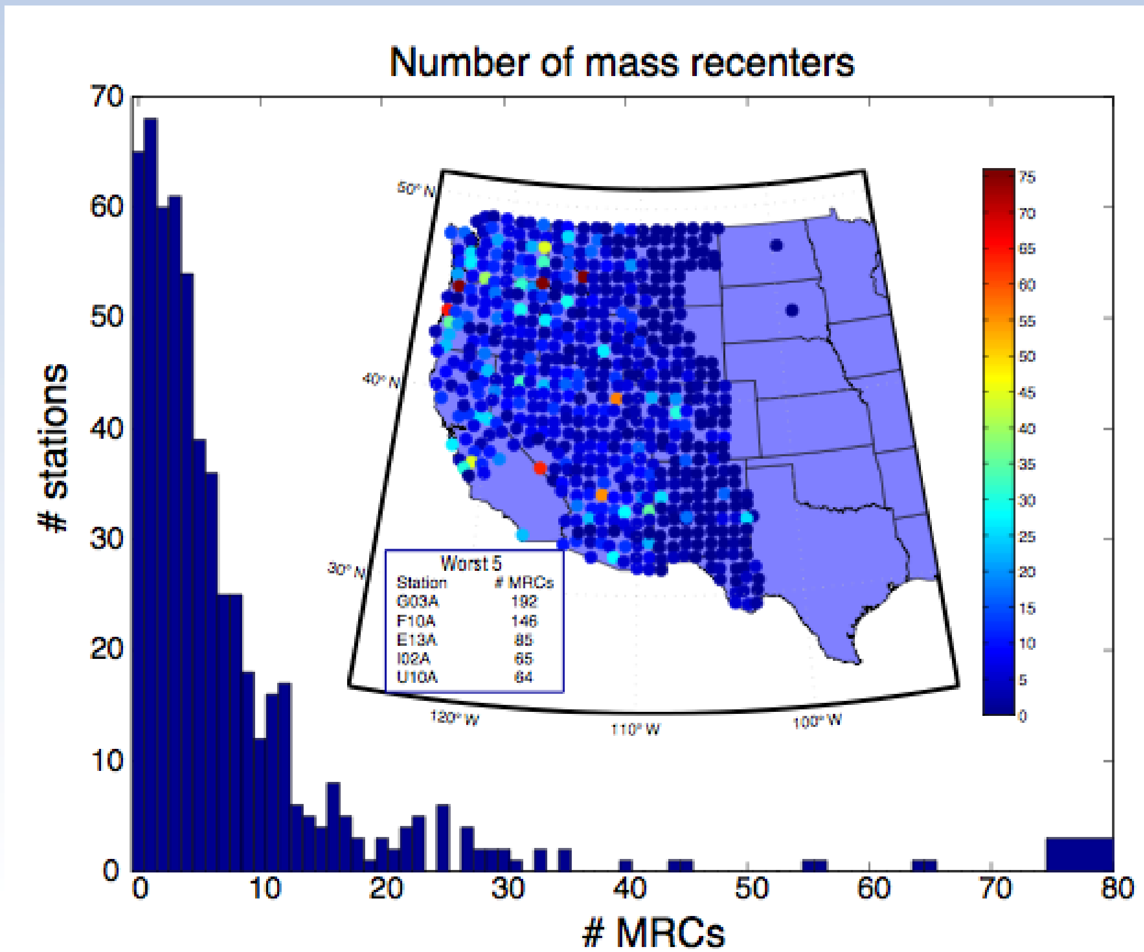
- **Examination of clock quality channels for test interval (2007) indicates clock quality is excellent**



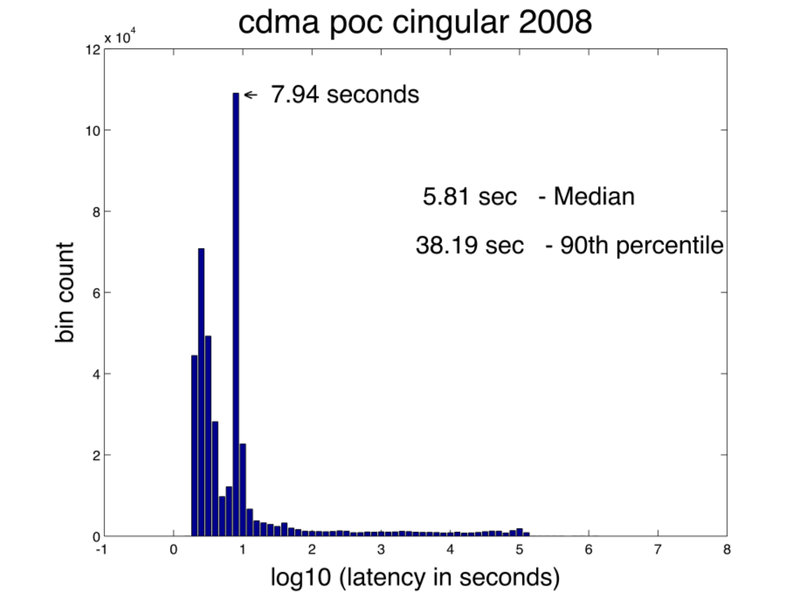


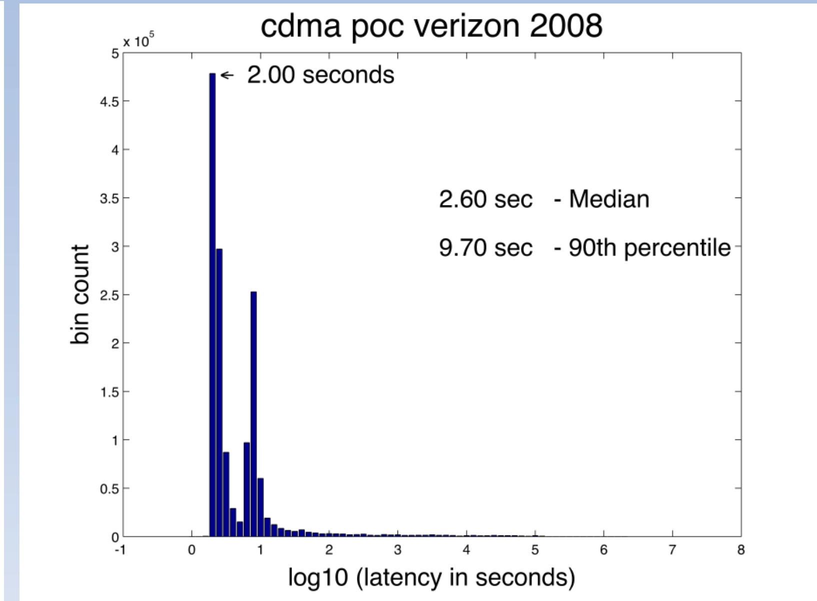
Mass Position

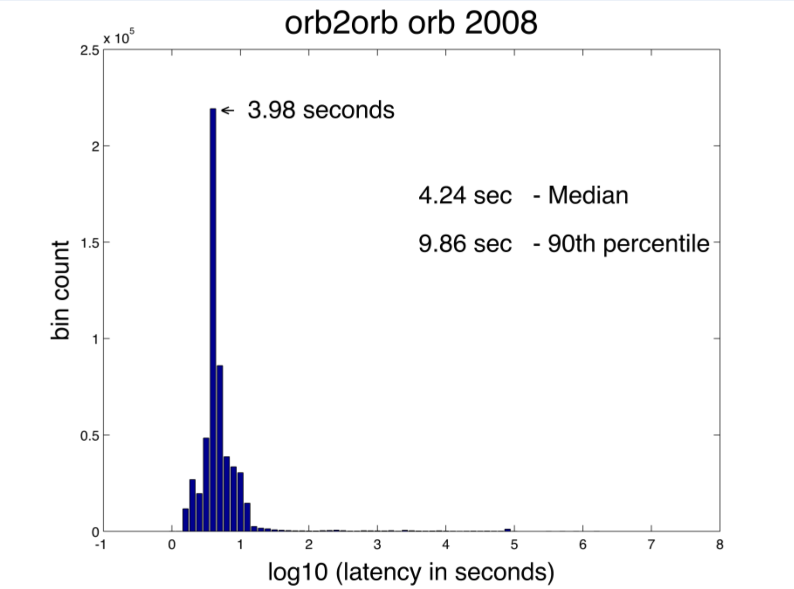
Sensor Mass Recenter operation affects data quality and broadly indicates the long-period quality of site. Most stations have 10 or fewer mass re-centers over a one year period

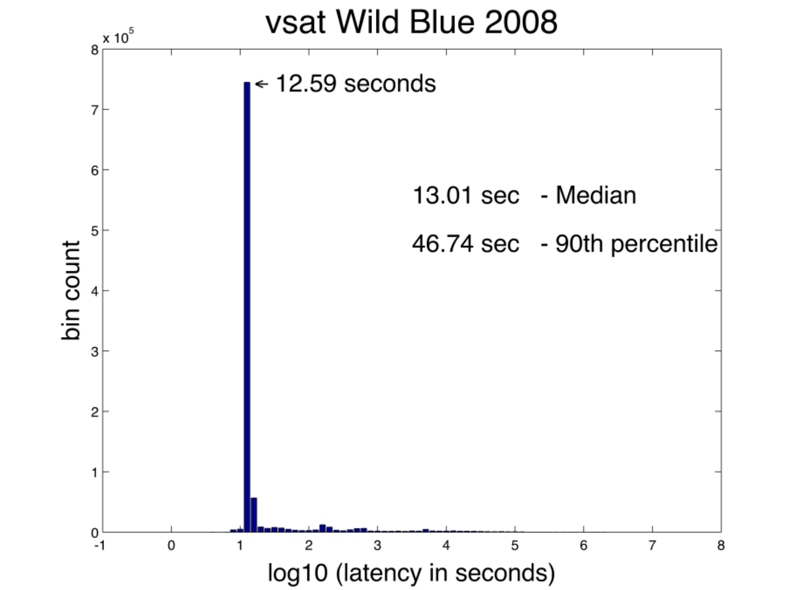


Status: RT Latency

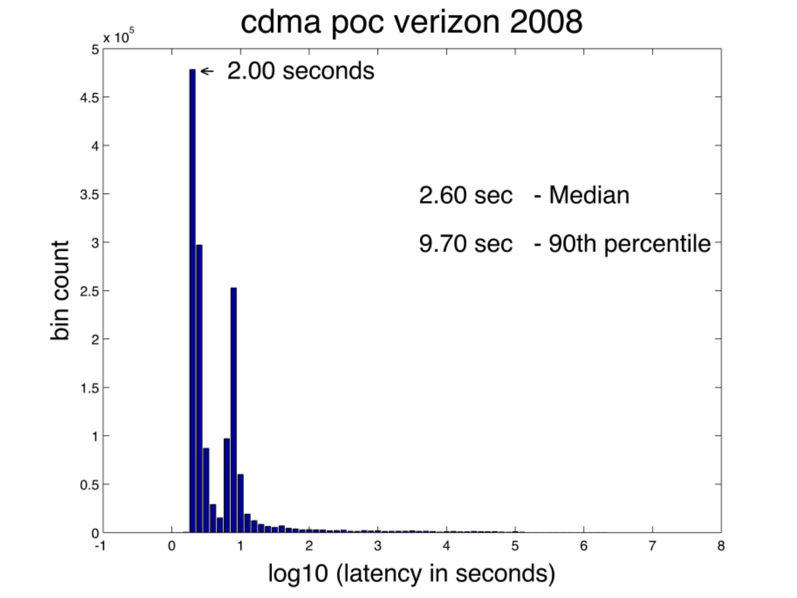




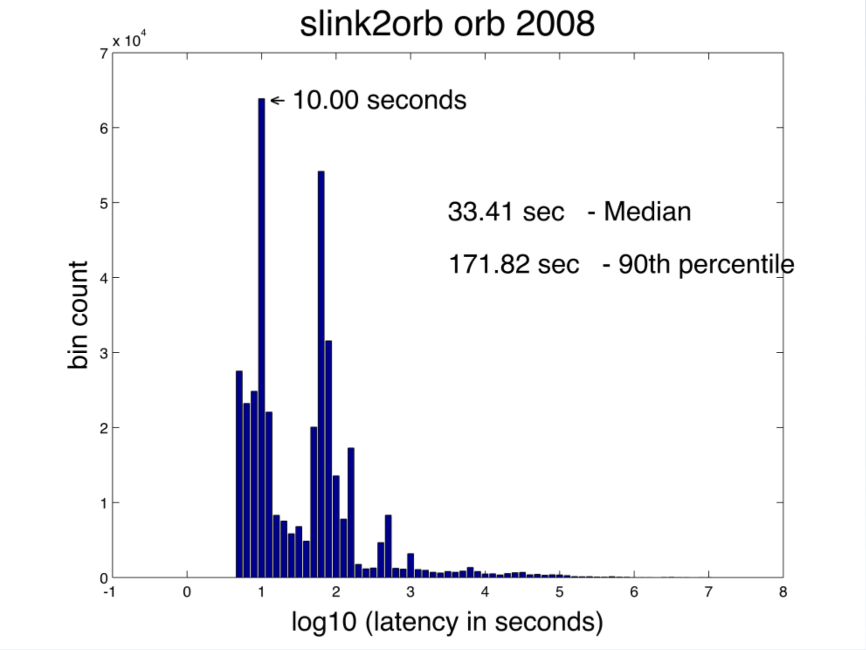


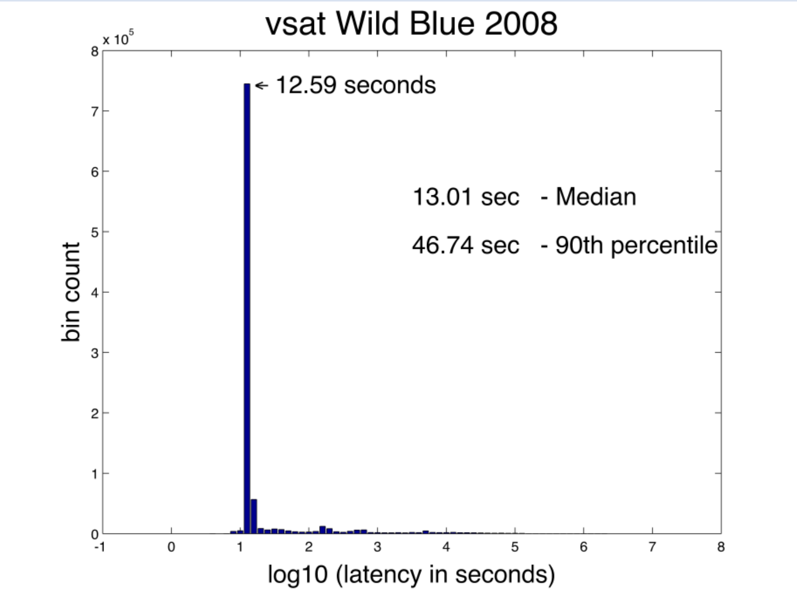


Status: Forwarding Latency



Typical of DMC feed to UW





Performance Metrics

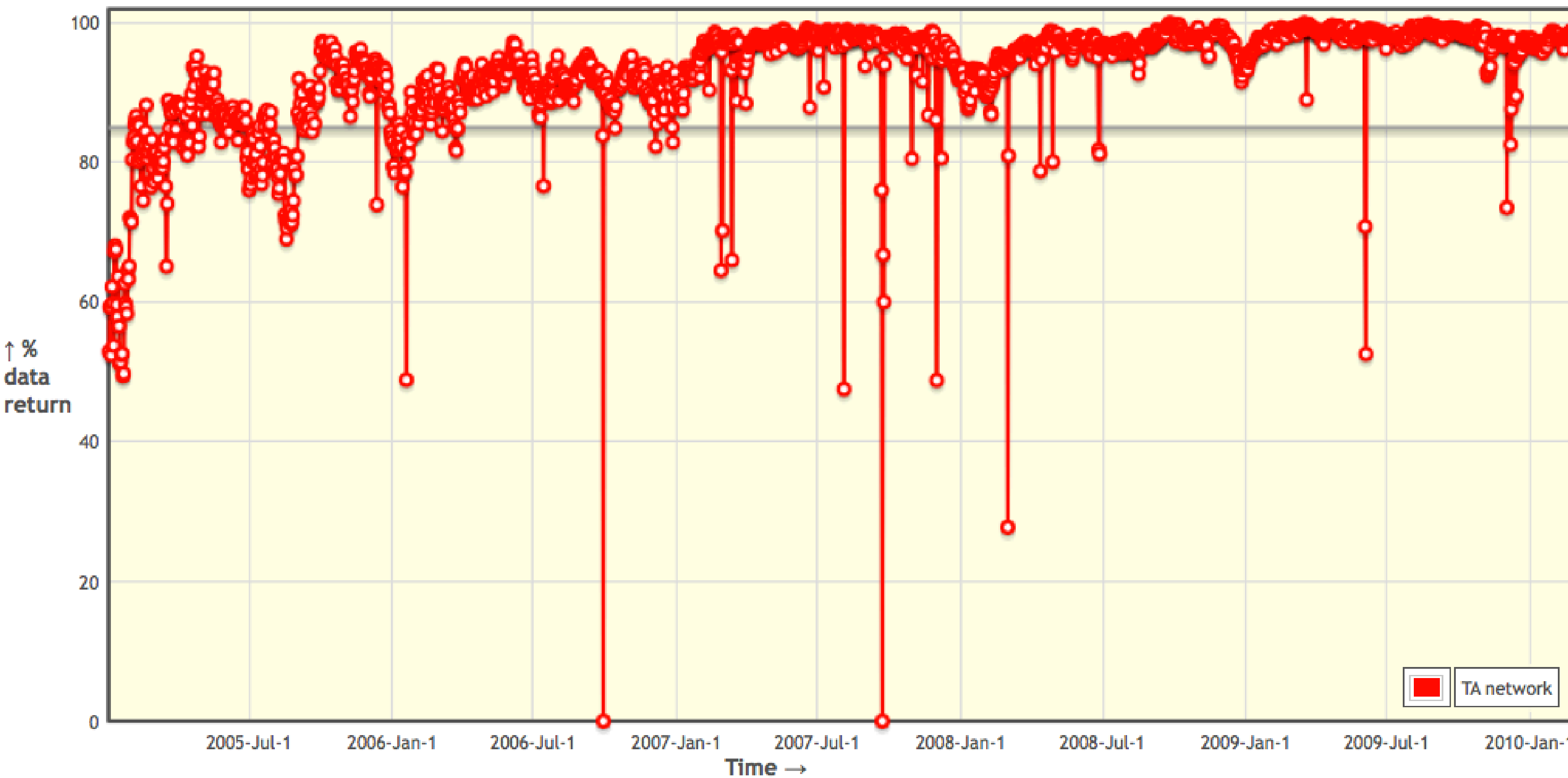
- Metrics must have meaningful relationship to science
- Exploit measures already being computed - i.e., data mining from ANF and DMC databases

Integrity
Accuracy
Quality
Performance

Metric	Description	Who
Mass position	Percent of time offscale (Bob B. will provide scale). Requires scan of mass position channels.	ANF
Mass Recenter	Number of mass recenters & time between recenters	ANF
Clock quality	Statistics of clock quality LCQ channel. Requires scan of LCQ time series.	ANF
Clock error	Statistics for times when clock error exceeds 1% of sample interval. Requires scan of LCE channels.	ANF
Latency	From data tracked at ANF	ANF
PDF by sensor type	PDFs aggregated by sensor type (Streckeisen, Guralp, Trillium). PDFs and mode vs frequency.	DMC
Mode calcs for large events	Provides low frequency calibration	ANF
Tidal amplitudes	Provides low frequency calibration. Likely only reliable for stations away from coast (e.g., won't use ocean loading calculations).	DMC
Calibration of network	Calibration results for entire network, with calibrations performed over a relatively short time period (e.g., one week).	ANF
Availability	Results for monthly, 3-month, and final data availability. Final data availability derived from stations for which we have completed post-station-removal baler backfill.	DMC
Gaps: gaps / day	Perhaps a histogram of gaps/station-day (i.e., x axis is # of gaps/station day; y axis is # of station days). This histogram would then (presumably) show that most station days have zero gaps, that the large majority of station days have very few gaps, and there are some outlier station days with many gaps. (will compare DMC and ANF results)	DMC/ ANF
Gaps: # days with no gaps	This metric could be addressed by the histogram described above. (will compare DMC and ANF results)	DMC/ ANF
Detection threshold	Perhaps based on magnitude? Consider variation of this, but based on event detection/formation statistics.	ANF
Event coherency	Measure coherency from teleseisms & regional ? events across the array for body & surface waves	ANF
Detections/station	Statistics on station detections & use DMC statistics to compare to other networks (quack)	ANF/ DMC

Status: RT Performance

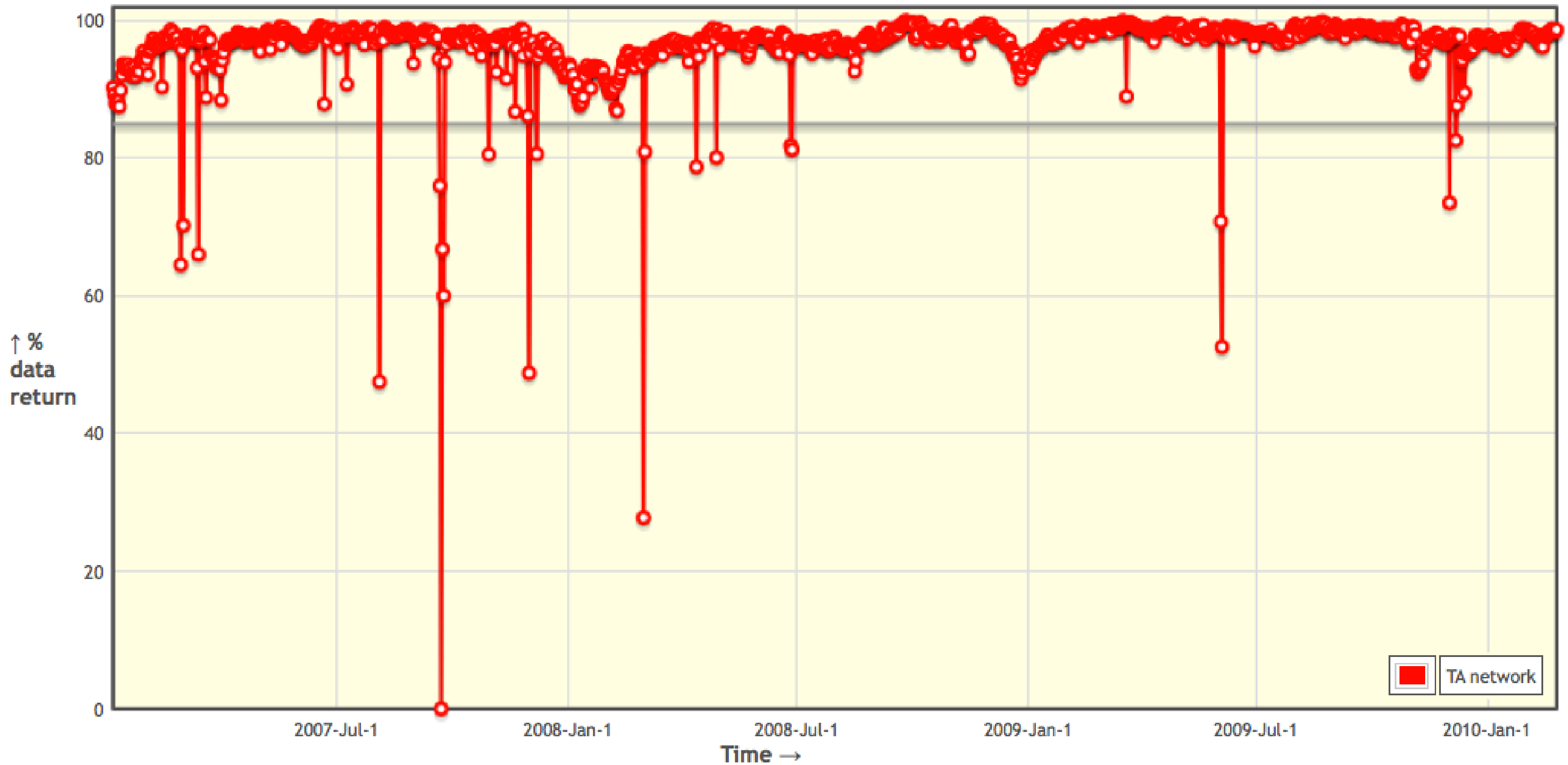
TA performance 2005 – 2010, 01



Status: RT Performance

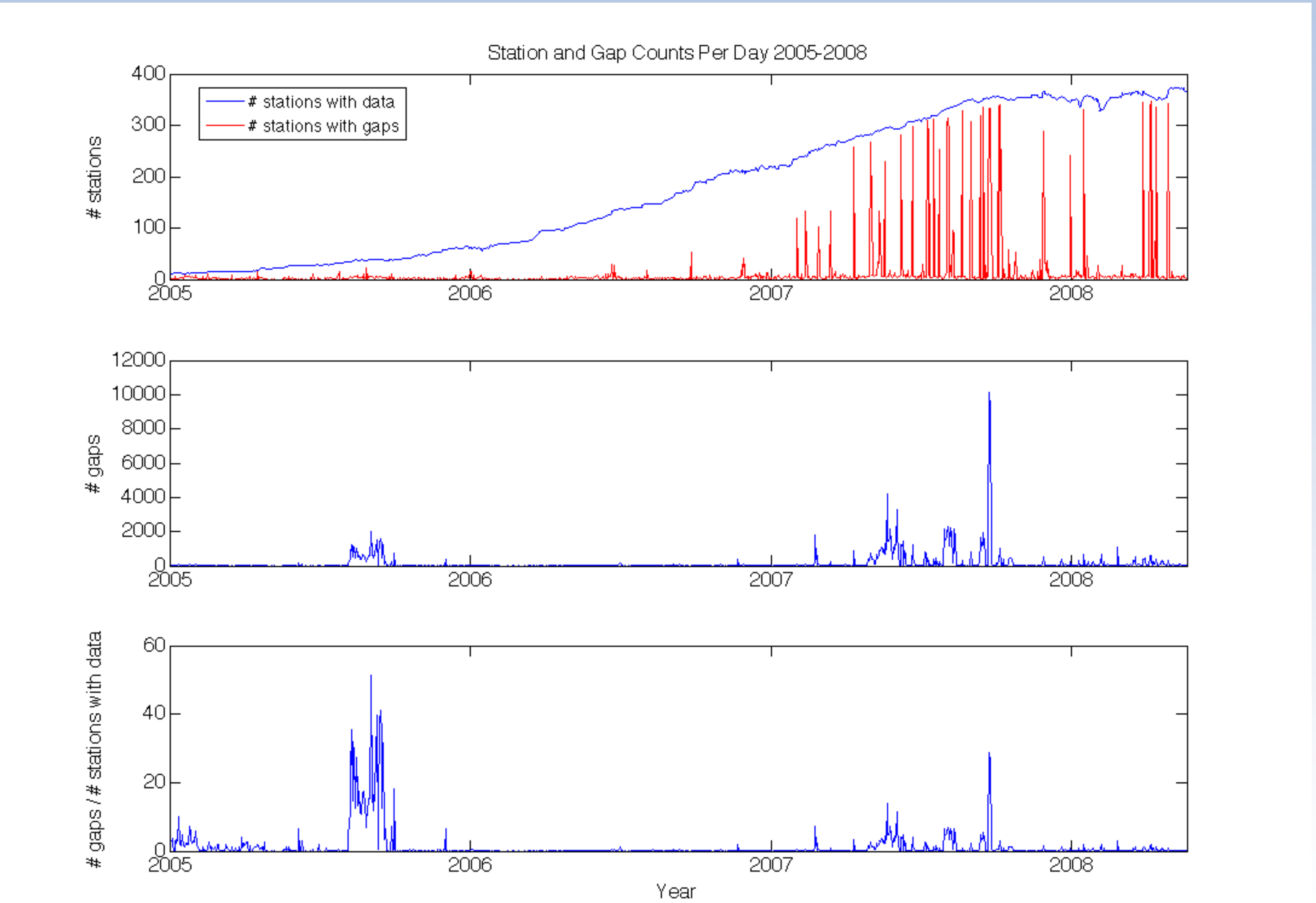
TA performance 2007 - 2010 01

98.68%

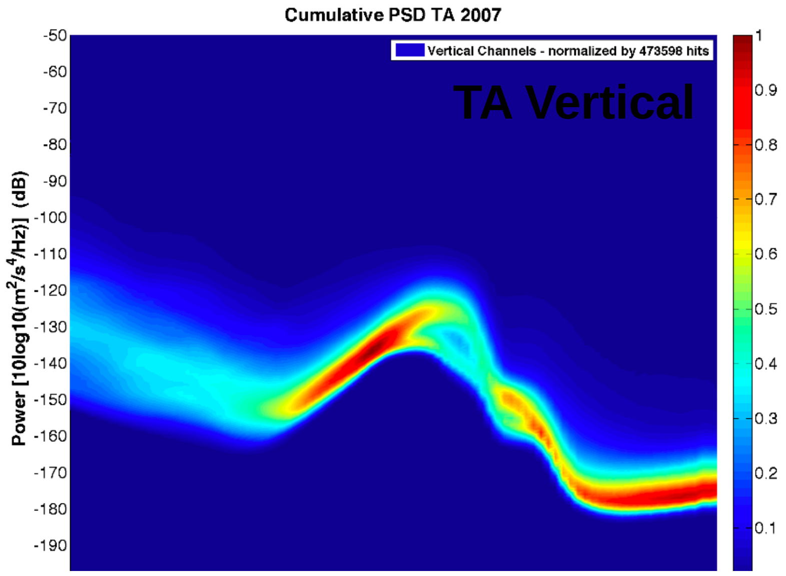


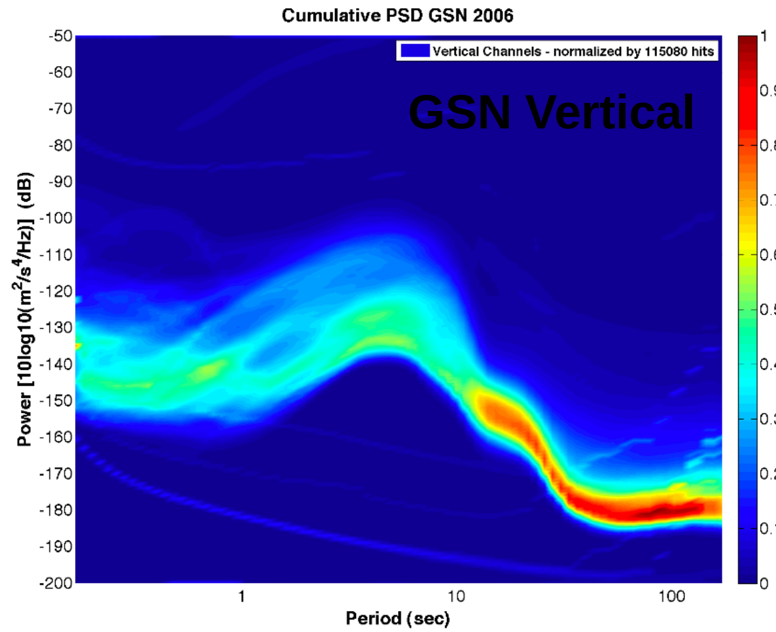
TA Gaps

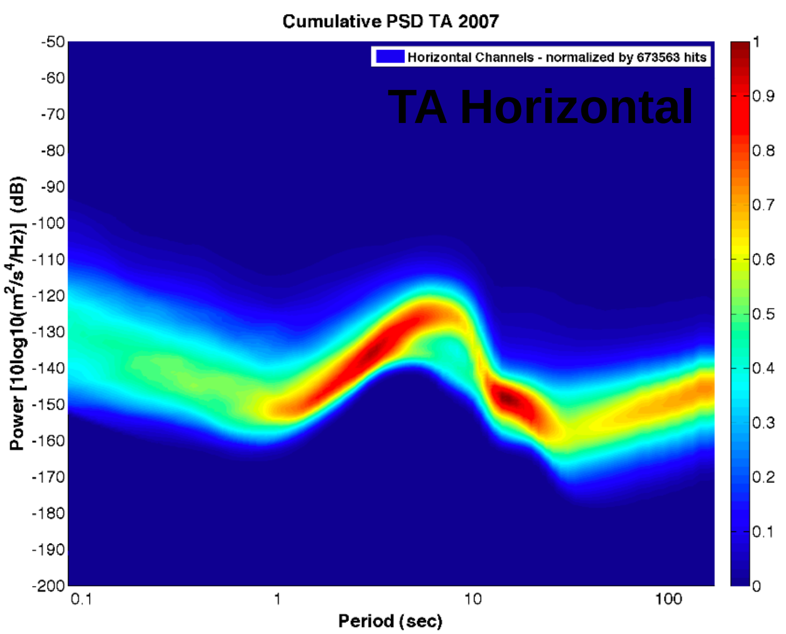
- **Examined data gaps as a function of time**
- **Examined cumulative gap statistics**

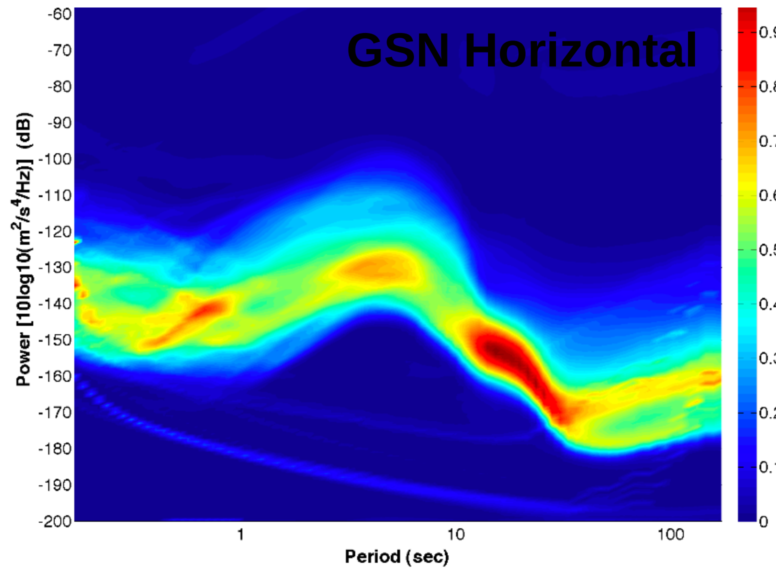


Power Density Functions





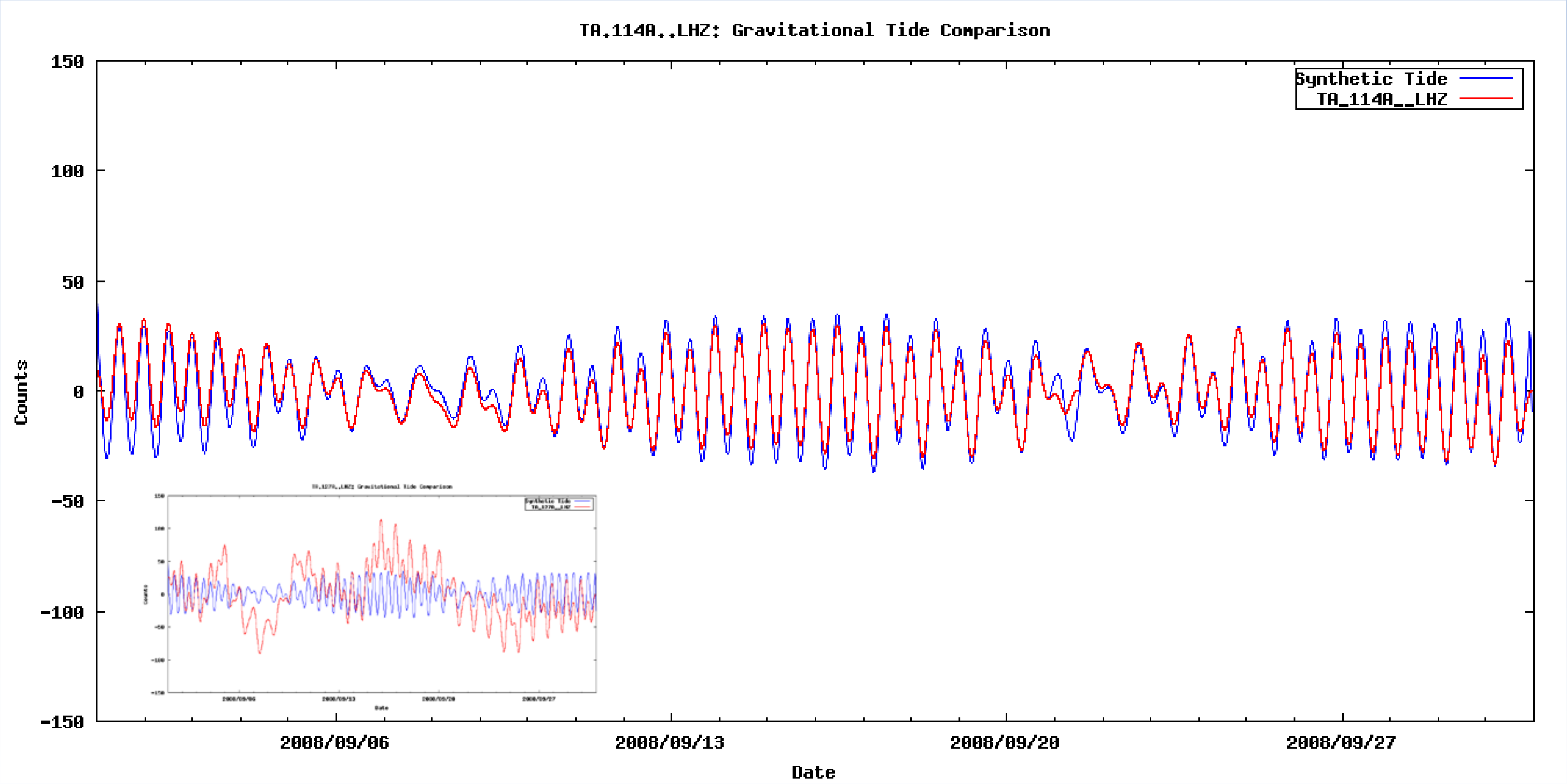




Tides

- All TA LHZ channels are compared to Earth tide synthetics
- The majority of stations have excellent fit to tides
- Small numbers of stations have transients
  - Mass re-centers
  - Temperature fluctuations

http://crunch.iris.washington.edu/synthetics/tide/

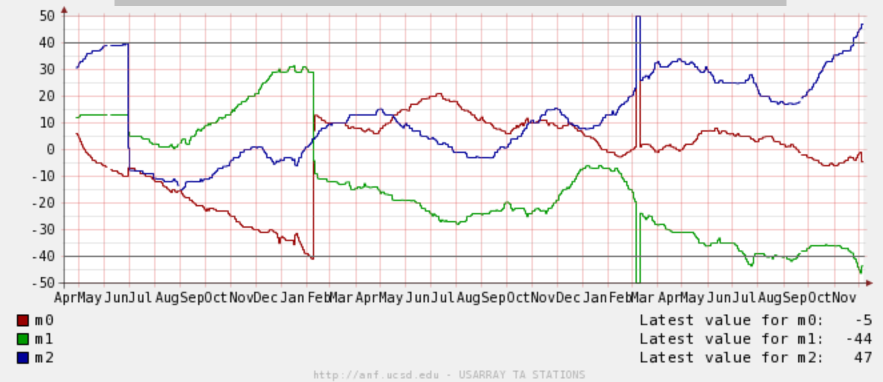


one month

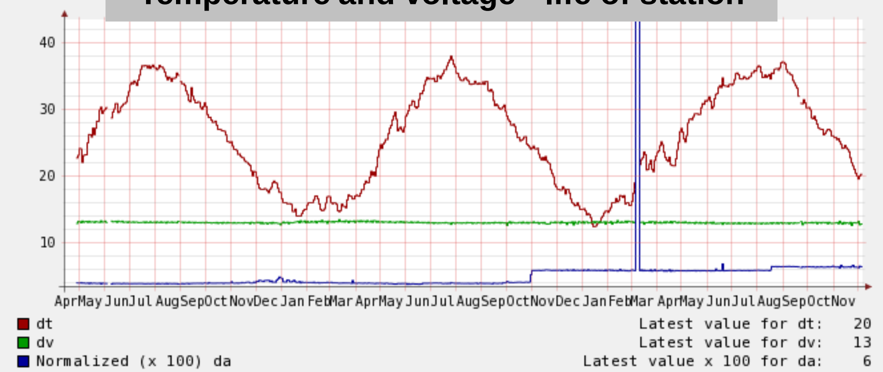
State of Health Review

- Real-time monitoring of SoH
  - Detect problems
  - Initiate corrective actions
- Station QC & SoH on the web
  - SoH channel displays for near-real-time and summary
  - Metrics for arbitrary time intervals

Mass position - life of station

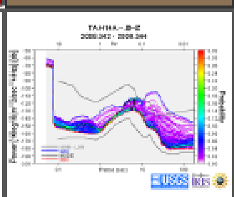
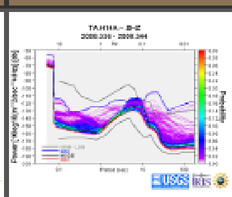
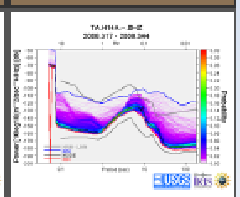
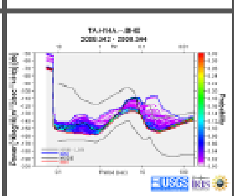
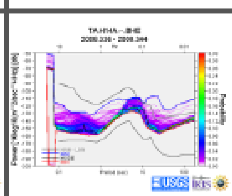
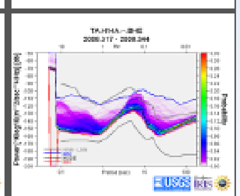
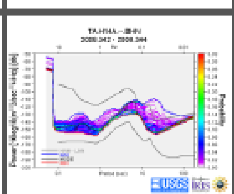
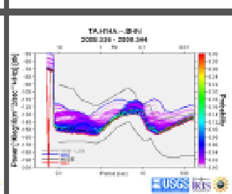
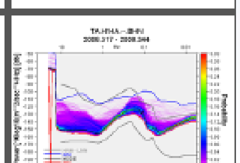


Temperature and voltage - life of station



From ANF station status web pages

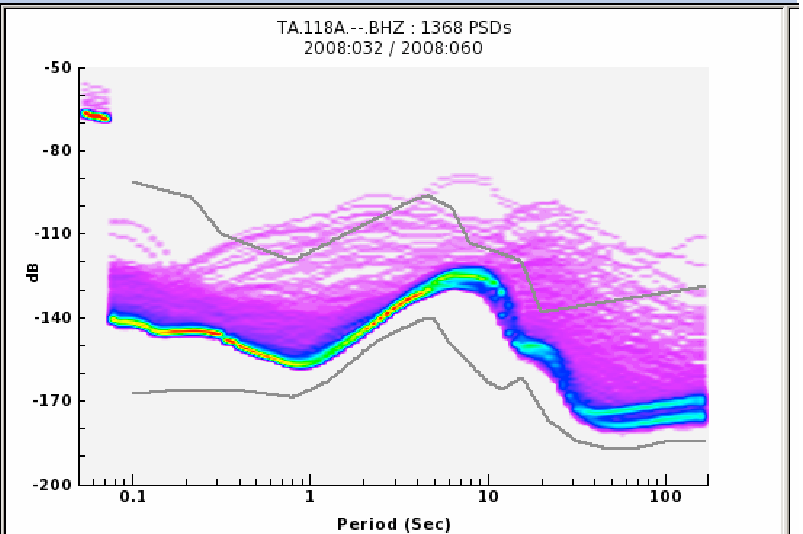
IRIS DMC PDF noise analysis by station-channel

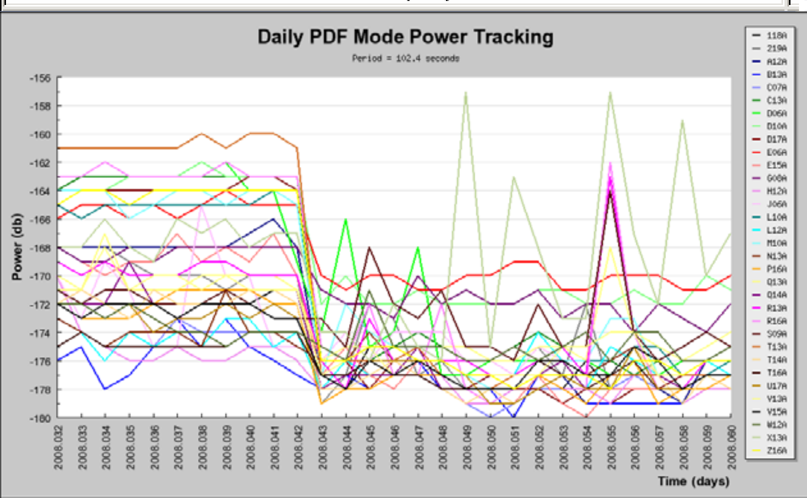
Channel	Time periods of PDF plots		
	Last available day 2008.342 - 2008.347	Last available week 2008.336 - 2008.347	Last available month 2008.317 - 2008.347
BHZ			
BHE			
BHN			

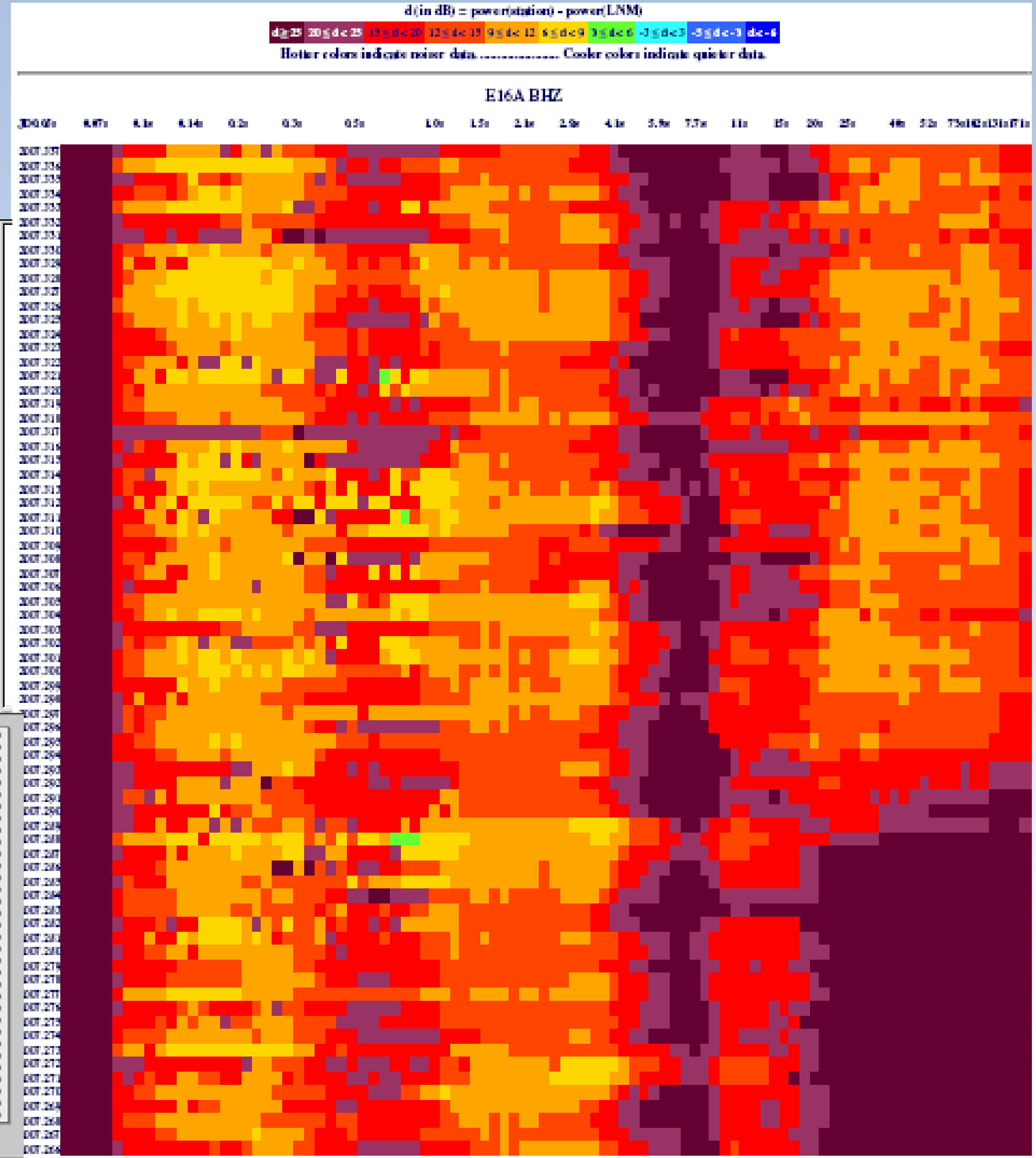
From DMC QUACK tool

Diagnostic View: Discovery!

Guralp Vertical:
mass position vs noise







Organization Summary

34 Team Members

Management: 2.0

Recon: 5
- **2.5 office**
- **2.5 field team**

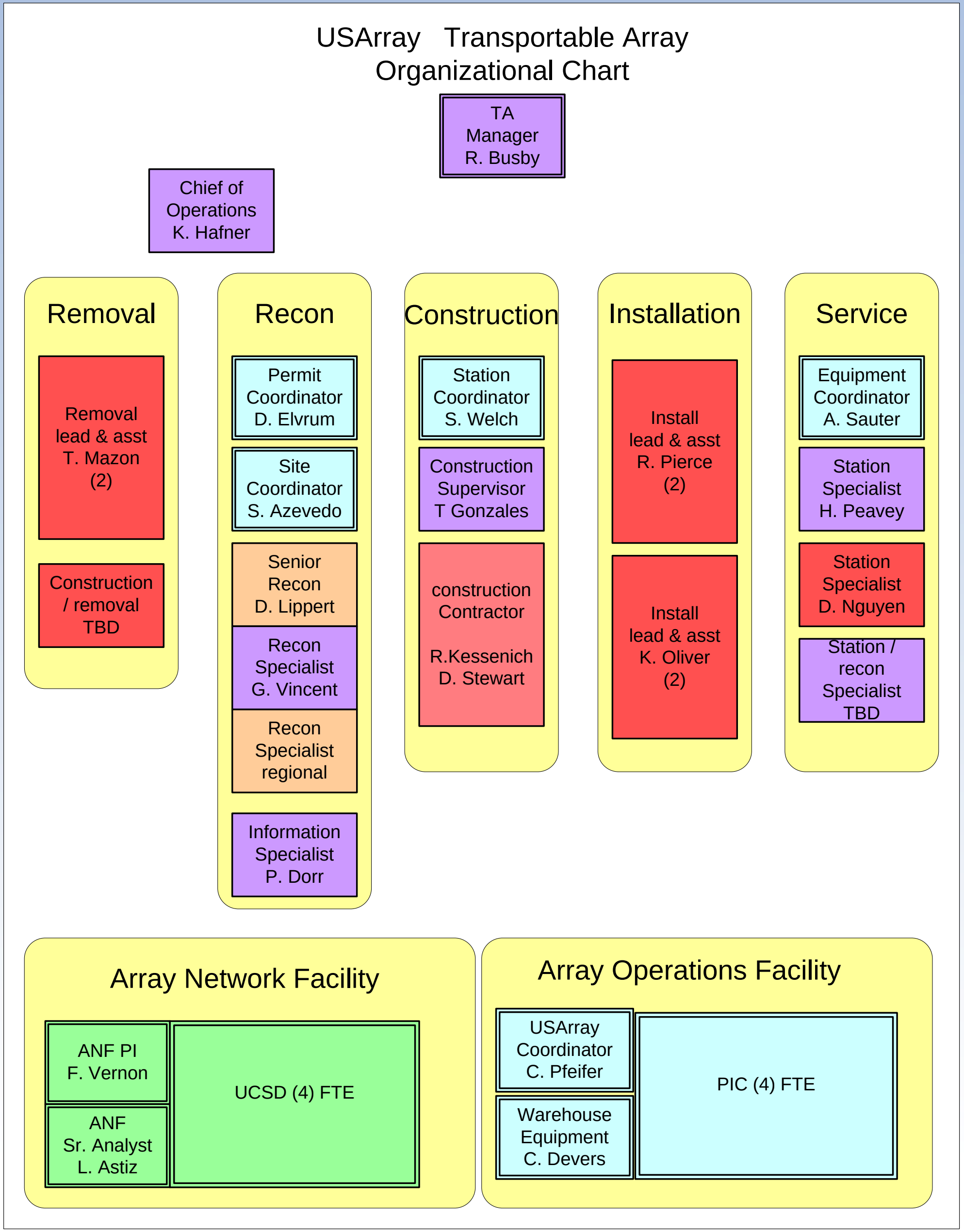
Construction: 4
- **1 office**
- **3 field crew**

Installation: 4
- **4 field crew**

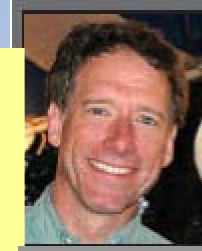
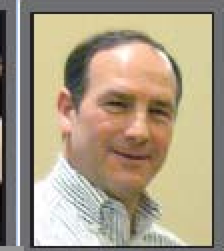
Service: 4
- **4 field crew**

Removal: 3
- **3 field crew**

Support Facilities: 12
- **AOF NM Tech 6**
- **ANF UCSD 6**



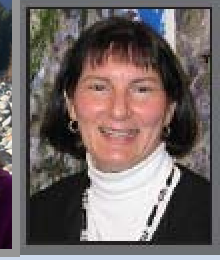
TA Team

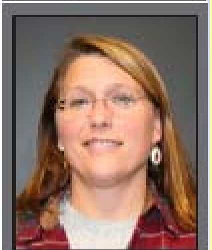

Management

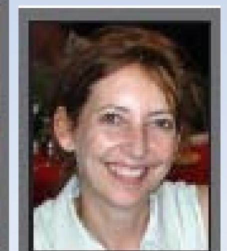
Robert Busby	Rob Woolley	Robin Morris	Perle Dorr
Katrin Hafner	Bob Woodward	David Simpson	Cecelia Kelton



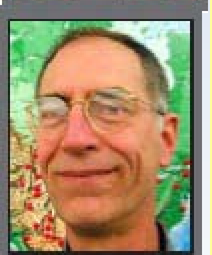
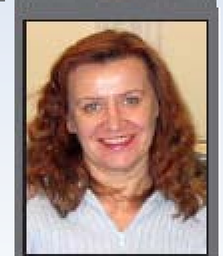


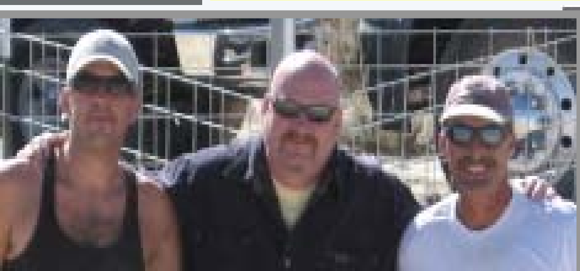
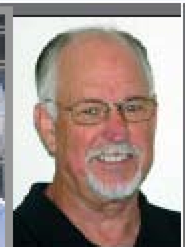
TA Coord Office	**Recon**	**Construction**	**Installation**
Steve Welch	Don Lippert	Tony Gonzales	Bob Pierce
Denise Elvrum	Graylan Vincent	Rick Stout	Ken Oliver
Sandi Azevedo	Joseph Goode	Ron Kessenich	Jerry Hollinan
Allan Sauter	Patrick Hickey	Mack Hardy	Elgin Hinson
	Larry Jaksha	Steve Christman	Doug Ford
		Mike Flanagan	

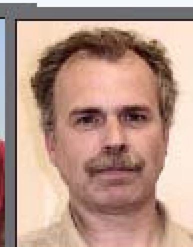
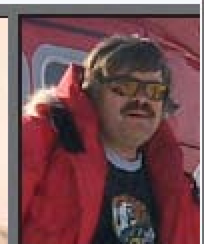
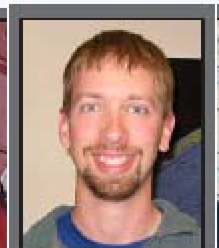


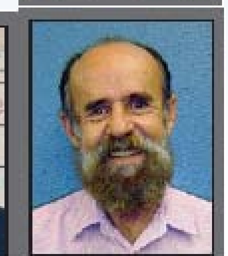


AOF	**ANF**	**DMC**	**Service**
Cathy Pfeifer	Frank Vernon	Tim Ahern	Howard Peavey
Cyndie Devers	Jennifer Eakins	Chad Trabant	Doan Nguyen
Greg Chavez	Rob Newmann	Peggy Johnson	
Noel Barstow	Luciana Astiz	Gillian Sharer	
Bruce Beaudoin	Vladislav Martynov		**Removal**
Elena Prusin	Trilby Cox		Tom Mazon
Mike Gorton	Geoff Davis		Mark Miller
Derry Webb	Brian Battistuz		
	Taimi Mulder		



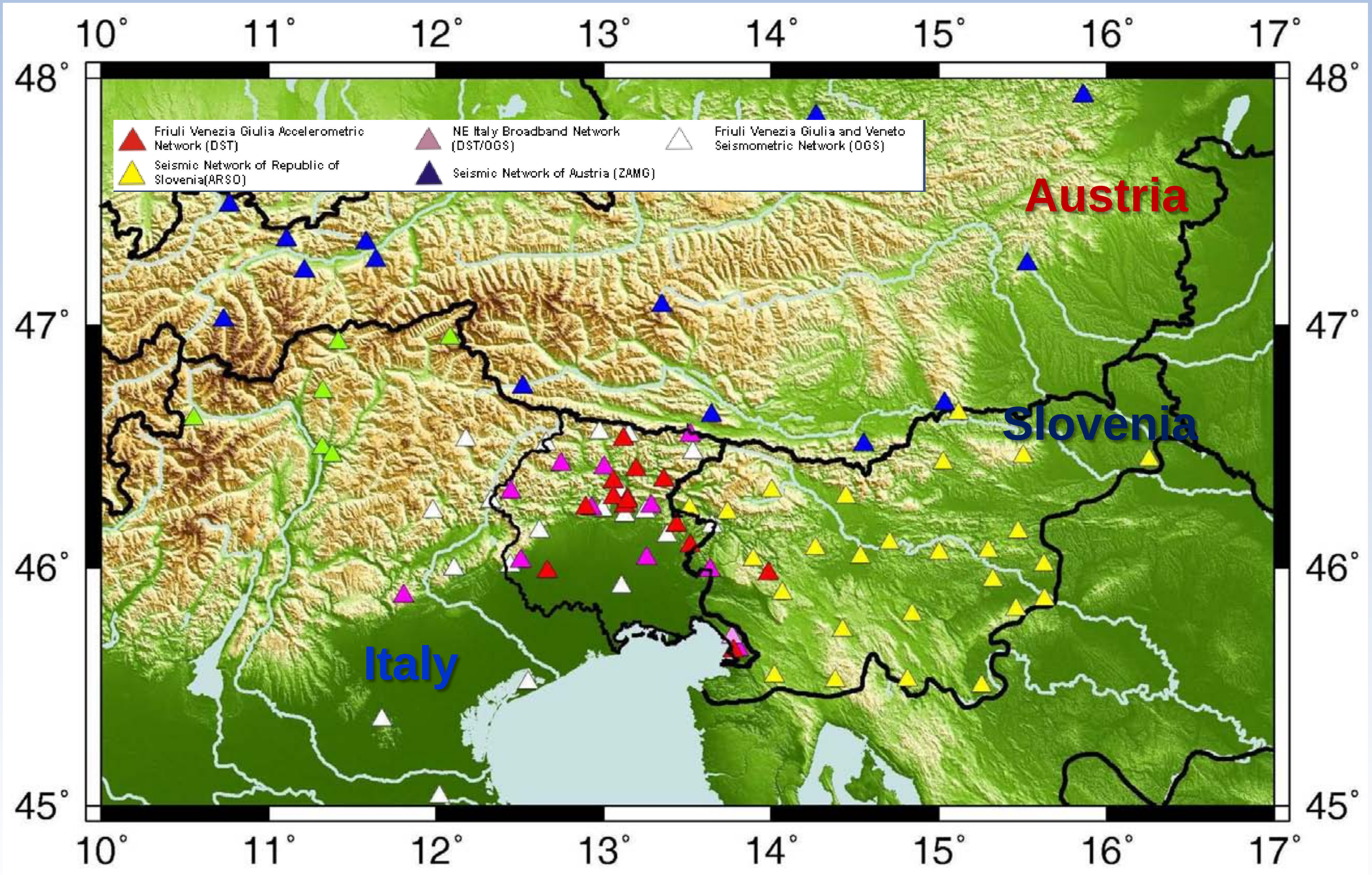
USArray Technology Standard in Arab World and Neighboring countries

- Saudi Arabia KACST
- Saudi Arabia KSU
- Saudi Arabia Aramco
- Oman SQU
- Dubai Municipality
- Kuwait (KISR)
- Iraq (IMA)
- Morocco (CNRST)
- Algeria CRAAG
- Pakistan (WAPDA)

Real-time data exchange in Gulf

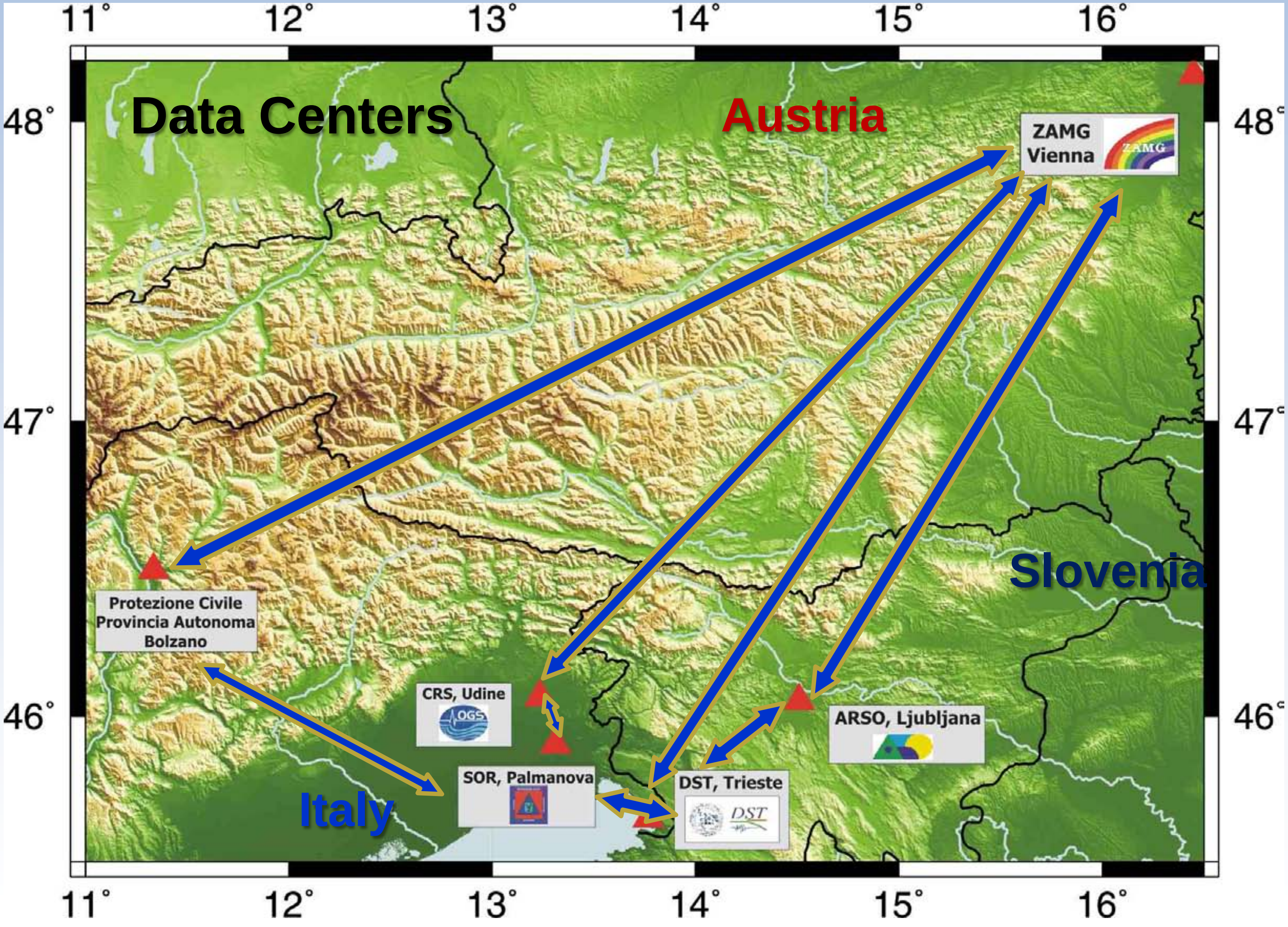
- Oman
- Dubai
- Kuwait
- Abu Dhabi
- GSN

Example: Other USArray TA (Aspen) Based Technology Networks - Interreg III - Italia-Austria-Slovenia



Stations distribution

Example: Other USArray TA (Aspen) Technology Based Networks - Interreg III - Italia-Austria-Slovenia



Example 1: Data Availability of other Aspen Based Real-Time Networks

Network	# Stations	Duration	Data Availability	Number Employees
Austria	38 Aust. + 3 Czech + 10 N. Italy (Maint. & operated jointly)	2009	99.93%	1,5 Analysts + 3 Tech.
		2008	99.97%	
		2007	99.65%	
		2006	99.04%	
		2005	99.91%	

- **1,945 Events with a local magnitude (our catalogue) since 2005**
- **9,434 events worldwide since 2008**
- **The number of automatic events is about 1,500/year**
- **All above manually (re)located**

Example 2: Data Availability of other Aspen Based Real-Time Networks

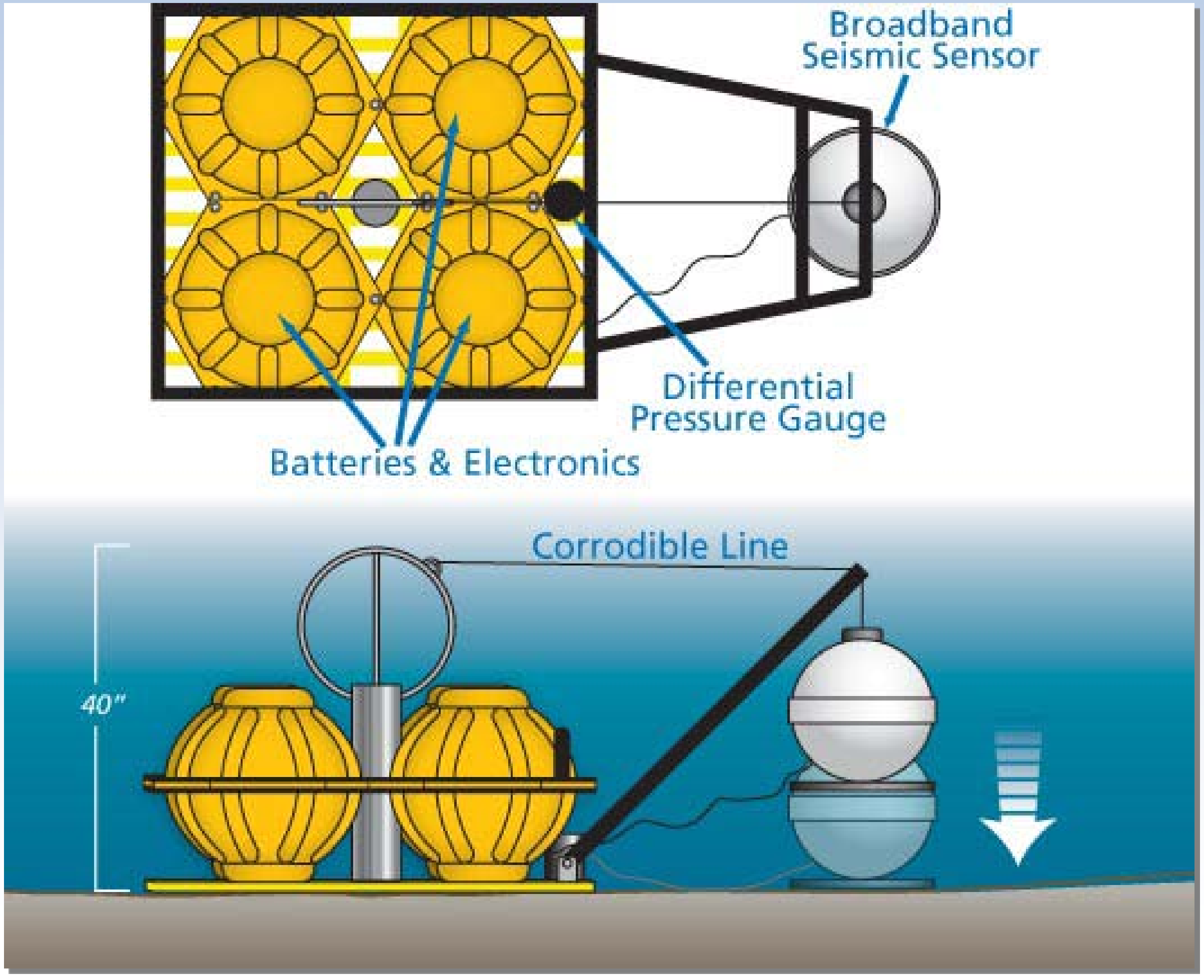
Network	# Stations	Duration	Data Availability	Number Employees
Slovenia	26	2009	98.2%	1,5 Analysts + 4 Tech.
		2008	97.6%	
		2007	91.9%	
		2006	95.6%	
		2005	90.9%	

- **7,591 Events with a local magnitude (our catalogue) since 2005**
- **22,655 events worldwide since 2008**
- **The number of automatic events is about 7,600/year**
- **All above manually (re)located**

Best Performance Network Award!

- **Definition of categories?**
- **Evaluation criteria?**
- **Any network shall be allowed to participate in contest**
- **KMI to support. What is expected or appropriate by community?**
- **Other?**

New Developments: Proven USArray Technology goes under water: Real-Time (Cable) Broad-Band OBS



Deployed Woods Hole Oceanographic Institution (WHOI) Q330 based Ocean Bottom Seismograph (OBS)

WHOI D2 short-period seismometer
on the TAG hydrothermal mound in Spring 2003.
WHOI operates 50 D2s as part of the
US Ocean Bottom Seismic Instrumentation

WHOI Cable Ocean Bottom Seismograph

Q330 based system + additional electronics

WHOI Modular Packaging

New Developments: Proven USArray Technology goes under water: Real-Time (Cable) Broad-Band OBS

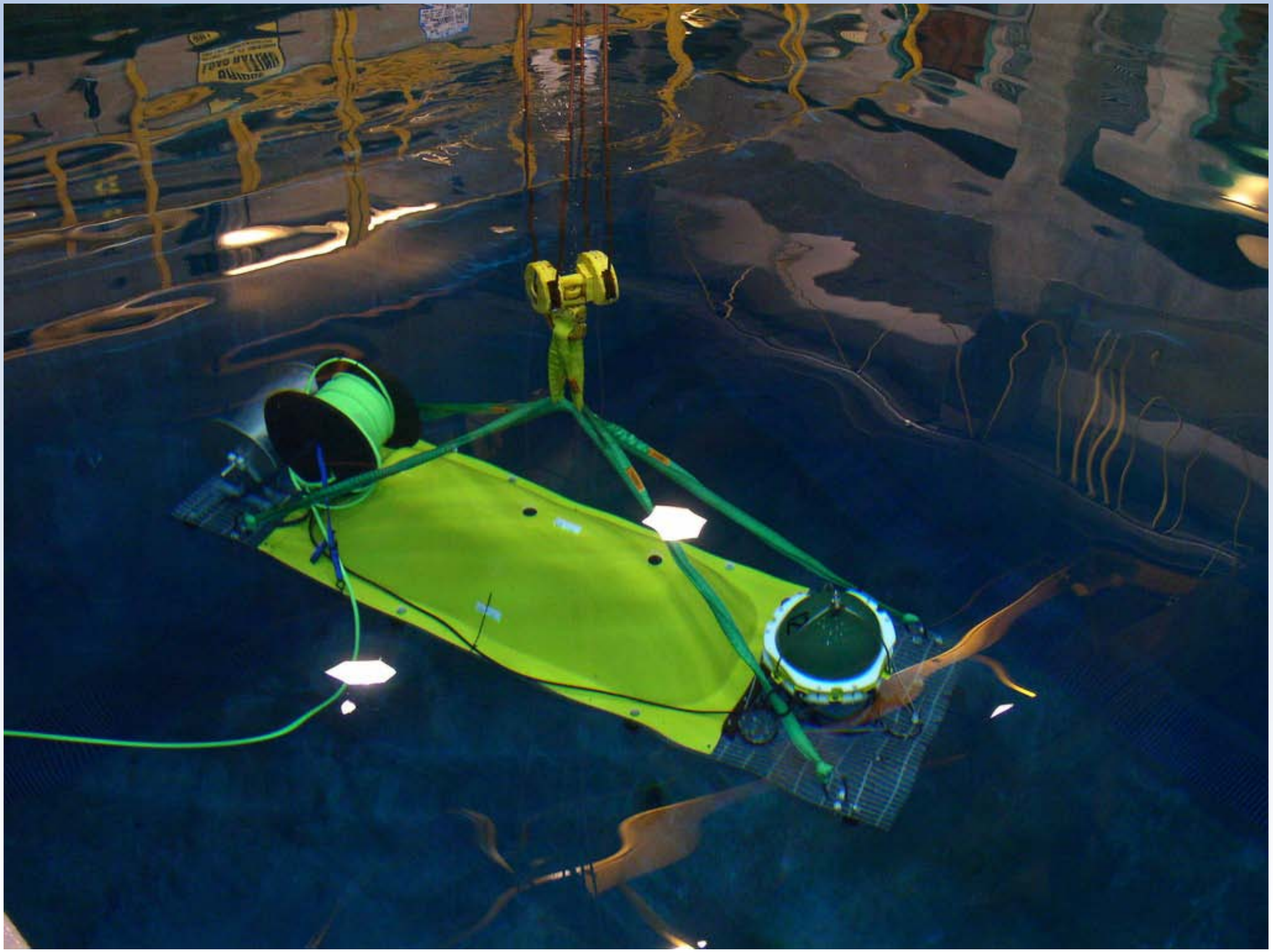
- First Aspen OBS Deployment: Oman
  - OBS data to Shore via Cable
  - Shore to Data Center via VSAT comm.
  - Integration with Existing Data Center at SQU (Muscat)

New Developments: Proven USArray Technology goes under water: Real-Time (Cable) Broad-Band OBS

- UCSD LOOKING Deployment : MARS Cable Observatory (Prototype for NSF funded Ocean Observatory Initiative, OOI Real-time Networking)
  - Q330+Marmot, Cable OBS & Real-Time
- Antelope is part of Real-time Networking
- Cyber Infrastructure Budget: Construction ~$30M; $50M/ 7year Operation

UCSD LOOKING Deployment : MARS Cable Observatory-Antelope (Marmot) and Q330 at Ocean Bottom

UCSD LOOKING Deployment: MARS Cable Observatory



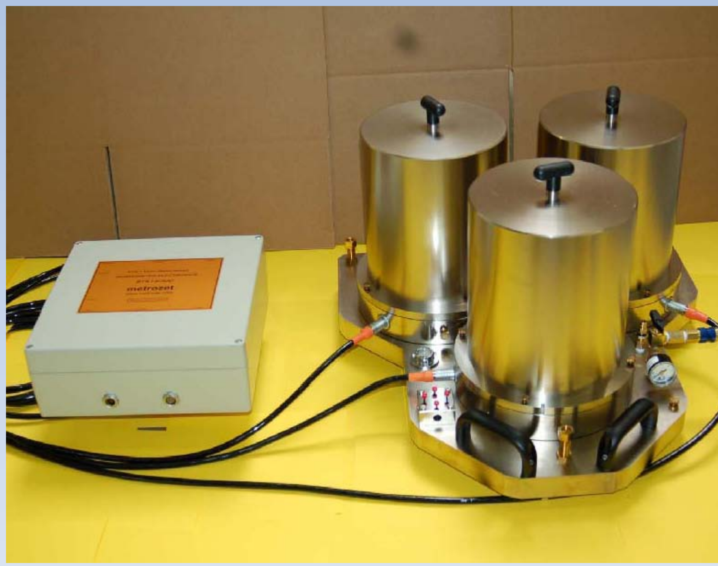
Summary & New Developments

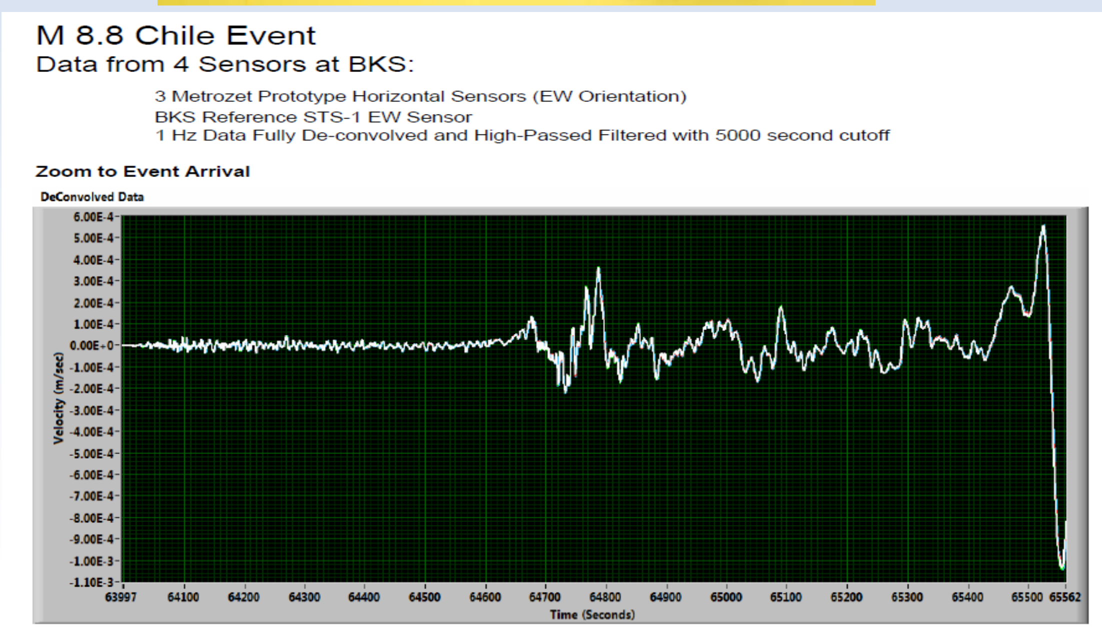
- **Clearly current Aspen System Architecture demonstrated undisputed and exceptional record of performance and operation in variety of environments and applications worldwide:**
  - **Q330 family**
  - **Antelope System Software**
  - **Use of COTS products**
  - **Exemplary Q330 & Antelope system integration; a true joint work under the hood…**
  - ***USArray and PBO as large scale projects provided opportunity to work on challenges going beyond a small size network…..***
    - **System daily field stressed & improved: All other Network Operator benefits**

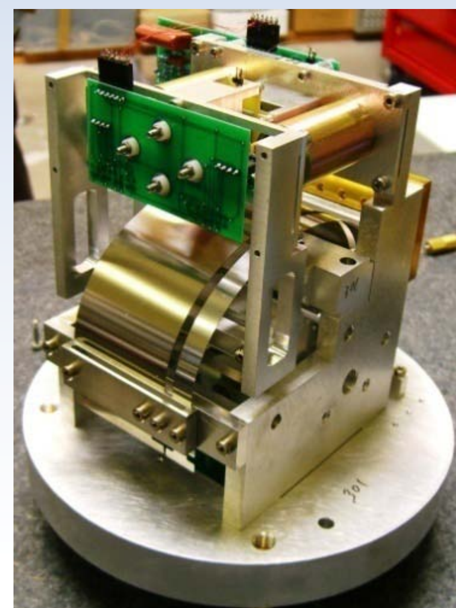
New Developments

- New Product Option:
  - Q330HR all 6-channels @ 151 dB
- New Product: Q330HRS, SSA, April, 2010
- New Product: Q330S+, June 2010
- New Development:
  - Next Generation of STS-1 type of Very Broadband (VBB) seismometer
  - Portable Broadband seismometer (PBB-100S)
- Research and Development:
  - MEMS ultra-low power broadband seismometer (40sec)
  - MEMS ultra-low power accelerometer (~12 dB better than EpiSensor)

Next Generation of STS-1 type of Very Broadband (VBB) Seismometer

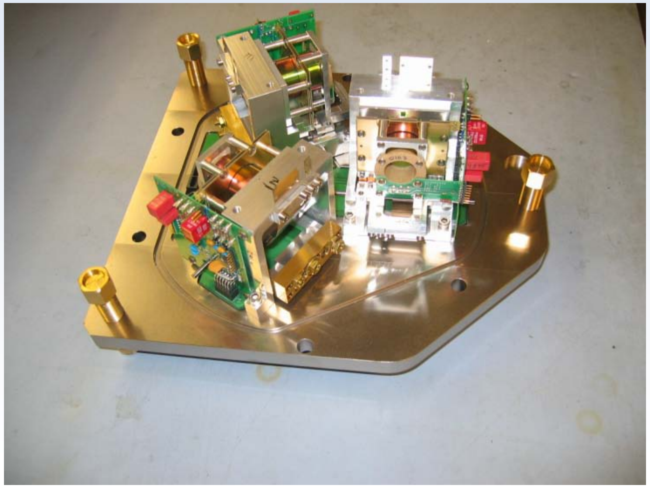






Portable Broadband Seismometer

PBB-120

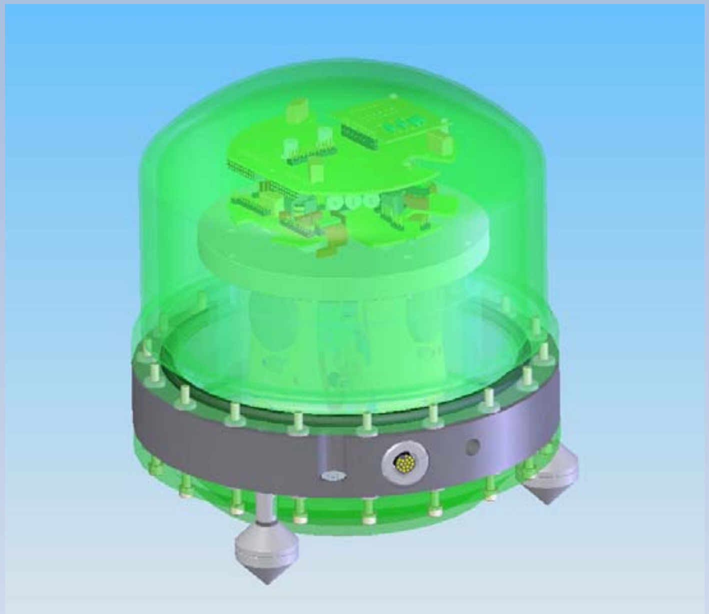


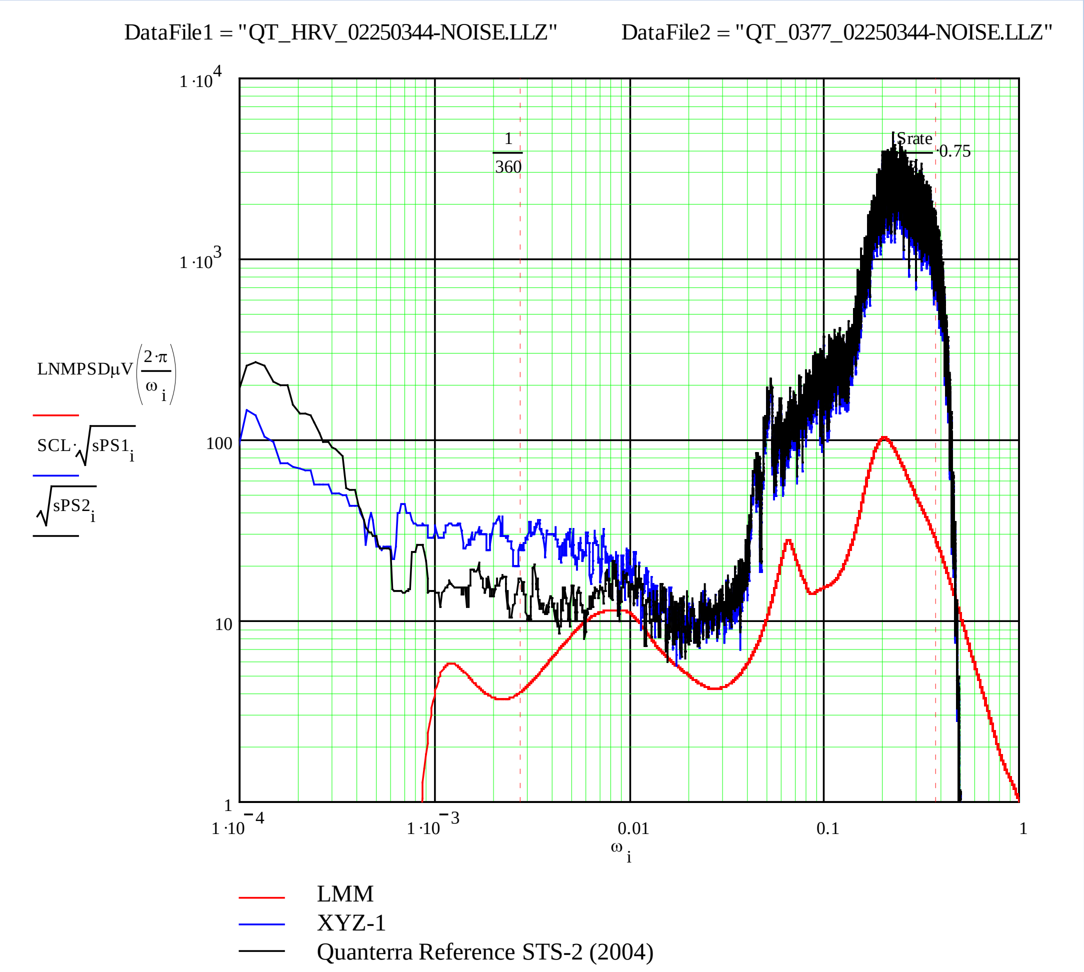
Sensor Technology	Triaxial, orthogonal feedback sensor elements with temperature-compensated leaf springs
Mass centering	Standard local and remote operation
Leveling	Bubble level and locking feet
Alignment	Laser alignment tool included
Bandwidth	120 seconds to 100 Hz, pole/zero data provided
Self-noise	Below NLNM 35 seconds to 10 Hz
Sensitivity	1500 V-s/m, factory trimmed to 0.5%
Velocity Output	Industry-standard 40V peak-to-peak, matched to Quanterra data logger input, orthogonal
Mass Position Output	Independent, orthogonal mass position outputs
Calibration	Available; compatible with Quanterra data logger for remote network diagnostics
Host Box	Included with each unit; isolates more than 95% of total power from the sensor elements
Serial Port	RS-232 available for local or remote operation
Power Supply	1W from typical from isolated 9-36V input
Shock Survival	Mass lock allows more than 50g shocks with no degra-dation of linearity or hysteresis
Environmental	Pressure-sealed sensor housing with true warpless baseplate; EMI/RFI shield
Packaging	IP68; survives brief periods of submersion to 1M depth

New Developments

- XYZ-1 Broadband Seismometer, Streckeisen & Kinemetrics collaboration:
  - Comparable with other sensors of the same price range: $14-16K
  - Typical no-centering range +/- 25 C
    - Portable deployments
  - Tilt range without centering; +/- 0.03°
    - Total tilt range (centering included) 16 tilt ranges without centering, corresponding to +/- 0.48°
  - Mass locking only required for long-haul transportation
  - Power: 560mW @ 12VDC

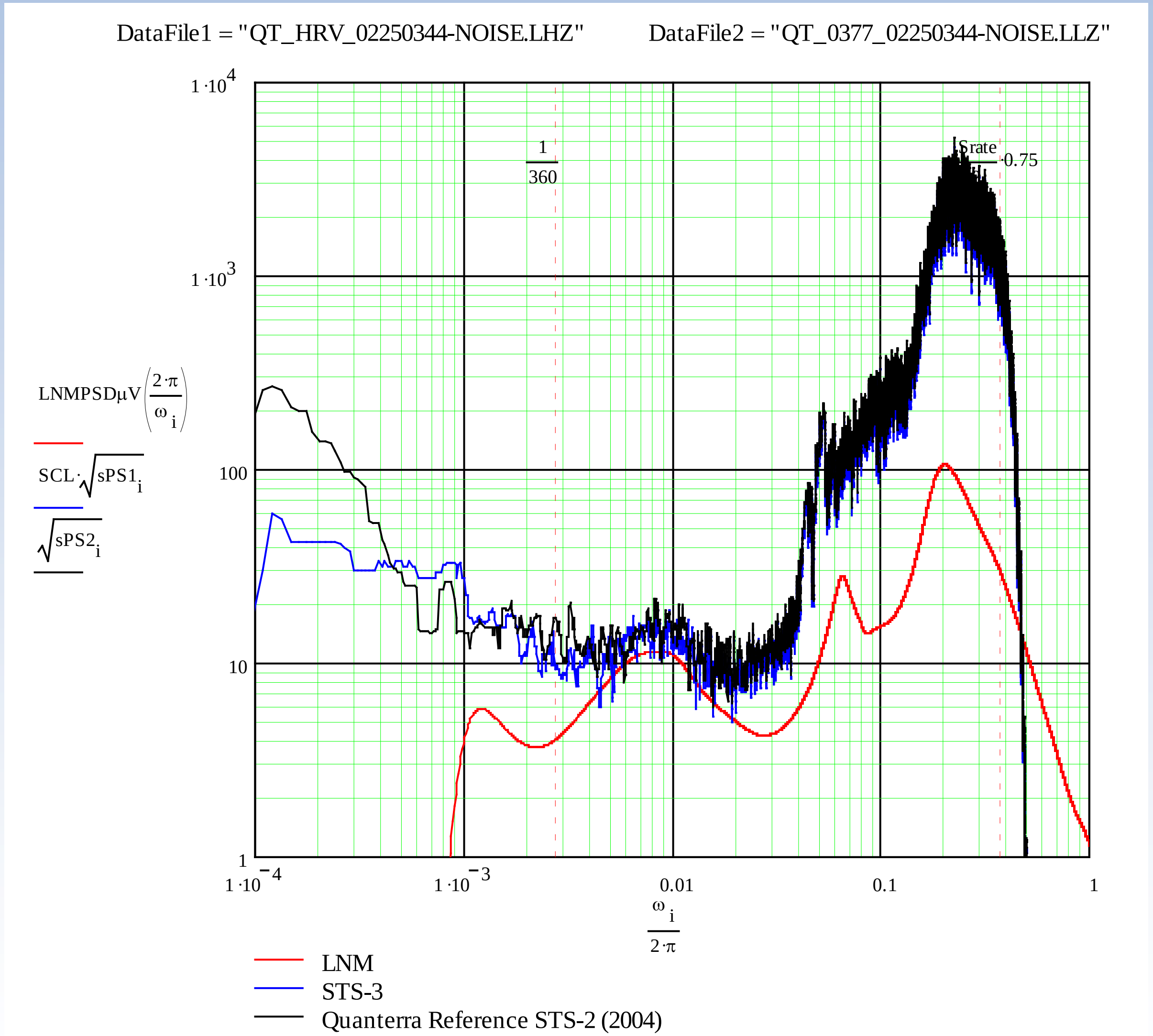
KMI: XYZ-1





DataFile1 = "QT_HRV_02250344-NOISE.LLZ"
DataFile2 = "QT_0377_02250344-NOISE.LLZ"
1·10^4
1·10^3
100
10
1
1·10^-4
1·10^-3
0.01
0.1
1
ω i
1/360
Srate·0.75
LNMPSDμV(2·π/ω i)
SCL·√sPS1 i
√sPS2 i
LMM
XYZ-1
Quanterra Reference STS-2 (2004)

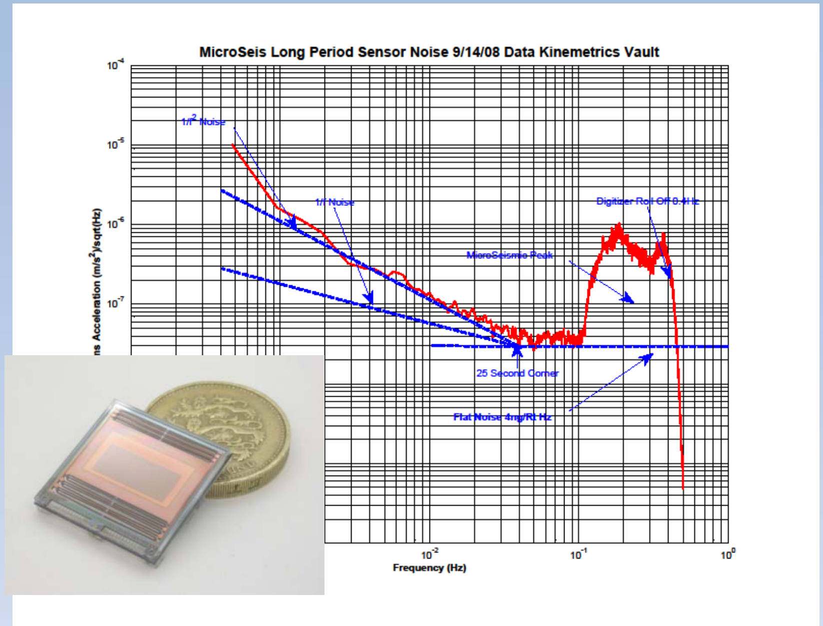
STS-3 vs. STS-2

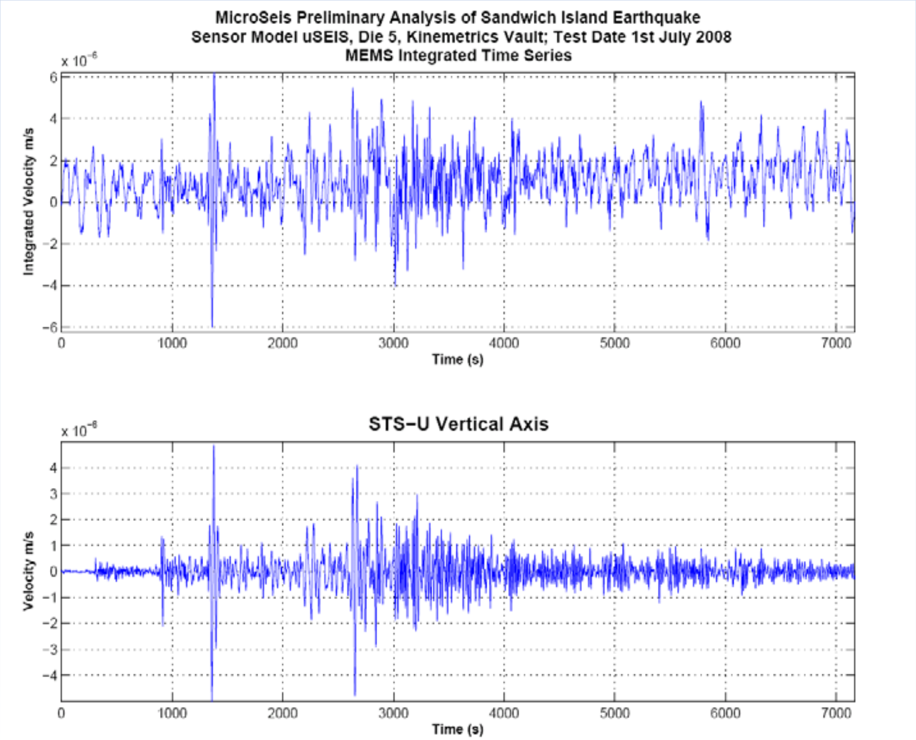


- Vert scale µV/√Hz

R&D: Silicon Sensors

- Improve the performance to a noise floor of 3 ng/√Hz within a factor of 3 of our theoretical performance and also resolved the earth tides on the device
- Imperial College have been given the go ahead for both a Mars and Lunar mission with this device.





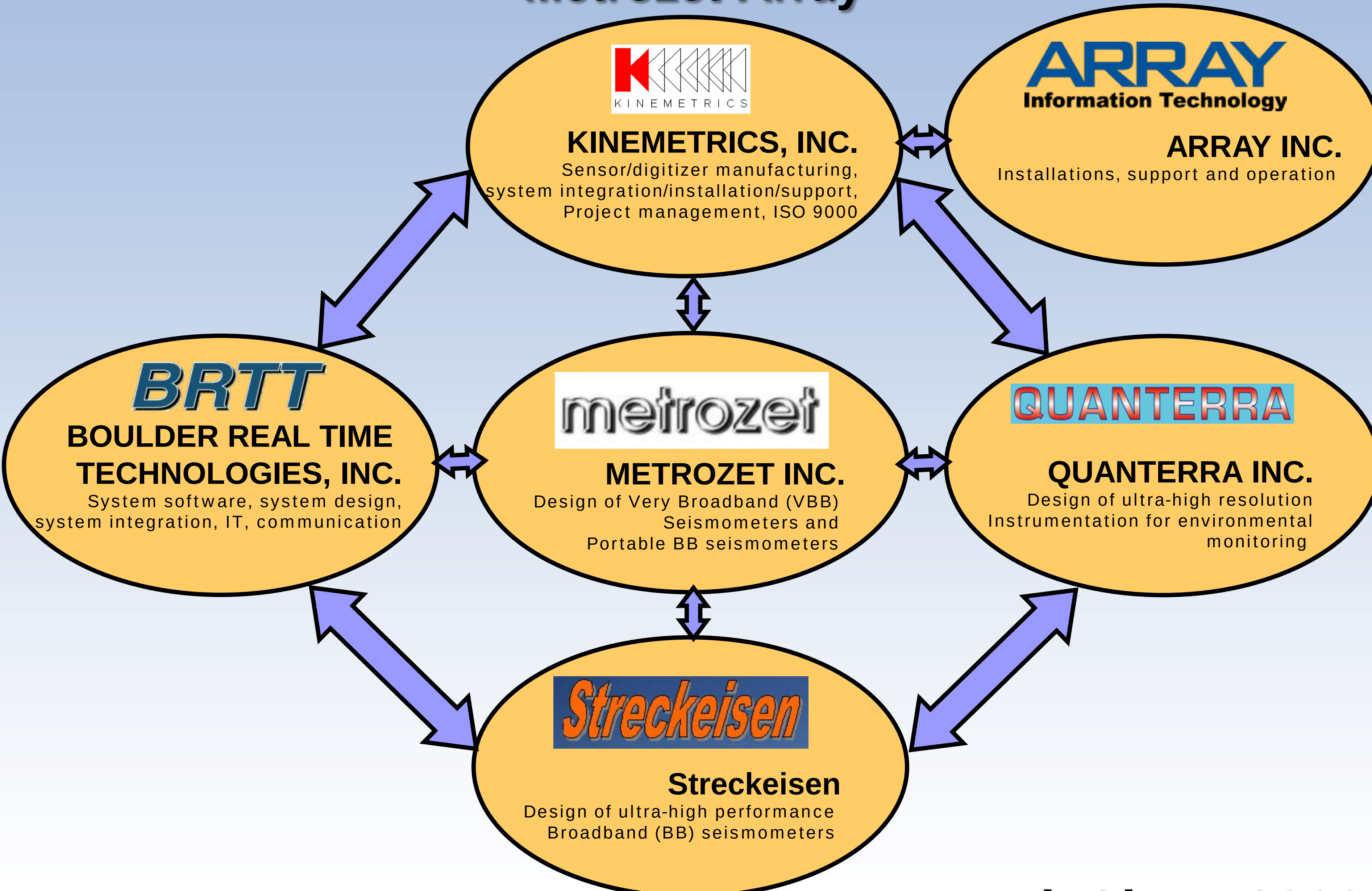
Research & Development Risks

- Prototype device yield (limited devices)
- Noise Performance (Best performance of a MEMS device)
- Spurious Resonances (Resolved per theory)
- Device Fragility (Resolved)
- Temperature Sensitivity (Initially Higher than theory already have some improvement)
- Circuit/Sensor Integration
  - Concept works (DT, Coils, Proof Mass)
  - Stability of system to shock pulse
  - Special requirements for temperature Sensitivity

Major New Developments

- Antelope System Software to support several thousand of data acquisition channels
- Antelope agnostic to variety data formats and data types
- Antelope v5.0 to support 64-bits addressing space; (i.e. 2^{64} ORB to be released this year; current v4.11 version support 32-bits)
- Continued work on web capabilities, visualization and GIS integration
- More from BRTT…

Kinemetrics-BRTT-Quanterra-Streckeisen Metrozet-Array



Team Work Since 2009

And Kinemetrics 40 years anniversary would be impossible without …

- IGPP, UC San Diego
- IRIS (GSN, PASSCAL, DMC, EarthScope – USArray)
- UNAVCO (EarthScope – PBO)
- University of Alaska, Fairbanks
- Caltech, Pasadena
- UC Berkeley
- UC Los Angeles
- UC Santa Barbara
- University of Nevada, Reno
- University of Colorado, Boulder
- Columbia University, Lamont-Doherty Earth Observatory
- USGS
- ORFEUS, Holland
- Geophone, Germany
- GeoScope IPGP, France
- ZAMG, Austria
- Geological Survey, Slovenia
- DPC, Italy
- ERI, University of Tokyo
- Malaysian TWS, Malaysia
- JAMSTEC, Japan
- KACST/KSU, Saudi Arabia
- SQU, Oman
- Kisr, Kuwait
- Dubai Municipality
- GeoScience, Canada
- GeoScience, Australia
- ….and many others……

And We Thank you for support all these years…..