WRITTEN TESTIMONY OF

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BEFORE THE UNITED STATES HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

FIELD HEARING TO REVIEW THE FEDERAL NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM (NEHRP)

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Introduction

Chairman Rohrabacher and members of the Committee, thank you for the opportunity to be here today to discuss the National Earthquake Hazards Reduction Program. My name is Frank Vernon and I am the Director of the USArray Array Network Facility at University of California San Diego's Scripps Institution of Oceanography (Scripps), where I also received a Ph.D. in Geophysics. I have many years of experience as a seismologist leading basic and applied research programs around the globe.

Most of my career has been focused on developing distributed networked real-time and autonomous sensor networks in terrestrial and marine environments. In 1982, in partnership with the USGS, we deployed the first digital telemetry network in the US along the San Jacinto Fault in southern California, known as the ANZA network. Its mission was and still is to provide high quality research data while supporting real time monitoring and now earthquake early warning requirements. As the technology base supporting ANZA evolved, it was used as the foundation of systems to provide in-country monitoring of the Soviet and US nuclear test sites (1987-1988), earthquake monitoring in Kyrgyzstan (1991-2000), multiple telemetry arrays under the Incorporated Research Institutions for Seismology (IRIS) (1991-2003), and USArray (2003-present). These programs received support from multiple federal agencies including the NSF, USGS, DOD, and DOE. Since 2010 I have been a PI on very dense seismic deployment around the San Jacinto fault zone, focusing on earthquake source physics, fault structure, and providing real-time seismic monitoring capability for southernmost California.

Based on evolving new telemetry technologies and requirements, Han-Werner Braun and I started the HPWREN program (2001-present) creating a large-scale wireless high-performance data network that is being used for interdisciplinary research and education applications, as well as a research test bed for wireless technology systems in general. Originally funded by NSF and now self-sustaining, HPWREN provides wide area wireless internet access throughout southernmost California including remote regions of San Diego, Riverside, and Imperial counties and the offshore regions primarily serving environmental sensor networks and public safety. Under UC San Diego's HPWREN program, research being conducted on building "last kilometer" wireless links and developing networking infrastructure to capture real-time data from multiple types of sensors from seismic networks, hydrological sensors, oceanographic sensors, wildfire cameras, meteorological sensors, as well as data from coastal radar and GPS.

My testimony is organized as follows: 1. NSF Funded Earthquake Research At UCSD; 2. USGS Seismic Monitoring; and 3. Closing recommendations.

NSF Funded Earthquake Research At UCSD

NEHRP

At the present time, UC San Diego has four active NSF-NEHRP Funding grants providing a total of $4.3M spanning 2016-2020. All the active NSF grants are through Division of Civil, Mechanical, and Manufacturing Innovation part of the Directorate of Engineering.

The Natural Hazards Engineering Research Infrastructure (NHERI) is supported by the National Science Foundation (NSF) creating a distributed, multi-user national facility that provides the natural hazards research community with access to research infrastructure that includes earthquake and wind engineering experimental facilities, cyberinfrastructure, computational modeling and simulation tools, and research data, as well as education and community outreach activities. This includes the *Experimental Facility with Large, High Performance, Outdoor Shake Table* (LHPOST), operated by the UC San Diego Jacobs School of Engineering, to support research in structural and geotechnical earthquake engineering (Prof. Joel Conte, Principal Investigator).

LHPOST is used for research in large structures by many different universities. Two of these NSF funded research projects are led by faculty at the UC San Diego Jacobs School of Engineering. One of these projects, *Collaborative Research: Seismic Resiliency of Repetitively Framed Mid-Rise Cold-Formed Steel Buildings* (Prof. Tara Hutchinson, Principal Investigator), is investigating the response of cold-formed steel building systems under earthquake loads. Cold-formed steel buildings potentially will have low installation and maintenance costs with high durability. The second project, *Collapse Simulation of Shear-Dominated Reinforced Masonry Wall Systems* (Prof. P. Benson Shing, Principal Investigator), will obtain experimental data to understand the behavior of Reinforced Masonry wall structures up to the point of collapse, and then will use the data to advance and validate analytical modeling capabilities.

Between 1990 and 2016, UC San Diego has completed 35 NSF-NEHRP funding grants with a combined total of $15.3M. The completed NSF grants were through either Division of Civil, Mechanical, and Manufacturing Innovation under the Directorate of Engineering, or from the Division of Earth Sciences component of the Directorate of Geosciences.

Division of Earth Sciences

There are many projects that research earthquakes and earthquake faults that are not directly part of the NEHRP program. However, the research results are used to inform NEHERP from ground motion estimation, seismic hazard, earthquake fault structures, and earthquake source physics. One of these projects that I was a Principal Investigator on was the *NSF/CD: Collaborative Research: Structural Architecture and Evolutionary Plate-Boundary Processes along the San Jacinto Fault Zone*, a collaborative project led by USC (Y. Ben-Zion), with UCSD (myself and Y.

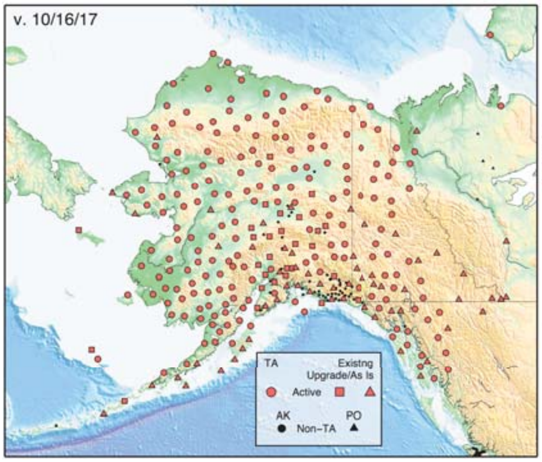
Fialko), SDSU (T. Rockwell), Georgia Tech (Z. Peng), and UNAVCO (D. Mencin). The goal of this large multi-institutional project was to examine the dynamics associated with earthquake rupture. The studies carried out are providing much more comprehensive constraints on the way that a major fault zone behaves. Specifically, the project combines detailed imaging of the San Jacinto Fault (SJF) in Southern California using multiple seismic arrays to characterize the fault zone in the subsurface. It couples this with surface outcrop and mapping of the fault zone, paleoseismic analysis, GPS analysis of crustal deformation, and theoretical work on seismic propagation to understand how factors such as fault damage, juxtaposition of different rock types, and segmentation affect the behavior of the fault zone. The long-term goal of this type of research is to bring together current ideas about the rupture process and outline an approach that may be able to provide a quantitative understanding of the evolution of fault zone structures and related deformation phenomena (seismicity, strain fields) in actively deforming regions.

In the late Spring of 2014, as part of the San Jacinto project, we had the opportunity to deploy the first complete academic “Large N” experiment to observe the unaliased two dimensional seismic wavefield. This experiment deployed 1108 high frequency instruments in an area 600 meters by 600 meters, spanning the surface trace of San Jacinto Fault at Sage Brush Flats. This is a new methodology being introduced into earthquake seismology, which is enabled by the technological advancement of petroleum industry instrumentation. Researchers at Caltech, were the first to analyze earthquake and ambient noise data from an oil industry survey in Long Beach. Our experiment was the first of this type where the target was the structure of a tectonic fault (instead of an oil field). This was the beginning of a rapidly developing integration of emerging geophysical industry techniques with advances of continuous earthquake monitoring to address earthquake research questions.

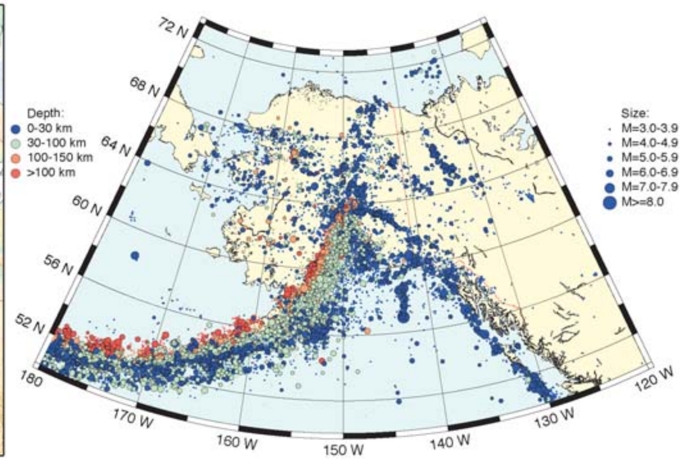
EarthScope/USArray

The USArray project is the seismological component of the NSF EarthScope program. The core of the USArray project is known as the Transportable Array (TA) comprised of ~500 broadband seismic stations deployed in a nominal 70 km grid bounded by the borders of the lower 48 states. Each station was deployed ~2 years and the TA was moved in a rolling manner to the east. EarthScope was started in 2003 as a MREFC and transitioned to operations and maintenance in 2008. Under my direction, Scripps operates the USArray Array Network Facility and is responsible for: the data acquisition and delivery from all Transportable Array stations (~500 at full deployment) to the national archive at the IRIS Data Management Center; station command and control; verification and distribution of metadata; providing useful interfaces for personnel at the Array Operations Facility to access state of health information; and quality control for all data. Data are acquired over multiple types of communication links including wireless, satellite, and wired networks. Many researchers and students domestically and internationally have written hundreds of refereed journal articles and hundreds of Ph.D. theses based on TA data.

After the TA completed work in the Lower 48 in 2015, the project was divided into two parts. Under NSF funding, funding was secured to deploy approximately 280 TA stations in Alaska until 2019. All stations are now in the ground, including 72 cooperating stations from existing networks operated largely by the Alaska Earthquake Center but also including stations operated by Alaska Volcano Observatory, National Tsunami Warning Center, and Canadian Hazard Information Service. The array is a grid of stations spaced about 85 km apart covering all of mainland Alaska and parts of the Yukon, British Columbia, and the Northwest Territories (Figure 1). The focus of the Alaska deployment is to use local, regional, and teleseismic earthquakes to improve our understanding of Earth structure and earthquake activity in Alaska.

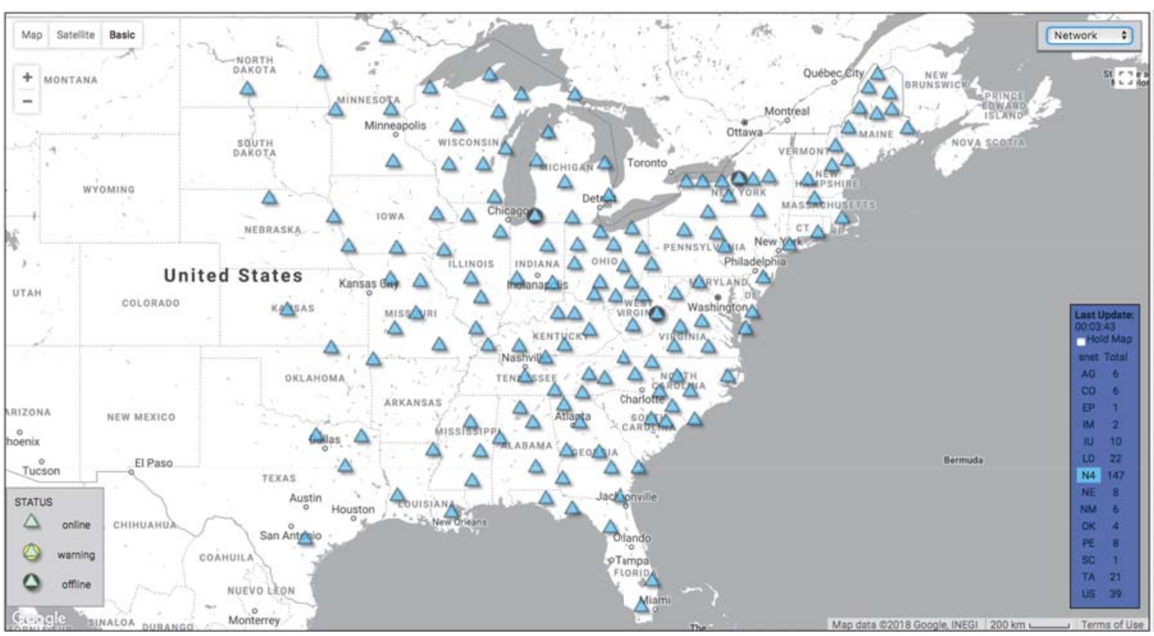


Currently locations of the USArray Transportable Array including contributed stations from other networks. Figure curtesy of Robert



Seismicity from 1970-2012 and vicinity from the Alaska Earthquake Center and the USGS PDE catalogs. Figure curtesy of Natasha Rupert (AEC)

Approximately 160 deployed stations of the TA were transitioned into the Central and Eastern US Network (CEUSN) starting in 2014. CEUSN data streams have been integrated into the Advanced National Seismic System (ANSS) and the operations are now being transitioned to USGS internal operations.



Map of the former TA/CEUSN seismic stations currently transitioning to the Advanced National Seismic System.

The transition of TA stations into permanent CEUSN/ANSS seismic stations is a positive outcome leveraging the permitting, siting, construction, installation, and field equipment under the TA and providing much needed enhanced coverage throughout the eastern US. In my opinion, it was a missed opportunity when the USArray TA was being proposed, that the USGS and NSF did not come up with a plan and budget to transition all TA sites into ANSS permanent stations. If this had occurred, the lower 48 states would have ~1600 stations providing coverage on a nominal 70 km grid recording all earthquakes in that region with magnitude 1.5 and above. With the current TA deployment in Alaska, there is still the opportunity to decide to transition the TA stations into the permanent Alaska Seismic Network, a key component of the ANSS.

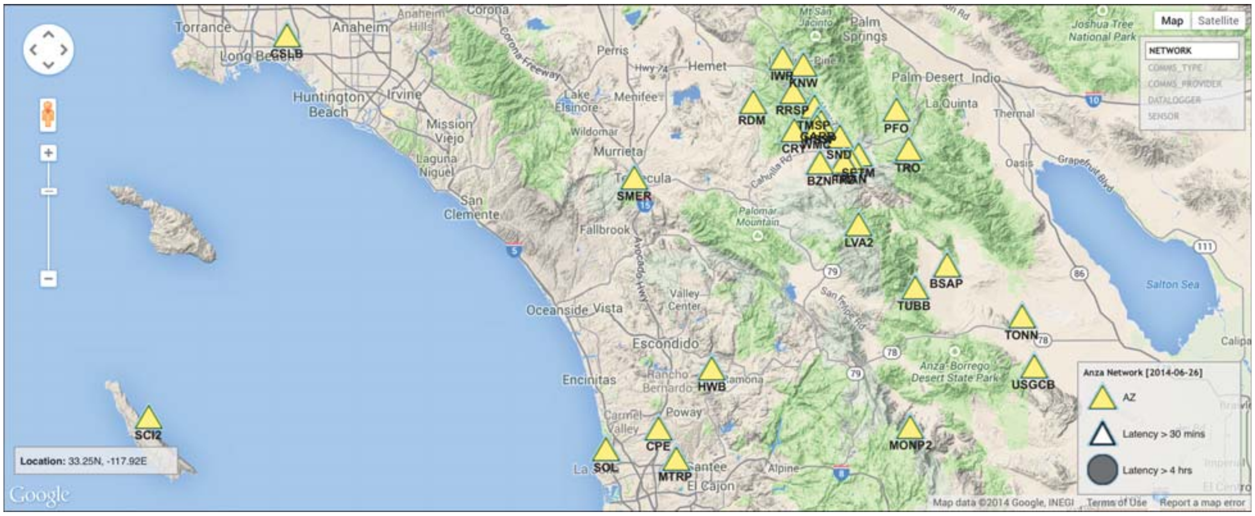
Another offshoot of the USArray TA was funded through the American Recovery and Reinvestment Act leveraging the existing permitting, field program, and telemetry to augment sites with infrasound and meteorological sensors. The NSF project, *MRI-R2: Acquisition of a Semi-Continental Scale Atmospheric Acoustic Transportable Array* (PIs: F. Vernon, M. Hedlin) created a real-time infrasound array whose sensing elements are co-located with the 400 seismic stations in the USArray Transportable Array component of the NSF EarthScope program. This continuously sampled array, of an unprecedented scale, provides opportunities for groundbreaking and interdisciplinary research in atmospheric acoustics, atmospheric science, and seismology. The dense network of infrasound sensors allows us to study the nature of long-range infrasound propagation from regional to continental distances and study the sources of infrasound signals. Over the past few years we also have been able to augment the TA with meteorological sensors from a variety of funding sources. Now, essentially all TA stations in Alaska are providing near real time data meteorological data in addition to the core seismic mission. These stations are predominantly in extremely remote areas that had no prior coverage. These data are made available to the National Weather Service for incorporation into forecast models.

USGS/ANSS Seismic Monitoring

ANZA Seismic Network

In 1982 I started my Ph.D. research project, building the ANZA seismic network to study earthquakes along the San Jacinto fault in southern California. The ANZA seismic network originally was a joint USGS-UCSD project and was the first earthquake digital telemetry network. The ANZA network is still operational today having kept pace with evolving technology to monitor local and regional seismicity in southern California. The network provides real-time data to the ANSS, the California Integrated Seismic Network (CISN), and the greater San Diego community. The ANZA seismic network was funded by the USGS since its initiation in 1982 until 2014 through NEHRP. Since 2014 the ANZA network has survived on private funds and internal UCSD funds. The ANZA seismic network continues to freely provide real time data to CISN and ANSS, as an external network to both organizations. More than 20 Ph.D. theses and 100+ refereed journal articles have been based on ANZA data.

The ANZA seismic network currently consists of twenty-eight operational stations. Most of the stations are located along the San Jacinto fault starting with IWR and RDM towards the top of the map, and TONN and USGCB on the right side of the map. The San Jacinto fault is one of the two most dangerous faults in southern California, the other being the San Andreas Fault.



Map of the ANZA Seismic Network stations.

Advanced National Seismic System

According to the USGS Circular 1429 *Advanced National Seismic System Current Status, Development Opportunities, and Priorities for 2017–2027*, the ANSS is a collaboration of federal, state, and academic partners. The role of the ANSS includes immediate earthquake notifications to governments and emergency managers, determining earthquake source characteristics, and providing ANSS websites with real-time earthquake information, a suite of real-time situational awareness products, a catalog of information (the ANSS Comprehensive Catalog), and products for engineers served by the Center for Engineering Strong Motion Data. Currently there are approximately 3000 ANSS stations operated by eleven regional seismic networks and the USGS. Total funding for the ANSS from the USGS Earthquake Hazards Program in fiscal year (FY) 2016 was $30.8 million, including $8.2 million for the implementation of earthquake early warning on the west coast.

One ongoing issue is the balance of research and operations under the USGS Earthquake Hazards Program. The *Scientific Earthquake Studies Advisory Committee Report 2017-2018* states that

> "SESAC reaffirms its principle that monitoring should not consume more than 50% of the EHP budget. The momentum of ShakeAlert (EEW) presents a challenge now and will present an even greater challenge in the future. Earthquake early warning resonates with the public and Congress. It exists as a product of the modernization of the ANSS plus regional networks. It will require more resources as EEW continues to expand. Implementation for a similar system elsewhere in the US would be impossible to meet with current funding levels. It is easy to forget/ignore that products like EEW are founded on solid, basic science into the nature of earthquakes. This fundamental understanding of earthquake science comes from highly-trained people dedicated to their work, not from instruments and technology. There is a diverse body of research (seismology, geology, geodesy, laboratory) that must be integrated to understand the nature of earthquakes and quantify the available data in order to deliver successful products. The success of the EHP

> has been its ability to merge monitoring and research. As earthquake monitoring grows, earthquake hazard assessment and earthquake research must grow in equal measure."

At present the ANSS is about 40% of its original design goals. Current funding levels are sufficient to maintain current operations but are insufficient for addressing the future needs of earthquake early warning, as well as the future needs monitoring of urban areas, critical facilities, and structures. A significant increase in funding to the NEHRP funding will be needed to achieve the goals of the ANSS with earthquake early warning capabilities and to sustain the research needed to reach these goals.

Closing recommendations

Overall the NEHRP program has been extremely beneficial towards our understanding of earthquakes and their related hazards. The strengths of the program are the partnerships between academic organizations, state agencies, and federal NEHRP agencies.

Based on my experience of deploying and operating seismic networks and field experiments under NSF and USGS funding, as well as conducting research on these data, I would like to make the following recommendations for NEHRP.

1. Keeping a well-funded basic and applied research NSF programs in earthquake engineering, the properties of earthquake sources, and ground motion estimation will be key for making advances in understanding earthquake hazards and earthquake risks.
2. Keep a sustainable Advanced National Seismic System including continuing support for the existing eleven regional seismic network operators.
3. Support research at ANSS partner facilities that improves their ability to deliver accurate earthquake assessments and products;
4. Permitting **–** Set up a streamlined expedited process for deploying earthquake monitoring sites across federal agencies. Permitting is extremely expensive and time consuming and significant cost savings could be achieved by simplifying and shortening the process. Language similar to Senate Bill 1768 is needed
    a. *''(V) Coordinating with the Secretary of Agriculture and the Secretary of the Interior on the use of public lands for earthquake monitoring and research stations, and related data collection."*
5. Shared resources between agencies should be encouraged. For example, if a seismic site is permitted and has telemetry, why not leverage this investment by adding other sensors such as meteorological sensors that can be used by the National Weather Service.
6. Integrate Alaska TA into Alaska Earthquake Center Operations and hence into the ANSS.
7. Keep equal amounts of resources for monitoring and research in the Earthquake Hazard Program budget as Scientific Earthquake Studies Advisory Committee recommends.

In closing, I would like to thank the Committee for the opportunity to testify on the review of the federal National Earthquake Hazards Reduction Program.

Short Bio for Frank Vernon

Dr. Vernon is a Research Geophysicist at the Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California at San Diego (http://scrippsscholars.ucsd.edu/flvernon). His current research interests are focused on developing distributed networked real-time sensor networks in terrestrial and marine environments. Currently he is the Director for the USArray Array Network Facility for the NSF EarthScope program (http://anf.ucsd.edu). This network currently has over 500 stations using seismic, acoustic, and atmospheric pressure sensors delivering real-time data to UCSD, which are redistributed to multiple sites. The ANF is responsible for real-time state-of-health monitoring for the network in addition to the real time data processing, archiving, and distribution. Data are acquired over multiple types of communication links including wireless, satellite, and wired networks.

Dr. Vernon is the PI on the ANZA broadband and strong motion seismic network that has operated since 1982 providing real-time seismic monitoring capability for southernmost California (http://eqinfo.ucsd.edu). Dr. Vernon is a PI on very dense seismic deployment around the San Jacinto fault zone, focusing on earthquake source physics, fault structure, and providing real-time seismic monitoring capability for southernmost California. In addition Dr. Vernon is PI on the HPWREN program creating a large-scale wireless high-performance data network that is being used for interdisciplinary research and education applications, as well as a research test bed for wireless technology systems in general (http://hpwren.ucsd.edu). HPWREN provides wide area wireless internet access throughout southernmost California including San Diego, Riverside, and Riverside counties and the offshore regions. Under UCSD's HPWREN program, research being conducted on building "last kilometer" wireless links and developing networking infrastructure to capture real-time data from multiple types of sensors from seismic networks, hydrological sensors, oceanographic sensors, wildfire cameras, meteorological sensors, as well as data from coastal radar and GPS.

Dr. Vernon obtained a B.A. in Physics with Specialization in Earth Sciences from UCSD in 1977, and a Ph.D. in Earth Sciences from UCSD in 1989. He is author or co-author on more than 130 scientific articles and is currently editor for the AGU Earth and Space Sciences Journal.