

CECIL  
AND  
IDA GREEN  
INSTITUTE  
OF  
GEOPHYSICS  
AND  
PLANETARY  
PHYSICS

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## MARINE CONTROLLED SOURCE EM

Captain Nick blessing SUESI during  
deployment at Orca Basin.



# IGPP 2017

## DIRECTOR'S WELCOME

Here is the 2017 Annual Report of the Cecil and Ida Green Institute of Geophysics and Planetary Physics, in which we provide descriptions of our research activities carried out during the past year. This report, as well as its predecessors dating back to 2006, is designed to give prospective graduate students, and anyone else who is interested in geophysics, an overview of our research, which spans a broad range of subjects in geophysics, oceanography, geology, and, indeed, planetary science.

Much of our work could be described as pure science, but the subject matter is often of broad societal interest, such as understanding earthquake mechanisms and cycles, studying the behavior of ice sheets, improving methods for energy exploration (both renewable and conventional), monitoring carbon dioxide sequestration, the effects of drought on California groundwater, the effects of atmospheric water on storm systems, modeling Earth's magnetic field, and so on. A lot of what we do involves long-term monitoring of the sea, land, and atmosphere by operating and using a variety of instrument networks as well as shipboard systems. IGPP has a strong history of instrument development, but also the development of theoretical and numerical methods. We hope you find this report useful and agree that IGPP continues to be one of the leading research centers for geophysics.

Steven Constable, Director, IGPP

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# RESEARCHERS

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Laurence Armi, Professor\*  
Jeff Babcock, Academic Administrator\*  
George Backus, Professor Emeritus\*
- 9. Jon Berger, RTAD Research Scientist
- 11. Donna Blackman, Research Scientist
- 13. Yehuda Bock, Distinguished Research Scientist
- 15. Adrian Borsa, Assistant Professor  
Catherine Constable, Professor\*
- 17. Steven Constable, Professor
- 19. J. Peter Davis, Specialist
- 20. Catherine Degroot-Hedlin, Research Scientist
- 22. Matthew Dzieciuch, Project Scientist  
Peng Fang, RTAD Specialist\*
- 24. Yuri Fialko, Professor
- 26. Helen Amanda Fricker, Professor  
Jennifer Haase, Associate Research Scientist\*  
Alistair Harding, Research Scientist\*
- 28. Michael Hedlin, Research Scientist  
Glenn Ierley, Professor Emeritus\*
- 30. Deborah Lyman Kilb, Project Scientist
- 32. Gabi Laske, Professor-in-Residence
- 34. Guy Masters, Distinguished Professor
- 36. Bernard Minster, Distinguished Professor
- 38. Walter Munk, RTAD Professor
- 40. John Orcutt, Distinguished Professor  
Robert L. Parker, Professor Emeritus\*
- 41. Anne Pommier, Assistant Professor
- 43. David Sandwell, Distinguished Professor
- 44. Peter Shearer, Distinguished Professor
- 46. Len Srnka, Professor of Practice  
Hubert Staudigel, RTAD Research Scientist\*  
David Stegman, Associate Professor\*
- 47. Frank Vernon, Research Scientist
- 49. Peter Worcester, RTAD Research Scientist
- 50. Mark Zumberge, Research Scientist

\* no annual report available

RTAD = retired with active research program



# GREEN FOUNDATION

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The Cecil H. and Ida M. Green Foundation for Earth Sciences supports visiting scholars and resident scientists at IGPP. Established with a gift from the late Cecil Green in 1971, the Green Foundation holds an endowment managed by the UCSD-IGPP Director and overseen by an independent Board of Directors. A selection committee comprised of IGPP faculty screens nominees and applicants for both the Green Scholar and the Miles Fellowship.

## The Green Foundation is currently supporting:

Green Scholar: John Delany, University of Washington

Green Scholar: James Badro, IPGP, France

Green Scholar: Peter Wadhams, Cambridge, UK

Green Scholar: Shawn (Songqiao) Wei, postdoc

Green Scholar: Junle Jiang, postdoc

Miles Fellow: Adina Püsok, postdoc

UCSD membership in Southern California Earthquake Center [www.scec.org](http://www.scec.org)

Calibration of Differential Pressure Gauge: John Orcutt, Glenn Sasagawa, Mark Zumberge

San Diego Trough Seismicity: Gabi Laske

SIGMELTS Electrical Properties Code Development: Anne Pommier



# GRADUATE PROGRAM

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## More than the Oceans...

Our multidisciplinary program offers graduate students a unique hands-on, collaborative learning environment. In addition to our core academic curriculum, we emphasize observational techniques and the collection of novel datasets. IGPP students participate extensively in field experiments, instrument development, laboratory investigations, and shipboard expeditions. Our graduates go on to careers in research, education, industry, and public policy. Scripps has strong working relationships with the National Science Foundation, NASA, NOAA, the US Geological Survey, and the Office of Naval Research, and can provide graduates with long-term networking and professional support.

## Graduate Students who successfully defended in 2017

**Maggie Avery** (*Cathy Constable*): *Long-term geomagnetic variations: Linking paleomagnetic observations, statistical analyses, and numerical geodynamo simulations*

**Wenyuan Fan** (*Peter Shearer*): *Kinematic earthquake source imaging: theory and applications*

**Bill Savran** (*Joint Doctoral Program*): *Developing Stochastic Models as Inputs for High-Frequency Ground Motion Simulations*

**Daniel Trugman** (*Peter Shearer*): *Deviant Earthquakes: Data-driven Constraints on the Variability in Earthquake Source Properties and Seismic Hazard*

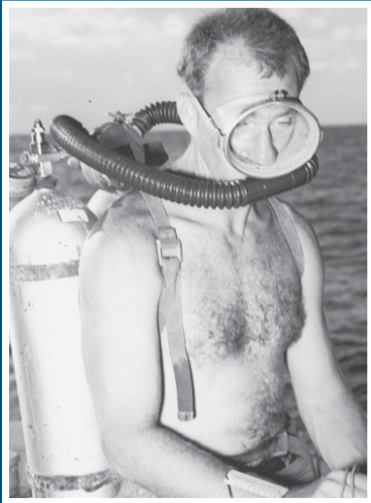
**Kang Wang** (*Yuri Fialko*): *Observations and modeling of crustal deformation due to recent large earthquakes around the Tibetan Plateau*

**Xiaohua Xu** (*David Sandwell*): *Earthquake cycle study with geodetic tools*

**Qian Yao** (*Joint Doctoral Program*): *Dynamic Modeling of Earthquake Sources on Rough Faults*

**Yuxiang Zhang** (*Kerry Key*): *MARE3DEM: A Three-dimensional CSEM Inversion Based on A Parallel Adaptive Finite Element Method Using Unstructured Meshes*

# Celebrating Wa

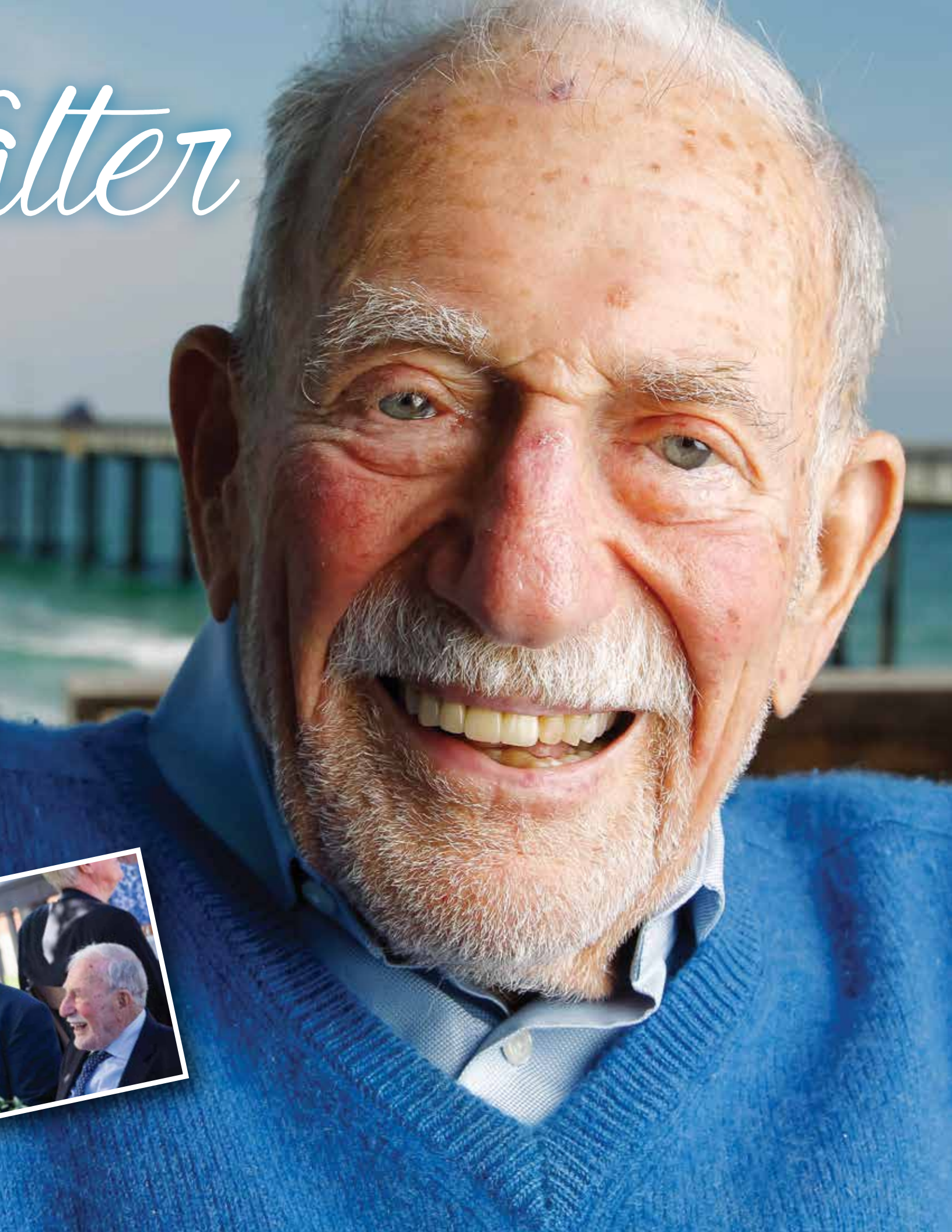


Walter H. Munk, Professor Emeritus—and founding director—of Geophysics at IGPP, turned 100 on 19 October 2017. Scripps Institution of Oceanography and UC San Diego celebrated Walter's lifetime of achievements with events that allowed the whole community—scientific and San Diegan—to celebrate the "Einstein of the Ocean's" centennial thoroughly and memorably.

Scripps started the celebrations with a series of symposia: "Internal Waves, Turbulence, and the Overturning Circulation of the Ocean" May and "Ocean Acoustics, National Security, and Walter Munk" in August. Walter's birthday month events kicked off October 7 with the San Diego International Film Festival screening of "Spirit of Discovery," a documentary exploring Walter Munk's career. On October 18 San Diego City Councilmember Barbara Bry, State Assemblymember Todd Gloria, California State Senator Toni Atkins, UC San Diego, and the public came together to officially name the La Jolla Shores boardwalk Walter Munk Way. To conclude weeks of celebrations and cake, on October 26, UC San Diego welcomed Prince Albert II of Monaco to campus for a Centennial Conversation with Walter Munk at the Robert Paine Scripps Forum—where the two discussed ocean exploration and the importance of oceanographic research.



After



# DUNCAN CARR AGNEW

Professor

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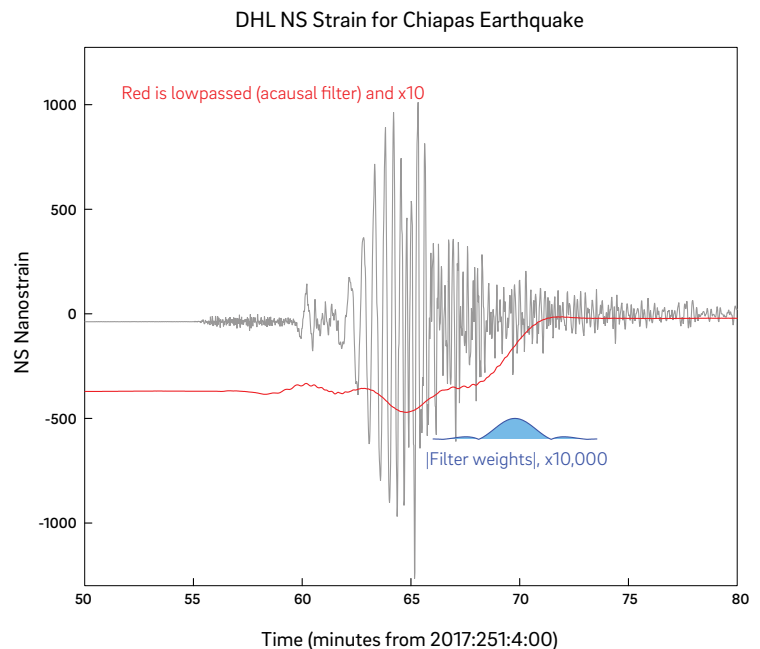
# FRANK K. WYATT

Principle Development Engineer, RTAD

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*Research Interests: Crustal deformation measurement and interpretation, Earth tides, Southern California seismicity.*

We have long used long-base laser strainmeters to collect continuous deformation data at locations close to the two most active faults in Southern California. Pinyon Flat Observatory (PFO, operating since 1974) is 14 km from the Anza section of the San Jacinto fault (2-3 m accumulated slip since the last large earthquake) and Salton City (SCS, since 2006) within 15 km of the same fault further SE. Two other sites (Cholame, or CHL, since 2008, and Durmid Hill, or DHL, since 1994) are within three km of the San Andreas fault: CHL, at the N end of the segment that ruptured in 1857, and DHL at the S end of the Coachella segment (4-6 m accumulated slip). Surface-mounted laser strainmeters (LSM's), 400 to 700 m long and anchored 25 m deep, provide long-term high-quality measurements of strain unmatched anywhere else: though in geological settings ranging from weathered granite to clay sediments, the LSM's record secular strain accumulation consistent with continuous GPS, something not otherwise possible. The LSM's record signals from 1 Hz to secular; at periods less than several months, they have a noise level far below that of fault-scale GPS networks. We have recorded a seismic transients at CHL, DHL, and PFO. A recent interesting result was the detection at DHL of strain related to fault creep triggered by a distant teleseism: the Chiapas earthquake of September 7, 2017, a shallow (50 km) thrust event, magnitude 8.1, 3000 km away. Figure 1 shows the strain observed, which is notable in beginning after the peak dynamic strains. This may indicate that it was triggered on the San Andreas fault to the NW of the strainmeters (where it was recorded on creep meters operated by Prof. Roger Bilham of the University of Colorado, though at low time resolution), subsequently propagating to the SE to create the delayed signal on the strainmeters. Another research project was observing the resonance associated with the ellipticity of the core-mantle boundary in the harmonic constants for the ocean tides. This is usually measured with observations of either the Earth's nutations using ultra precise measurements with radio telescopes. But, improbably, it can also be seen in a dataset collected with float gauges and tide poles, and processed by human computers. The resonance changes the ratio of the amplitude of two constituents of the ocean tide, to 96% of what it would otherwise be. We examined the compilation of ocean-tide harmonic constants prepared by the International Hydrographic Bureau between 1930 and 1980, which includes data back to 1848 and analyses back to the 1870's. These data, though showing considerable scatter in this ratio, also clearly show the expected decrease—this effect could have been observed long before it actually was.



*Figure 1: Raw and low passed data from the DHL strainmeter, showing the seismic signal from the Chiapas earthquake. An acausal filter was used, but the weights do not extend far enough to significantly distort the time at which the strain signal starts.*



## RECENT PUBLICATIONS

- Gomberg, J., A. Wech, K. Creager, K. Obara, and D. Agnew (2016). Reconsidering earthquake scaling, *Geophys. Res. Lett.* 43, 6243-6251, <http://dx.doi.org/10.1002/2016GL069967>
- Agnew, D. C. (2017). An improbable observation of the diurnal core resonance, *Pure and Applied Geophysics*, 1-11, <http://dx.doi.org/10.1007/s00024-017-1522-1>
- Donner, S., C.-J. Lin, C. Hadziioannou, A. Gebauer, F. Vernon, D. C. Agnew, H. Igel, U. Schreiber, and J.M.Wassermann (2017). Comparing direct observation of strain, rotation, and displacement with array estimates at Pinon Flat Observatory, California, *Seismol. Res. Lett.*, 88, <http://dx.doi.org/10.1785/0220160216>

## JONATHAN BERGER

Emeritus Researcher RTAD

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*Research Interests: Global seismological observations, marine seismo-acoustics, geophysical instrumentation, deep ocean observing platforms, ocean robotics, global communications systems*

We have proposed to continue development of an ocean bottom seismic observatory whose prime purpose is to meet the requirements of the Global Seismographic Network including the capability to deliver online seafloor seismic observations from the Earth's remote oceans in near real-time. Through the use of a wave glider, a transformative technology our concept for a Remote Ocean Online Seafloor Seismic Observatory (ROOSSO) is illustrated in Figure 2.

The proposed system will

1. Provide shielding of the seismometer from seafloor turbulence,
2. Provide continuous near real-time streaming of sensor data from seafloor to land with a latency of less than a few minutes,
3. Provide enough stored energy for at least a two-year service interval.

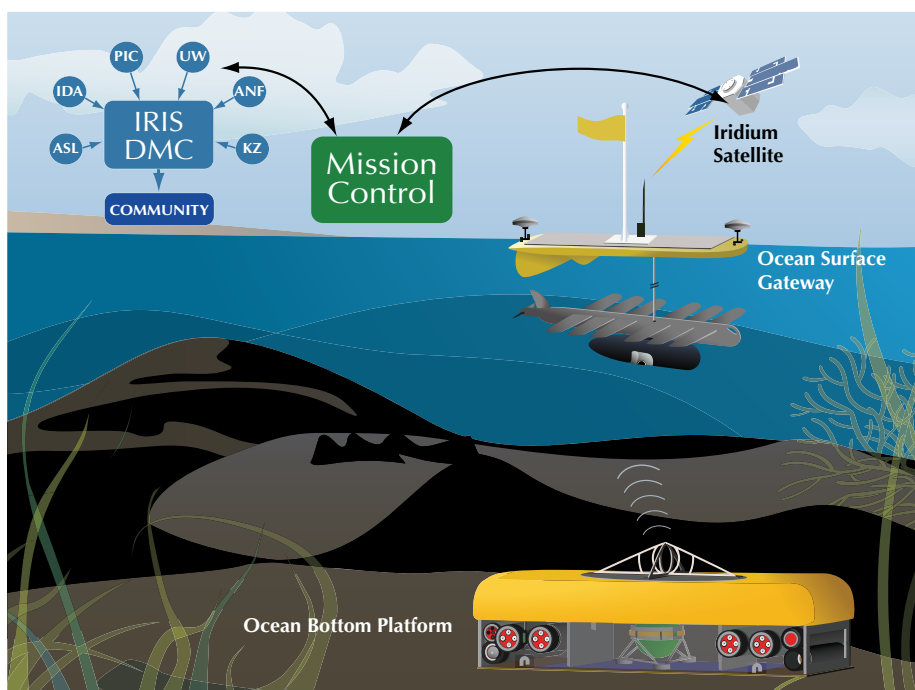


Figure 2. ROOSSO System Concept. The ocean bottom package sitting on the seafloor telemeters sensor data through the ocean column to a free-floating Ocean Surface Gateway (OSG) hovering above the Ocean Bottom Platform (OBP). The OSG re-transmits the data via satellite to the shore while it holds station over the OBP.

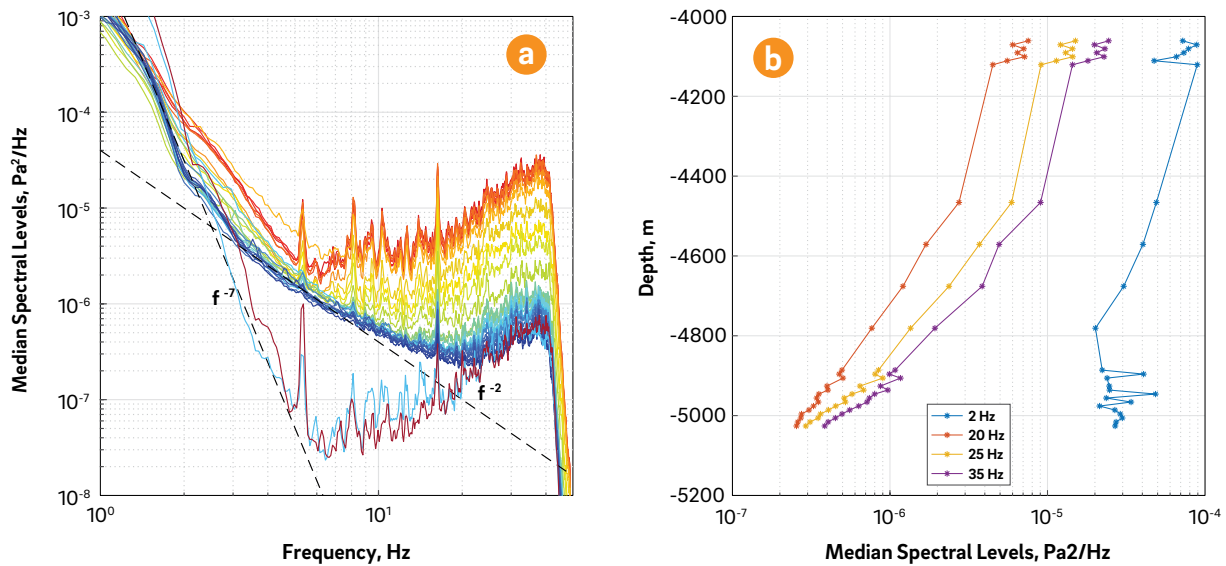


Figure 3. (a) Median spectral estimates of the 19 epochs and 27 hydrophone data sets from dark blue, 5036 m sensor, to red, 4061 m sensor, with a Nyquist of 50 Hz and a resolution of 0.1 Hz. The two lower spectra are of data from the low noise hydrophones on two near-by OBSs. The black dash lines are the functions  $0.004f^{-7}$ , and  $4 \times 10^{-5}f^{-2}$ . (b) The variation in power (averaged over 0.5 Hz) with depth for the indicated frequencies.

Meanwhile, I continued my analysis of the seismic and acoustic data collected during the OBSANP experiment in the deep ocean of the subtropical NE Pacific. The deep ocean acoustic floor (taken to be the pressure spectrum observed the few percent of the time when the overhead wind is small, ships are distant and marine life silent) has been measured across a 975 m vertical array anchored at 5048 m in the basin just north of the Murray fracture zone. From 1 to 6 Hz, the floor falls like  $f^{-7}$ , touching  $3 \times 10^{-8} \text{ Pa}^2 \text{ Hz}^{-1}$  at the upper end. From 40 to 800 Hz the floor falls like  $f^{-2}$  touching  $3 \times 10^{-9} \text{ Pa}^2 \text{ Hz}^{-1}$  at the upper end for the deepest sensor.

In the ship-dominated regime ( $f > 6 \text{ Hz}$ ) the acoustic floor rises about 15 dB up the array. As reported before, the energy is horizontally polarized. From analysis of a 150 m aperture sub-array at the sea floor, the beam width is less than the array resolution ( $8^\circ$  at 75 Hz). The beam narrows as  $f^{-1}$  for higher frequencies. Furthermore, the power in the beam appears to fall more steeply with frequency than the omnidirectional spectrum, an effect possibly attributable to scattering. Events on the marine-atmosphere boundary layer radiate sound into the ocean. Above about 6 Hz ships are an important source of this sound, and their influence must be discounted in order to study the acoustic signal in this band radiated by windsea processes. The usual approach in studying acoustic “noise” has been to designate the observed spectrum at some frequency as ship-generated or wind-generated by its level, shape and, sometimes, vertical gradient. Here we analyze data from a vertical hydrophone array fortuitously positioned for three days beneath the center of an anticyclone from which there was virtually no windsea acoustic radiation.

## RECENT PUBLICATIONS

- J. Berger, G. Laske, J. Babcock, and J. Orcutt (2016). An ocean bottom seismic observatory with near real-time telemetry. *Earth and Space Science*, 2. doi:10.1002/2015EA000137.
- J. Berger, J.R. Bidlot, M. Dzieciuch, W.E. Farrell, P.F. Worcester, and R.A. Stephen. Deep Ocean Acoustics, 1-800 Hz: Part I, The Acoustic Floor. (*JASA*, 2017 in press).

# DONNA BLACKMAN

Research Geophysicist

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*Research Interests: Mantle flow, mineral deformation, and tectonic evolution along plate boundaries using marine geophysics and numerical modeling.*

This year I continued research on mantle flow with anisotropic rheology and did some additional work on ocean crustal structure. I began serving a term as Earth Section Head for Scripps and continued as Secretary of the Green Foundation for Earth Sciences at IGPP. As NSF/OCE evolved their approach to providing access to Marine Seismic data acquisition and Ocean Bottom Seismometers, I worked with colleagues at Scripps and nationally, as ex-officio member of the Marine Seismic Research Oversight Committee, to discuss approaches that could fulfill needs while following the new approaches laid out by NSF/OCE.

To understand the feedbacks between deformation induced mineral alignment in the mantle and upper mantle flow pattern, my Cornell & CNRS colleagues and I link local viscosity solutions to a FEM calculation of regional flow. Local viscosity is determined throughout the model, based on the behavior of a mineral aggregate (a rock) with crystal preferred orientation (CPO) that develops as it deforms along a flow path from the base of the model to the given position in the simulated ocean spreading center region.

Through a series of numerical runs, we explored the rheologic effects of CPO and impacts on the pattern of flow and associated seismic signals. What was new this year is that we completed several more iterations (a few weeks runtime each) for cases where the olivine aggregates have power law stress:strain rate response. The new results confirmed our earlier conclusions, which were based on just a few iterations: anisotropic viscosity tensors associated with CPO characterize most of the model

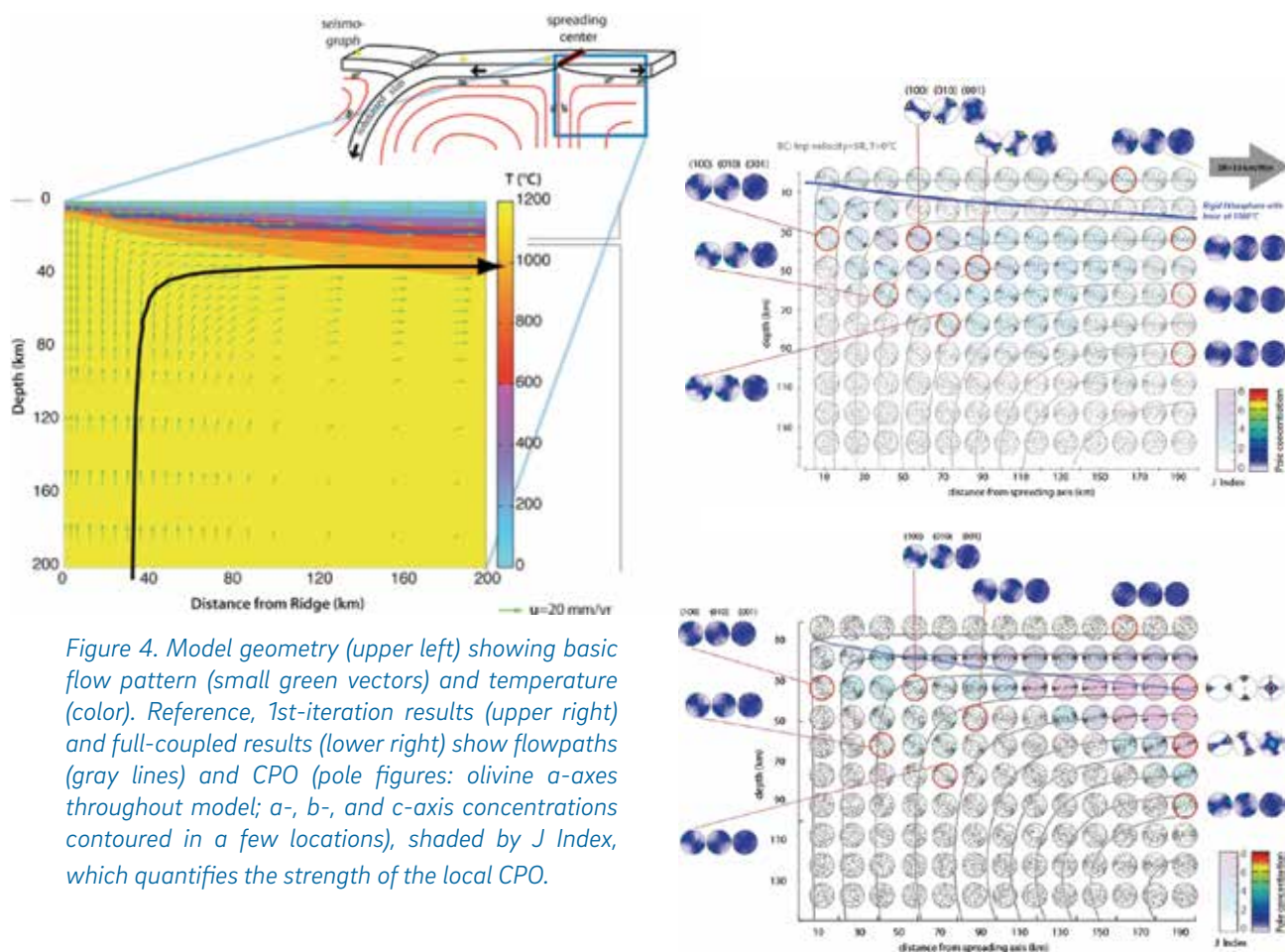


Figure 4. Model geometry (upper left) showing basic flow pattern (small green vectors) and temperature (color). Reference, 1st-iteration results (upper right) and full-coupled results (lower right) show flowpaths (gray lines) and CPO (pole figures: olivine a-axes throughout model; a-, b-, and c-axis concentrations contoured in a few locations), shaded by J Index, which quantifies the strength of the local CPO.

space and this directional dependence in strength impacts the pattern of upper mantle flow. For background asthenosphere viscosity of  $10^{20}$  Pa s and a rigid lithosphere, the modification of the corner flow pattern is modest, but the changes could affect melt production rates. Stronger fabric is predicted below the ridge flanks than had been predicted with previously-published 1st-iteration models, where effects of CPO on rheology were ignored. The predicted SKS splitting is modestly different ( $\sim 0.5$  s) for oceanic plates less than 20 Myr old. Surface waves, predicted in collaboration with Gabi Laske, have twice the magnitude of Rayleigh wave azimuthal anisotropy for fully coupled models than for 1st-iteration models.

I began work linked to a project of Jeff Gee's compiling recently-collected gravity data from Pito Deep- a tectonic window into fast-spread crust in the Pacific. The study combines the new, closely-spaced track data with prior, more typical underway survey data in the region. Part of the effort is to determine how best to process data that were collected at slow, ROV towing speeds. Initial work at sea by grad student Adrien Doran suggests that stable results should be obtainable, but additional analysis is required to determine data uncertainties for these acquisition conditions. Knowing the uncertainty level will be key for gauging how hard to push on density models as we try to improve the fit between predicted and observed data. Ultimately, the aim of the work is to better characterize the density distribution of the crust in, and immediately around, Pito Deep and to relate that to crustal formation and evolution processes.

Two new avenues developed as I was invited to join large, interdisciplinary teams to develop multi-year proposals on Planetary Ocean Worlds and Eritrea. The latter overlaps with my prior work since it would involve modeling mantle flow and melting, and almost certainly anisotropy, to try to match observations from proposed new geophysical and geologic data from the Gulf of Zula, north of Afar, where ocean spreading may just be initiating. The Ocean Worlds effort would be more of a departure from my past work, but would employ geophysical approaches I've applied previously to analyze Earth's seafloor morphology and properties to assess the likelihood of fluid flow that could be associated with biogeochemical activity. That team is specifically designed to bring together (Earth) ocean and planetary experts from geophysics through to microbiologists, somewhat reminiscent of the Ridge 2000 'mantle to microbe' goal.

## RECENT PUBLICATION

Blackman, D.K., D.E. Boyce, O. Castelnau, P. R. Dawson, and G. Laske, Effects of crystal preferred orientation on upper mantle flow near plate boundaries: Rheologic feedbacks and seismic anisotropy, *Geophysical J. Intl.* doi: 10.1093/gji/ggx251, 2017.



# YEHUDA BOCK

Distinguished Researcher and Senior Lecturer  
Director, Scripps Orbit and Permanent Array Center (SOPAC)

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*Research Interests: GPS/GNSS, space geodesy, crustal deformation, early warning systems for natural hazards, seismogeodesy, GPS meteorology, data science, sensors*

The SOPAC research group's most recent focus is on use of space geodesy, seismology, and Lidar and UAV imaging to mitigate the effects of natural hazards on people and structures through improved early warning and rapid response to events such as earthquakes, tsunamis, volcanoes and severe weather. We approach our projects in a holistic manner from the design and deployment of geodetic and other sensors, real-time data collection and analysis, physical modeling and where applicable, communicating actionable information the "last mile" to emergency responders and decision makers during disasters. We maintain a database of high-rate GNSS and accelerometer measurements (Figure 5) for historical earthquakes, using the data for studies of early postseismic deformation and other applications. We also maintain a global archive of GNSS data, metadata and data products with accompanying IT infrastructure and database management system for the International GNSS Service (IGS) and the California Spatial Reference Center (CSRC) (Figure 6). The SOPAC group currently includes Peng Fang, postdoc Emilie Klein, graduate students Dara Goldberg, Dorian Golriz and Minghua Wang, Anne Sullivan, Maria Turingan, Matt Norenberg, Allen Nance and Songnian Jiang.

## LOCAL TSUNAMI WARNING SYSTEM

Current tsunami warning systems for subduction zone earthquakes are limited to ocean basin-wide warnings. Although populations closest to the earthquake source are most vulnerable to devastation, there exists no adequate early warning system for local tsunamis, such as the 2004 Mw9.3 Sumatra-Andaman earthquake and tsunami that caused 250,000 deaths on the nearby island of Sumatra and the 2011 M9.0 Tokoku-oki, earthquake and tsunami with 12,000 casualties and severe damage to infrastructure in Sendai, Japan. The reason is that traditional tsunami warnings are dependent

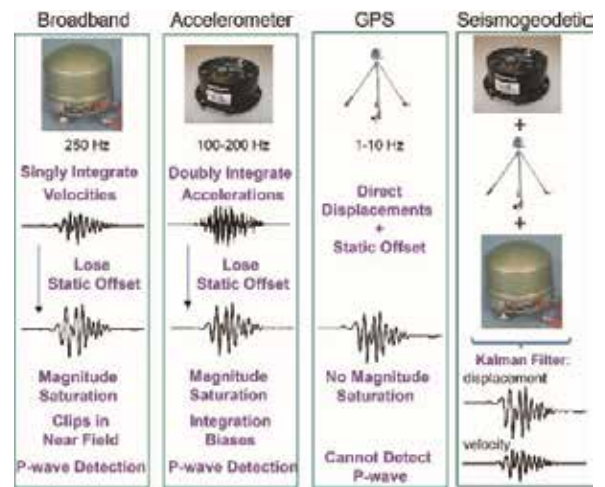


Figure 5. Advantages of seismogeodetic data for near-source monitoring, compared to GPS and seismic data alone. We are applying seismogeodesy to earthquake and local tsunami warning systems with NOAA's National and Pacific Tsunami Warning Centers, and to structural health monitoring with the Jacobs School of Engineering and Qualcomm Institute on campus.

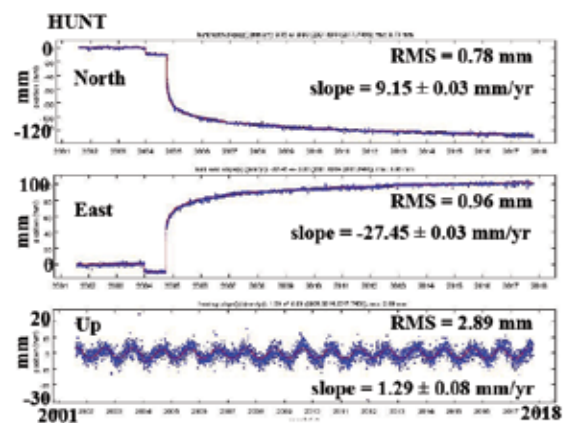


Figure 6. Sixteen-year daily GNSS displacement time series. Station HUNT is near the San Andreas fault near Parkfield. The detrended modeled displacements shows coseismic and postseismic deformation from the 2003 Mw6.5 San Simeon and 2004 Mw6.0 Parkfield earthquakes. The velocities are with respect to the global reference frame (ITRF2014).

on offshore ocean buoys and teleseismic data making it difficult to obtain rapid estimates of magnitude and fault mechanism for local events. High-rate data from local near-source GNSS networks collocated with strong motion instruments (seismogeodesy—Figure 5) can be analyzed in real time to estimate coseismic displacement waveforms (dynamic and static). This allows for the detection of P-wave arrivals, rapid earthquake magnitude through scaling relationships, and fault mechanism and slip from fast CMT and static fault slip inversions, typically within 2-3 minutes for the largest events, as input to tsunami warnings and inundation models. In the U.S., NOAA's National and Pacific Tsunami Warning Centers in Alaska and Hawaii are responsible for tsunami warning in the Pacific Basin. SOPAC under a NASA project is working with NOAA to implement a seismogeodetic-based local tsunami warning system at the two centers.

## GPS DISPLACEMENT TIME SERIES AND GEODETIC DATUMS

SOPAC estimates daily GPS displacement time series using the GAMIT/GLOBK software for global and regional networks with a focus on Western North America—the longest time series start in 1992 as part of the PPGA project a forerunner of the SCIGN and PBO projects. We model the time series for tectonic signals of interest, including interseismic, coseismic and postseismic deformation (Figure 6), and look for interesting transients such as subsidence and episodic tremor and slip (ETS). SOPAC is working with Caltrans on a new geodetic datum for California defined by the coordinates and velocities of about 900 continuous GPS stations in the state, at epoch 2017.5. The datum is the basis for precise spatial referencing according to California's public resources code (previous epoch was 2011.00). In parallel we are researching the development of a dynamic datum for the state based on interpolation of true-of-survey-date daily coordinates to take into account the effects of tectonic motions and subsidence. These data are being used to georeference InSAR imagery in the Central Valley for subsidence studies as part of an ongoing project with David Sandwell and Xiaohua Xu.

## RECENT PUBLICATIONS

- Bock, Y. and D. Melgar (2016), Physical Applications of GPS Geodesy: A Review, *Rep. Prog. Phys.* 79, 10, doi:10.1088/0034-4885/79/10/106801.
- Bock, Y., et al., (2016), Twenty-Two Years of Combined GPS Products for Geophysical Applications and a Decade of Seismogeodesy, International Association of Geodesy Symposia, Springer International Publishing, doi:10.1007/1345\_2016\_220.
- Chen, M. C., Astroza, R., Restrepo, J. I., Conte, J. P., Hutchinson, T., and Bock, Y. (2017), Predominant period and equivalent viscous damping ratio identification for a full-scale building shake table test. *Earthquake Engng. Struct. Dyn.*, 46: 2459–2477. doi: 10.1002/eqe.2913.
- Crowell, B. W., Y. Bock, Z. Liu (2016), Single station automated detection of transient deformation in GPS time series with the relative strength index: A case study of Cascadian slow-slip, *J. Geophys. Res. Solid Earth*, 121:12, 9077 -9094, doi: 10.1002/2016JB013542.
- Goldberg, D., Y. Bock (2017), Self-contained local broadband seismogeodetic early warning system: Detection and location, *J. Geophys. Res. Solid Earth*, 122,4, 3197-3220, doi:10.1002/2016JB013766.
- Melgar, D., et al., (2016), Local Tsunami Warnings: Perspectives from Recent Large Events, *Geophys. Res. Lett.*, 43, 1109–1117, doi:10.1002/2015GL067100.
- Saunders, J. K., et al., (2016), Seismogeodesy using GNSS and low-cost MEMS accelerometers: perspectives for earthquake early warning and rapid response, *Bull. Seismol. Soc. Am.*, 106, 6, 2469–2489, doi: 10.1785/0120160062.

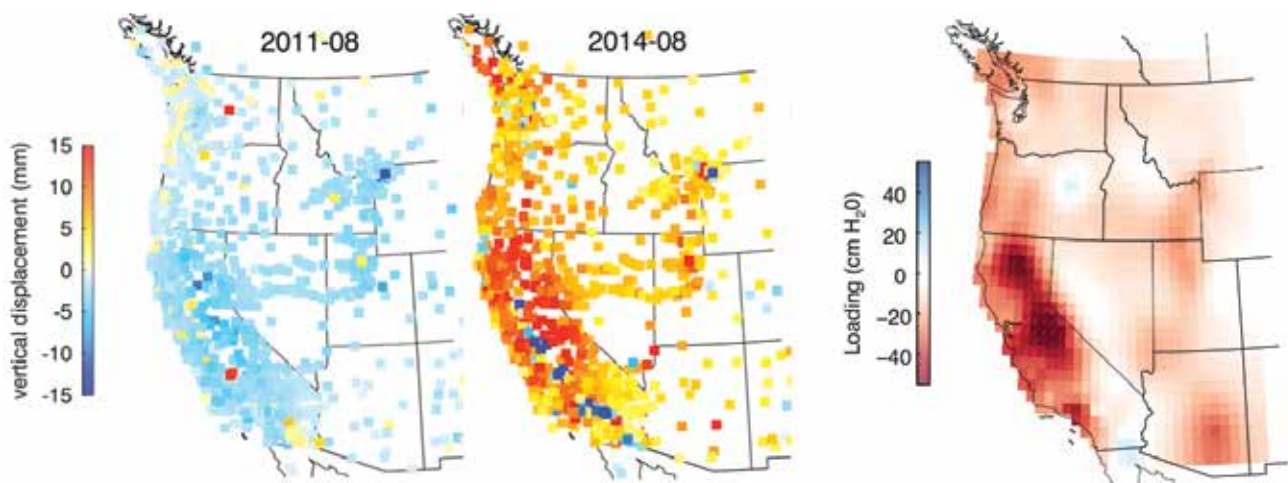
# ADRIAN BORSA

Assistant Professor

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*Research Interests: Remote hydrology from GPS and GRACE. Satellite altimeter calibration/ validation and measurements of topographic change. Differential lidar techniques applied to problems in geomorphology and tectonic geodesy. Kinematic GPS for positioning, mapping, and recording transient deformation due to earthquakes, fault creep and short-period crustal loading. GPS multipath and other noise sources. Dry lake geomorphology.*

My recent research involves the characterization of the hydrological cycle using crustal loading observations from GPS, in collaboration with SIO colleagues Duncan Agnew and Dan Cayan. Changes in water storage in lakes, aquifers, soil moisture, and vegetation results in elastic deformation of the crust that yields measurable vertical displacements of the surface. The seasonal signal from water loading has been extensively studied, but loading changes over longer periods are typically smaller and have not been broadly documented. Since 2013, however, drought in the western USA has caused rapid and widespread uplift of mountainous areas of California and the West. The vertical displacements from the drought are unprecedented in magnitude over the past decade of continuous GPS observations.



*Figure 7. Left: Spatial distribution of vertical displacements from Plate Boundary Observatory continuous GPS stations in the western USA in March of 2013 and 2014. Color indicates deviations of seasonally-adjusted elevations from decadal mean, with blues related to subsidence and yellow-reds related to uplift. Right: Mass load in mm of water equivalent derived from inversion of March 2014 vertical displacements, assuming elastic strains on a spherical Earth.*

The drought uplift signal, which exceeds 15 mm at locations in the Sierra Nevada, is large enough to be obvious by inspection of GPS time series. We apply a seasonal filter derived from the econometrics literature (the Seasonal-Trend-Loess estimator) to completely remove the annual signal due to water loading and pumping, and we invert the filtered GPS position data to recover the spatiotemporal loading required to account for observed uplift. In the case of the current drought, our estimate of the accrued water deficit ranges up to 50 cm and totals 240 gigatons, equivalent to a 10 cm uniform layer of water over the land area east of the Rocky Mountains. Currently, we are extending our analysis to look at short-term changes in loading from individual storms, and we are investigating drought-induced Coulomb stress changes on all faults in the UCERF3 fault model.

My other primary area of research has been the calibration and validation of satellite altimeter measurements using a reference surface at the salar de Uyuni, Bolivia. In collaboration with SIO colleague Helen Fricker, I have led three expeditions to the salar de Uyuni (in 2002, 2009 and 2012) to survey the surface with kinematic GPS. We have established that the surface is both exceptionally flat (80 cm total relief over 50 km) and stable (< 3 cm RMS elevation change over a decade), while maintaining coherent geoid-referenced topography at wavelengths of tens of kilometers. In 2013, using our salar digital elevation model (DEM), I found

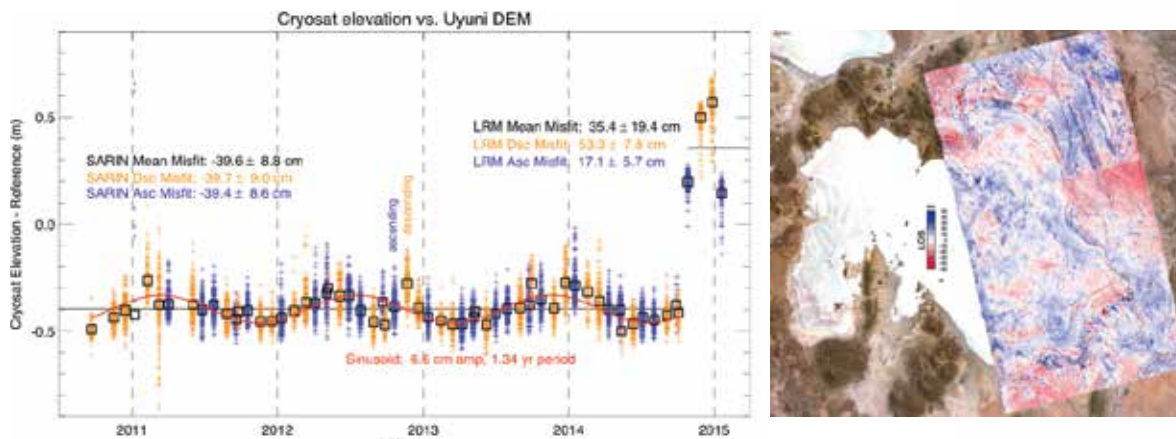


Figure 8. Left: Cryosat elevation validation relative to the salar de Uyuni DEM, with residuals showing a.) a uniform range bias of -40 cm for SARIN mode and +35 cm for LRM mode, b.) an 7 cm amplitude sinusoidal anomaly of 1.34 yr period that is still unexplained, and c.) higher range resolution than reported elsewhere, even with the sinusoidal anomaly. Right: ALOS InSAR results over the salar de Uyuni for the period 8/27/2010 - 1/12/2011, indicating that seasonal elevation change is <1 cm averaged over the salar surface.

and was able to identify the source of an inadvertent error in ICESat-1 processing that was the source of large shot-to-shot errors late in the mission period and that significantly changed ICESat-derived elevation change trends for the stable portions of the Greenland and Antarctic ice sheets.

Recently we have begun to explore surface change at the salar using ALOS InSAR observations, with the goal of linking absolute GPS measurements with relative motions provided by InSAR to provide a continuous time series of surface displacement for calibration purposes. We have also expanded our cal/val activity to the CryoSat mission and are currently evaluating improvements between Baseline B and Baseline C datasets. Our ongoing interaction with the CryoSat mission team has led ESA to switch CryoSat from SARIN to LRM mode for all passes over the salar de Uyuni from 2015 onward, allowing us to provide a cross-calibration of elevations from these different operational modes.

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- Trugman, D.T., P. Shearer, A. Borsa, Y. Fialko (2016). "A comparison of long-term changes in seismicity at the Geysers, Salton Sea, and Coso geothermal fields." *J. Geophysical Research: Solid Earth*, 121



# STEVEN CONSTABLE

Distinguished Professor

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*Research Interests: Marine EM methods, electrical conductivity of rocks*

Steven Constable heads the SIO Marine Electromagnetic (EM) Laboratory at IGPP. The two main field techniques we use are controlled-source EM (CSEM) sounding, in which a deep-towed EM transmitter broadcasts energy to seafloor EM recorders, and magnetotelluric (MT) sounding, in which these same receivers record natural variations in Earth's magnetic field. Both methods can be used to probe the geology of the seafloor, from the near surface to hundreds of kilometers deep, using electrical conductivity as a proxy for rock type. We have used these methods to study plate boundaries, marine gas hydrate, offshore geothermal prospects, hydrothermal venting and associated massive sulfides, offshore groundwater, and conventional oil and gas reservoirs.

This was a busy year in terms of data collection. In October 2016 we equipped an autonomous underwater vehicle (AUV) with our EM sensors and carried out a survey over a hydrothermal area off Japan that is thought to host seafloor sulphide deposits. Early in 2017 we recovered 38 of the 39 MT instruments we deployed in the Central Atlantic a year previously, all with data. PhD student Valeria Reyes-Ortega is currently modeling these data to study how the oceanic lithosphere ages from the ridge axis to tens of millions of years old. In June/July we carried out an extensive CSEM survey over four prospects in the Gulf of Mexico to image gas hydrate bearing strata, using our recently developed "Vulcan" mapping system (Figure 9). The Vulcans are electromagnetic recorders that are neutrally buoyant and towed behind our EM transmitter (Scripps Undersea Electromagnetic Source Instrument, or SUESI). In this survey we extended the length of the array to over 1.5 km, which is impressive when you think



*Figure 9. Preparing one of eight Vulcans (the yellow instrument) for deployment on a 1,600 m long array being towed behind our EM transmitter (SUESI with a smile) in the Gulf of Mexico. The entire system will be lowered to within 100 m of the seafloor to map gas hydrate.*



we are towing the array only 100 m above the seafloor. This equipment was then shipped off to carry out a gas hydrate survey for the Japanese government in September/October.

In August we collected 21 lake-bottom MT sites in Mono Lake, California. This work was done in collaboration with the USGS, which has been using MT to image hydrothermal and magmatic systems in the Mammoth Lakes and Long Valley Caldera area. There is a big hole in the data where the 20 km wide Mono Lake sits, so we re-packaged our seafloor instruments to be moored lake-bottom instruments (Figure 10).

Most recently we deployed 21 MT instruments across the Mendocino Fracture Zone on a UC Shipfunds supported project during the *R/V Roger Revelle's* transit from Newport, Oregon, to its home port in San Diego. These instruments will record both EM data and seismic signals for about 2 months, to be recovered early next year. The goal of this experiment is similar to the Central Atlantic project—to study differences in the lithosphere and mantle associated with the 26.5 million age difference across the fracture zone.

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Weitemeyer, K., S. Constable, D. Shelander, and S. Haines (2017): Mapping the resistivity structure of Walker Ridge 313 in the Gulf of Mexico using the marine CSEM method, *Marine and Petroleum Geology*, 88, 1013–1031, 10.1016/j.marpetgeo.2017.08.039

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Naif, S., K. Key, S. Constable, and R.L. Evans (2016): Porosity and fluid budget of a water-rich megathrust revealed with electromagnetic data at the Middle America Trench, *Geochemistry, Geophysics, Geosystems*, 17, 4495–4516, 10.1002/2016GC006556

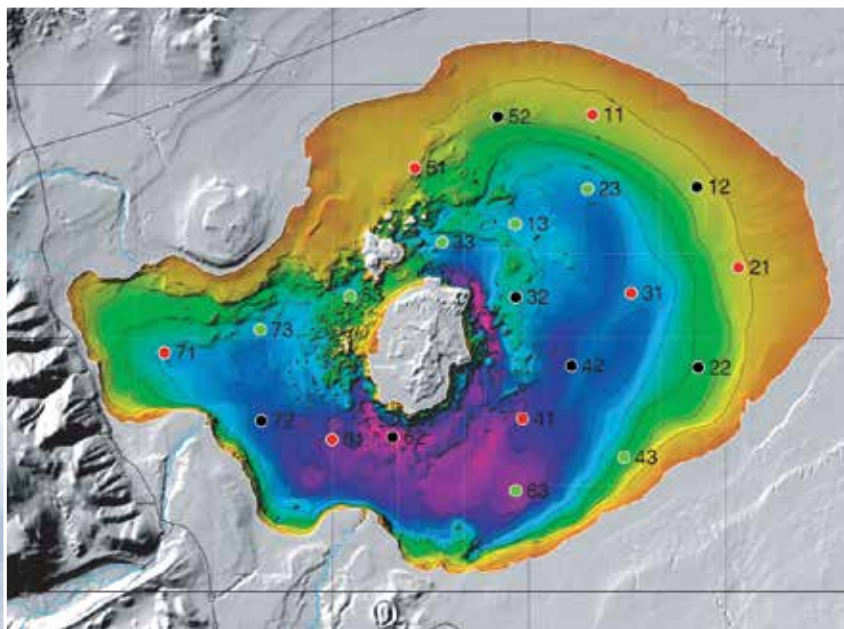


Figure 10. Approaching a moored lake-bottom MT instrument in Mono Lake, California. The inset map shows how every 2 days we moved 7 instruments around the lake, for a total of 21 sites. Mono Lake is about 35 m deep on the southern side.



# J. PETER DAVIS

Specialist

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*Research Interests: seismology, time series analysis, geophysical data acquisition*

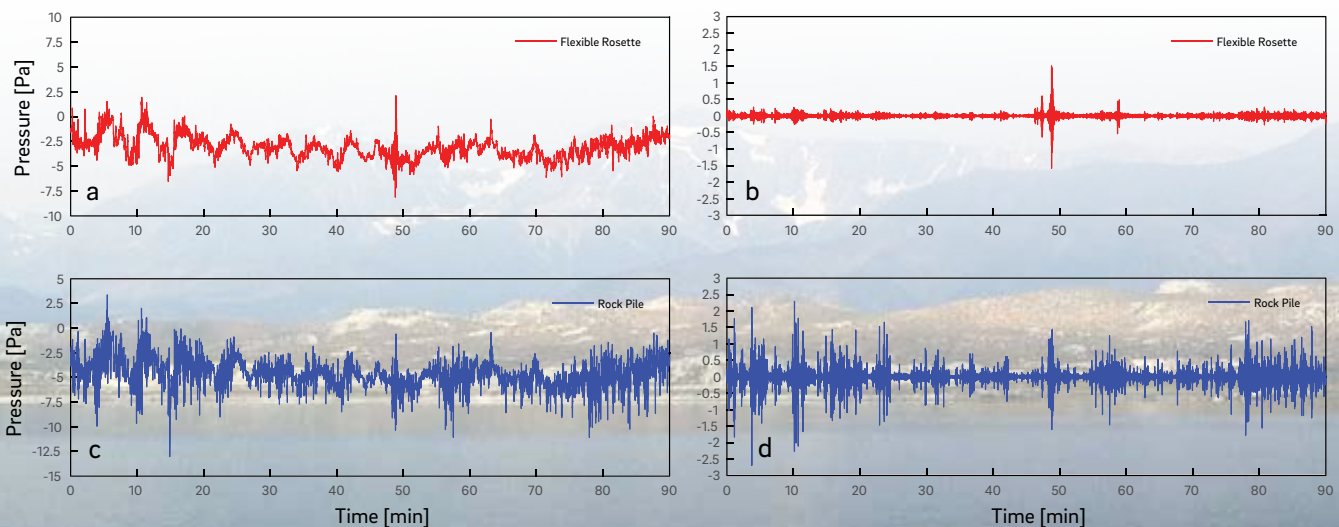
My research responsibilities at IGPP center upon managing the scientific performance of Project IDA's portion of the IRIS/USGS Global Seismographic Network (GSN), a collection of 41 seismographic and geophysical data collection stations distributed among 26 countries worldwide. IDA recently concluded upgrading the core data acquisition and power system equipment at all stations using funding provided by NSF via the IRIS Consortium.

The next major step in GSN equipment refurbishment involves replacement of obsolete primary sensors with new models provided by our funding agency. Figure 11 shows one of these sensors being lowered into a 100m deep borehole to insure the quietest possible setting for recording distant earthquakes.

We are also installing infrasound sensors at several of our sites. In order to maximize data quality, we experimented with several types of spatial filters to suppress local wind noise. Figure 12 shows the test results of two such filters when they recorded signals created by a rocket launch. We expect to record infrasonic waves from a wide variety of phenomena using these instruments.



*Figure 11. Dr. Carl Ebeling (left), IDA's chief engineer, and Bergur Bergsson (right) of the host Iceland Meteorological Office carefully lower a new seismometer package into the borehole at GSN station BORG (Borganes, Iceland).*



*Figure 12. Infrasound sensors located at Pinyon Flat Observatory recorded the successful launch of a SpaceX rocket from Vandenberg AFB on 2017:014 at ~18:18 UTC (just before the 50-minute mark in these subfigures). The pair of sensors, one with a flexible rosette hose filter (shown in red) and one with a rock pile noise reduction filter (shown in blue), recorded the event with differing quality. Waveforms in subfigures (a) and (c) are raw and scaled identically; those in subfigures (b) and (d) are bandpass-filtered between 0.7 and 2.0 Hz and scaled identically. The second signal arriving about 10 minutes after the first was probably generated as the rocket was landing on the barge in the Pacific Ocean.*

IDA staff members are working to fine-tune each station's instruments to enable scientists to extract the most accurate information possible from the data collected. One method for accomplishing this task is by examining key phenomena such as Earth tides and normal modes that should register the same on these important geophysical sensors. To the extent that measurements made with multiple instruments that have been calibrated in very different fashions match, we may have greater confidence that the instrument response information IDA distributes with GSN waveform data is accurate. Investigators use this information to compensate for the frequency-dependent sensitivity of sensors so that they may study true ground motion and its underlying physical causes.

IDA is also playing a leading role in the GSN program by evaluating new models of seismometers that may be deployed within the GSN in the future. IDA makes use of IGPP's Seismic Test Facility at Pinyon Flat Observatory to test the behavior of instrument prototypes under conditions likely probe the limits of a sensor's capabilities. Pinyon Flat is quiet enough to permit the recording of faint signals from distant earthquakes but also experiences violent shaking from local events on nearby faults.

## RECENT PUBLICATIONS

<http://dx.doi.org/doi:10.7914/SN/II>

## CATHERINE DE GROOT-HEDLIN

Research Scientist

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*Acoustic propagation modeling with application to infrasound; application of infrasound to nuclear test-ban verification and hazard monitoring; use of dense seismic and infrasound networks to analyze very long wavelength gravity waves, as well as infrasound and seismic signals.*

My main research area is in the physics of infrasound—sound at frequencies lower than human hearing—its applications to investigating both large scale atmospheric processes and explosions, either natural (bolides) or anthropogenic. Here, I outline two projects that I have worked on in the past several years.

**An automated event detector and locator:** I have developed an automated method to detect and locate events in two-dimensional space and time using large volumes of data. The method is used to create a catalog of infrasound sources in the eastern United States and southeastern Canada using infrasonic and seismic data recorded by the USArray Transportable Array (TA). There are two main reasons to develop this catalog. First, the catalog provides a list of sources that can be used for basic infrasound research, either for remote study of the events themselves or to study of properties of the atmosphere. Second, we need to understand and document the noise field or other sources that may hamper the performance of International Monitoring System infrasound arrays in monitoring the Comprehensive Nuclear Test Ban Treaty. The method has been successfully applied to TA data—over 1000 events were found in the Midwest and on the east coast in 2013. The method is currently being tested on seismic data to improve current methods of finding small seismic events.

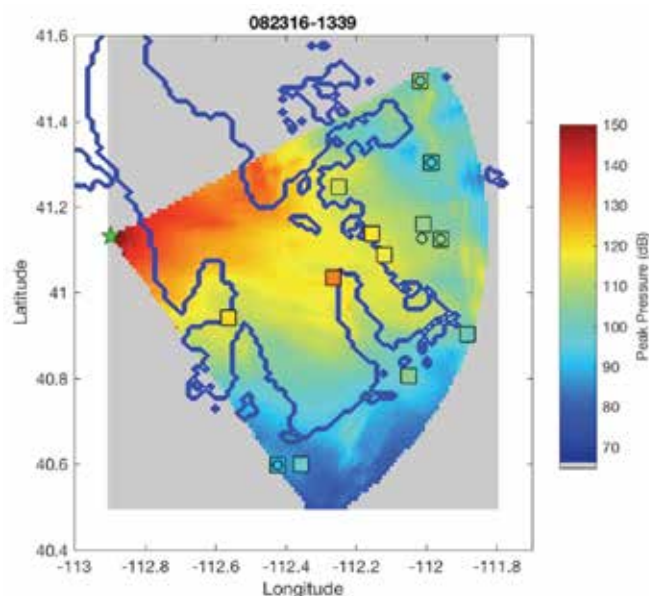


Figure 13. A map of predicted peak sound pressures for a 17,700 kg detonation at UTTR, which is marked by a green star. Winds carry the peak sound off to the northwest. Sound sensor sites, marked by squares and circles, are color-coded by the recorded peak sound pressure levels. Results show agreement within about 6dB.

**Numerical modeling:** A basic research goal in infrasound is to understand the transmission of infrasound through variable atmospheric conditions. To this end, I developed a computationally efficient numerical method to synthesize the propagation of nonlinear acoustic waves through the atmosphere. Nonlinearity, or shock wave propagation, arises when pressure perturbations associated with acoustic waves are a significant fraction of the ambient atmospheric pressure. Shock waves are associated with meteoroid explosions in the upper atmosphere, volcanic eruptions, or nuclear and chemical explosions. Work on this code has progressed to allow for the incorporation of realistic atmospheric effects, such as spatially varying sound speeds and wind speeds, topography, and atmospheric attenuation.

In a recent project, this code has been used to compute the penetration of sound into areas typically thought of as being in a "shadow zone", where sound refracts upwards, away from the Earth's surface due to the decrease in sound speed with altitude, much as light bends as it travels between air and water. In the summer of 2016, rocket motor were detonated at the Utah Test and Training Range (UTTR), and sound sensors were placed at up to 14 sites eastward of the blasts. Numerical codes were used to create a map to predict the peak sound levels in areas to the east of the detonations. Predicted peak sound levels are compared to observed levels in Figure 13.

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# MATTHEW DZIECIUCH

Project Scientist

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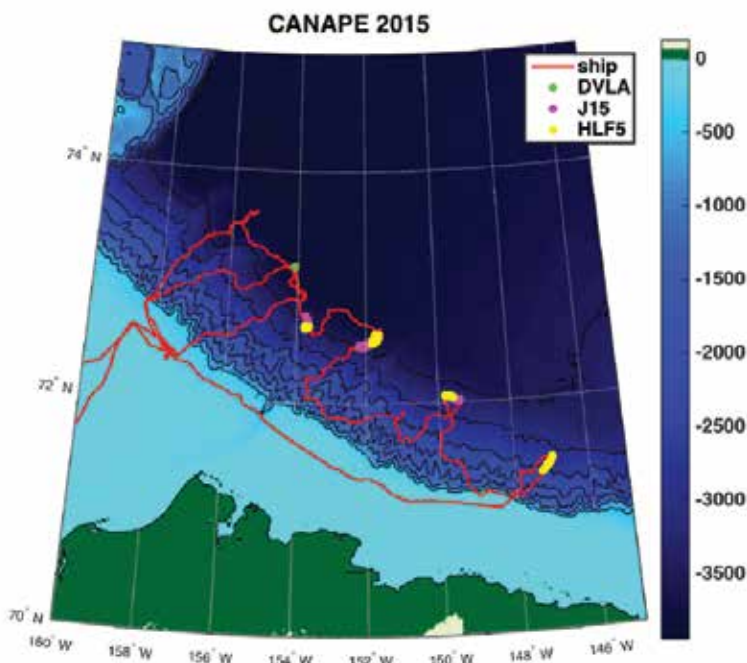
*Research Interests: Acoustical oceanography, ocean acoustic tomography, signal processing*

Low-frequency, long-range ocean acoustics experiments provide a wealth of knowledge about an otherwise opaque environment. The travel-time of sound waves propagating through the depths is affected by both small-scale and large-scale ocean processes. Acoustical oceanography seeks to use sound propagation in the ocean to understand some of the dynamic processes that are present.

Sound is an effective tool to study the ocean interior because it is trapped in a natural occurring waveguide (due to vertical gradients of pressure and temperature) present in all the worlds oceans. Some of the processes that can be studied include climate change, ocean circulation, internal waves, and tides. I am part of a group that has conducted several large experiments in regions as diverse as the Philippine Sea in the tropical Pacific, to the Beaufort Sea in the Arctic.

As an example, recently we deployed a 60 element vertical line array in the Arctic to learn about the propagation of sound under the ice, Figure 14. As the sound propagates under the ice, its attenuation is affected by the under-ice roughness. The under-ice roughness is a measure of the age of the ice, old ice is rougher than new ice. So the sound attenuation is a proxy for the sea-ice age. Information about the sea-ice age is very important in understanding the dynamics of the yearly ice melting cycle as it is under increasing stress from a warming planet. Furthermore this direct measurement is an complementary alternative to satellite measurements.

The results revealed that the ice attenuates the sound in a complicated manner shown in Figure 15. The deep hydrophone shows an attenuation that is steeper than the expected spherical spreading. That deep hydrophone measures sound that has traveled at steep angles and interacts with the sea-ice at every bounce and thus is strongly attenuated. The shallow hydrophone shows less attenuation particularly at shorter ranges. This is a bit of a mystery but perhaps there is enough of a duct present that some sound can become trapped and not strongly interact with the ice, at least over the part of the path. On-going modeling work using environmental data collected simultaneously will enable us to understand these results.



*Figure 14. A vertical line array of hydrophones (DVLA) was deployed at a xed location and then two sound sources, at 125Hz (J-15) and at 250 Hz (HLF-5) were deployed at various ranges to learn about the relationship between at-tenuation and range. Ship tracks reflect the tortuous route taken to avoid thick sea-ice.*

This experiment was conducted with funding from the Office of Naval Research and they have supported a larger experiment, which is deployed now, to further our ability to monitor and understand the changing Arctic.

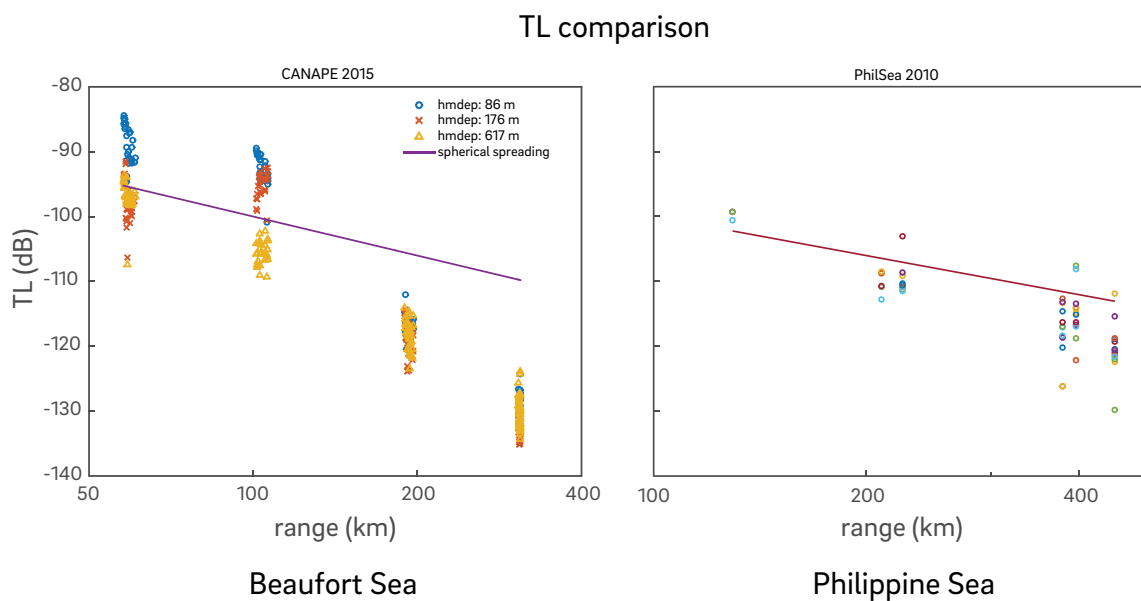
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*Figure 15. CANAPE2015 sound attenuation or transmission loss (TL) vs. range in the left panel. Deep hydrophones show a loss greater than spherical spreading (purple). Shallow hydrophones show a more complicated behavior due to the presence of a range-dependent duct, the so-called Beaufort Lens. The right panel shows a more typical attenuation situation without ice in the Philippine Sea.*

# YURI FIALKO

Professor

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*Research interests: earthquake physics, crustal deformation, space geodesy, volcanology*

Professor Fialko's research is focused on understanding the mechanics of seismogenic faults and magma migration in the Earth's crust, through application of principles of continuum and fracture mechanics to earthquakes and volcanic phenomena. Prof. Fialko is using observations from space-borne radar satellites and the Global Positioning System (GPS) to investigate how the Earth's crust responds to seismic and magmatic loading.

Among recent projects are studies of coseismic and postseismic deformation due to large earthquakes at the margins of the Tibetan Plateau. Prof. Fialko and former graduate student Kang Wang (now a postdoc at UC Berkeley) investigated how the Tibetan lithosphere responded to the 2015  $M_W$  7.8 Gorkha (Nepal) earthquake that occurred along the central Himalayan arc. This study involved analysis of space geodetic observations including Interferometric Synthetic Aperture Radar (InSAR) data from Sentinel-1A/B and ALOS-2 satellites, as well as Global Positioning System (GPS) data from a local network. InSAR observations reveal an uplift of up to ~70 mm over ~20 months after the mainshock, concentrated primarily at the downdip edge of the ruptured asperity (Figure 16). GPS observations also show uplift, as well as southward movement in the epicentral area, qualitatively similar to the coseismic deformation pattern. Because the earthquake area is characterized by strong variations in surface relief and material properties, finite element models were developed to explicitly account for topography and 3-D elastic structure. Kinematic inversions of GPS and InSAR data, and forward models of stress-driven creep suggest that the ob-

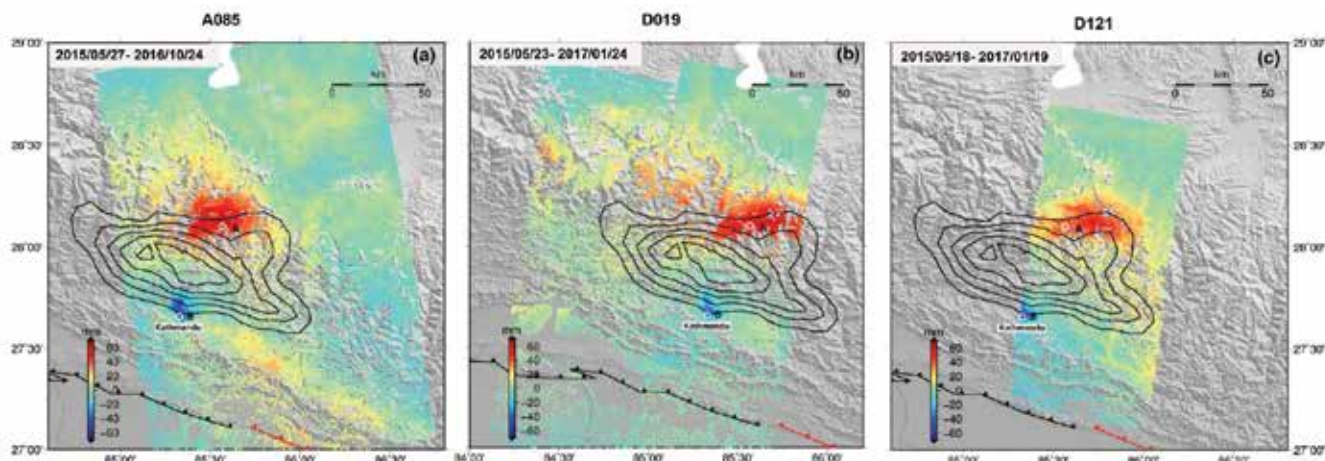


Figure 16. Postseismic line of sight (LOS) displacements from Sentinel-1's (a) ascending track A085, (b) descending track D019, and (c) descending track D121. Positive LOS displacements correspond to surface motion toward the satellite. Observation periods for each track are indicated in the top-left corner of each panel. From Kang and Fialko (in review).

served postseismic transient is dominated by afterslip on a down-dip extension of the seismic rupture. A poro-elastic rebound may have contributed to the observed uplift and southward motion, but the predicted surface displacements are small. Models also explored a wide range of visco-elastic responses, including 1-D and 3-D variations in the viscosity structure. All tested visco-elastic models predict opposite signs of horizontal and vertical displacements compared to those observed. Available surface deformation data appear to rule out the hypothesis of a low viscosity channel beneath the Tibetan Plateau which has been previously invoked to explain the long-term uplift and variations in topography at the plateau margins.



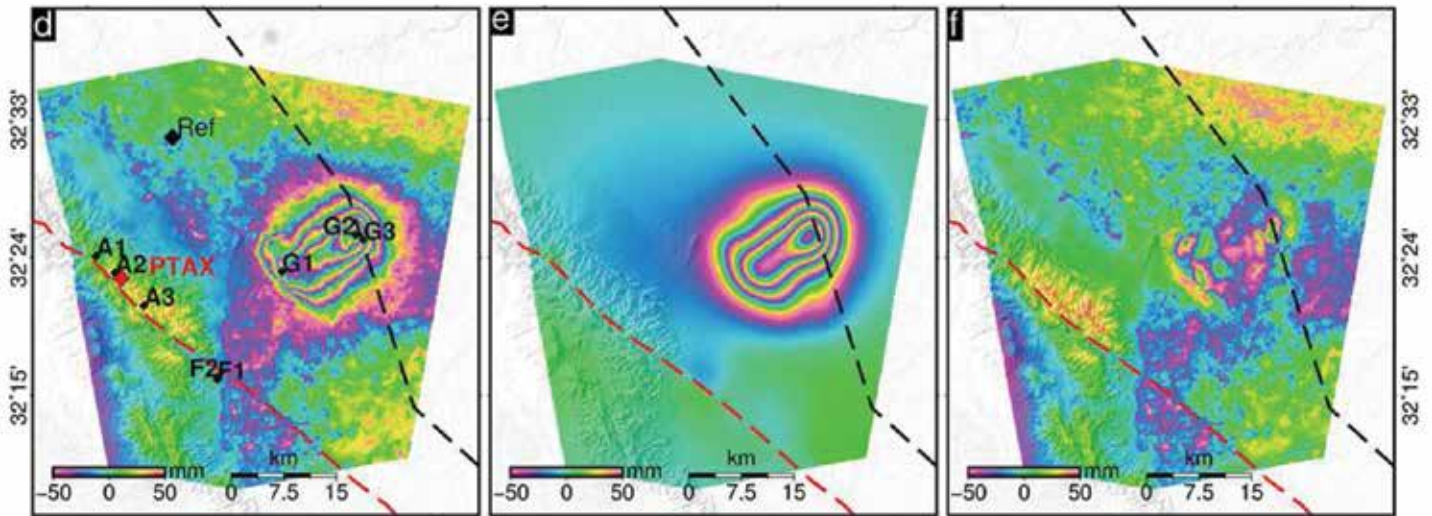


Figure 17. Observed (d), modeled (e), and residual (f) vertical surface displacements that occurred during 1 October 2011 to 24 July 2016 near the Cerro Prieto Geothermal Field (CPGF). Red dashed line denotes the surface rupture of the 2010 El Mayor-Cucapah earthquake. From Samsonov et al. (2017).

In another recent study Prof. Fialko and collaborators from the Canadian Space Agency used InSAR observations from RADAR-SAT-2 satellite to investigate deformation due to fluid extraction at the Cerro Prieto Geothermal Field (CPGF) and afterslip on the 2010 M7.2 El Mayor-Cucapah (EMC) earthquake rupture in Mexico during 2011-2016. Advanced multidimensional time-series analysis reveals subsidence at the CPGF with the maximum rate greater than 100 mm/yr (Figure 17) accompanied by horizontal motion (radial contraction) at a rate greater than 30 mm/yr. During the same time period, more than 30 mm of surface creep occurred on the Indiviso fault ruptured by the EMC earthquake. Inversions of InSAR data were used to estimate the rate of volume changes at depth due to the geothermal production at the CPGF and the distribution of afterslip on the Indiviso fault. The maximum coseismic slip due to the EMC earthquake correlates with the Coulomb stress changes on the Indiviso fault due to fluid extraction at the CPGF. Afterslip occurs on the periphery of maximum coseismic slip areas. Time series analysis indicates that afterslip still occurs 6 years after the earthquake.

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# HELEN AMANDA FRICKER

Professor, John Dove Isaacs Chair

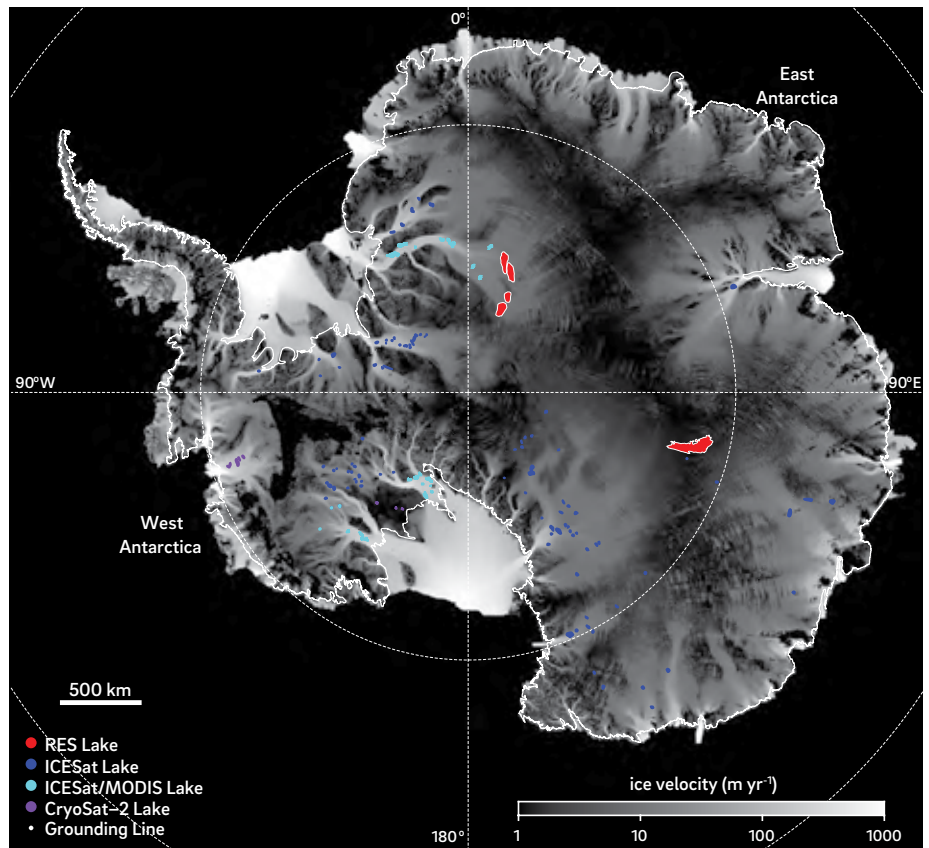
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*Research Topics: cryosphere, Antarctic ice sheet, subglacial lakes, ice shelves, satellite remote sensing*

In Fall 2017, we moved to MESOM with new OA Professor Fiamma Straneo to form a Polar Center.

Our research focuses on understanding the processes driving changes on the Antarctic ice sheet. One of the main unknowns is Antarctica's current contribution to global sea level, and predicting how that will increase in the future. Because Antarctica is so large, and it changes on long time scales (years to decades), satellite data are crucial for monitoring. The main techniques we use are satellite altimetry, either radar altimetry from ERS-1/ERS-2 and Envisat which provides a long record (1994-2012) or NASA's Ice, Cloud & land Elevation Satellite (ICESat), which provides accurate elevation data for ice sheet change detection for the period 2003-2009. I was a member of the ICESat Science Team and I am a member of ICESat-2 Science Definition Team. My group works on validating ICESat elevation data, using "ground-truth" from our repeated GPS surveys of the salar de Uyuni in Bolivia (in 2002, 2009 and 2012), led by IGPP Professor Adrian Borsa. Using these long, continuous records we can learn about the processes that are leading to accelerated mass loss. We focus mainly on two key dynamic components of the ice-sheet system: (i) the floating ice shelves and (ii) active subglacial lakes.

**i. Antarctica's floating ice shelves:** ice shelves surround the entire Antarctic continent and are where most of the mass loss takes place. Since ice shelves are floating, their melting does not contribute directly to sea level. However, ice shelves provide mechanical support to 'buttress' seaward flow of grounded ice, so that ice-shelf thinning and retreat result in enhanced ice discharge to the ocean. Our group specializes in monitoring Antarctic ice shelves from satellite altimetry (radar and laser), and we use the continuous time series to understand the mass loss processes from ice shelves. Funded by NASA, we use satellite radar and laser altimeter data from one NASA satellite and four ESA satellites to obtain estimates of ice-shelf surface height since the early 1990s. These data revealed accelerated losses in total Antarctic ice-shelf volume from 1994 to 2012. In East Antarctica, the first half of the record showed a mass increase, likely a result of increased accumulation. In West Antarctica, in particular the Bellingshausen and Amundsen Sea regions, ice shelves lost mass throughout the record with changes on multi-year time scales. Ice-shelf thinning in these regions was substantial: some ice shelves thinned by up to 18% in 18 years. This thinning raises concerns about future loss of grounded ice and resulting sea level. In West Ant-



arctica, the height changes are correlated with ENSO. Susheel Adusumilli (GP student) has generated updated time series for 1994 to 2016, and is writing a paper on these results for the Antarctic Peninsula for GRL.

I am a PI on a large NSF project ROSETTA-Ice to investigate the Ross Ice Shelf using airborne geophysical techniques (gravity, laser and radar). GP student Maya Becker participated in the 2016/2017 and 2017/2018 field seasons.

**ii. Subglacial lakes:** The Antarctic Ice Sheet is on average 2.2 km thick and rests on top of bedrock; the insulation, high pressures, and geothermal heat flux at the ice-bed interface leads to melting of the basal ice layers on the order of mm/year. When averaged over the entire ice sheet, this produces high volumes of subglacial water (estimated volume is 65 Gt/yr), much of which is stored in subglacial lakes and subglacial aquifers. In 2006, I discovered active subglacial water systems under the fast-flowing ice streams of Antarctica using ICESat data. This was inferred from observations of large height changes (up to 10m in some places) in repeat-track ICESat data, which corresponded to draining and filling of subglacial lakes beneath 1-2 km of ice. We continue to monitor active lakes, and we have found 124 in total throughout Antarctica. In the decade since the discovery of active Antarctic subglacial water systems, much progress has been made in our understanding of these dynamic systems; Matt Siegfried extended the record of volume change for all lakes under the CryoSat-2 mask up to 2017 (Figure 18).

I was PI on a large, interdisciplinary 6-year NSF project (Whillans Ice Stream Subglacial Access Research Drilling (WISSARD)) to drill into one of the subglacial lakes— Subglacial Lake Whillans (SLW) on Whillans Ice Stream (WIS)—and the region of the grounding line across which the subglacial water flows and enters the ocean. A new NSF-funded 4-year project Subglacial Antarctic Lakes Scientific Access (SALSA) began in the 2016-17 field season, and Matt Siegfried is leading the geophysics team, which includes GP student Susheel Adusumilli.

## RECENT PUBLICATIONS

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# MICHAEL A.H. HEDLIN

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*Research Interests: Study of large atmospheric phenomena, study of long-range propagation of subaudible sound in the atmosphere, seismo-acoustics*

**INFRASOUND:** The study of subaudible sound, or infrasound, has emerged as a new frontier in geophysics and acoustics. We have known of infrasound since 1883 with the eruption of Krakatoa, as signals from that event registered on barometers around the globe. Initially a scientific curiosity, the field briefly rose to prominence during the 1950's and 1960's during the age of atmospheric nuclear testing. With the recent Comprehensive Test-Ban Treaty, which bans nuclear tests of all yields in all environments, we have seen renewed interest in infrasound. A worldwide network of infrasound arrays, being constructed for nuclear monitoring, is fueling basic research into man-made and natural sources of infrasound, how sound propagates through our dynamic atmosphere and how best to detect infrasonic signals amid noise due to atmospheric circulation. This network has been supplemented with deployments, such as the 400-station seismo-acoustic USArray Transportable Array (TA), for basic research and enhanced monitoring of regions of great interest.

**RESEARCH AT L2A:** The Laboratory for Atmospheric Acoustics (L2A) is the home of research in this field at IGPP. Several faculty, post-docs and PhD students work full or part time in L2A, supported by engineers and technicians in the lab and the field. More information about this lab can be found at [l2a.ucsd.edu](http://l2a.ucsd.edu). Presently we study a broad suite of problems related to both natural and man-made sources.

**DENSE NETWORK STUDIES:** The global infrasound network is unprecedented in scale however it is still very sparse, with ~100 stations operating worldwide. To increase the density of sampling of the infrasonic wavefield we have used acoustic-to-seismic coupled signals recorded by dense networks, such as the 400-station USArray Transportable Array (TA) and various PASSCAL deployments. We have used the original (seismic-only) TA network to create a catalog of atmospheric events in the

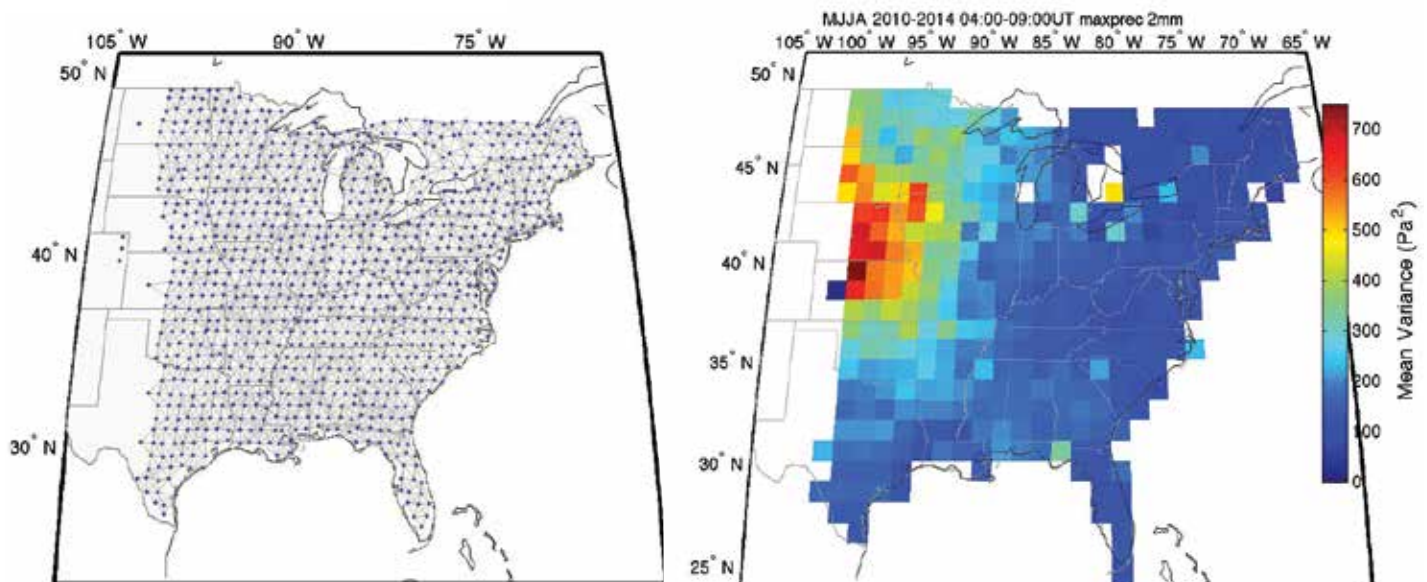


Figure 19. left) sites occupied by stations in the TA from January 1, 2010 through Sept 30, 2014. These stations have been grouped into 3-element arrays (triads) for the study of long-period atmospheric gravity waves. The panel on the right shows the variance of atmospheric pressure in the 2-6 hr passband during the thunderstorm seasons from 2010 through 2014. The highest variance to the west of the Great Lakes is due to gravity waves excited by convective storms.

western United States similar to commonly used seismic event catalogs. The acoustic catalog is used in part to find sources of interest for further study and to use the recorded signals to study long-range infrasound propagation. Recorded signals from instantaneous sources are commonly dispersed in time to several 10's of seconds. Modeling indicates that this is due to interaction of the sound waves with fine-scale structure in the atmosphere due to gravity waves. We are currently using infrasound to constrain the statistics of this time-varying structure.

The National Science Foundation funded our group to upgrade the entire TA with infrasound microphones and barometers. Our sensor package is sensitive to air pressure variations from D.C. to 20 Hz, at the lower end of the audible range. The upgrade converted the TA into the first-ever semi-continental-scale seismo-acoustic network. The network has moved east across the US as stations are redeployed. Figure 19 (left panel) shows station locations from January 1, 2010 through the end of September, 2014. We have divided this collection of stations into 3,600 elemental arrays (triads) to study atmospheric gravity waves. An early result is shown in the right panel of Figure 19. This map shows the variance of atmospheric pressure in the 2-6 hour pass-band at local night. Elevated variance of atmospheric pressure is due to the presence of atmospheric gravity waves. As expected, large gravity waves are common to the west of the Great Lakes and are from convective activity.

**FIELD OPERATIONS:** Our group has built infrasound arrays for nuclear monitoring in the US and Africa. We operate research arrays located near San Diego.

## RECENT PUBLICATIONS

- Brown, P., Assink, J., Astiz, L., Blaauw, R., Boslough, M., Borovicka, J., Brachet, N., Brown, D., Campbell-Brown, M., Ceranna, L., Cooke, W., de Groot-Hedlin, C., Drob, D., Edwards, W. Evers, L., Garces, M., Gill, J., Hedlin, M.A.H., Kingery, A., Laske, G., Le Pichon, A., Mialle, P., Moser, D., Saffer, A., Silber, E., Smets, P., Spalding, R., Spurny, P., Tagliaferri, E., Uren, D., Weryk, R., Whitaker, R., Krzeminski, Z., 2013, The Chelyabinsk airburst: Implications for the Impact Hazard, *Nature*, DOI: 10.1038/nature12741.
- de Groot-Hedlin, C.D., Hedlin, M.A.H., Hoffmann, L., Alexander, M.J. and Stephan, C., 2017, Relationships between Gravity Waves Observed at the Surface and in the Stratosphere over the Continental United States, *JGR Atmospheres*, in press.
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- Hedlin, M.A.H. and Drob, D.P., 2014, Statistical characterization of atmospheric gravity waves by seismoacoustic observations, *J. Geophys. Res. Atmos.*, doi: 10.1002/2013JD021304.
- Stephan, C., Alexander, M.J., Hedlin, M.A.H., de Groot-Hedlin, C.D. and Hoffmann, L., 2016, A case study on the far-field properties of propagating tropospheric gravity waves, *Monthly Weather Review*, v144, p2947-2961, DOI: 10.1175/MWR-D-16-0054.1.

# DEBORAH LYMAN KILB

Project Scientist

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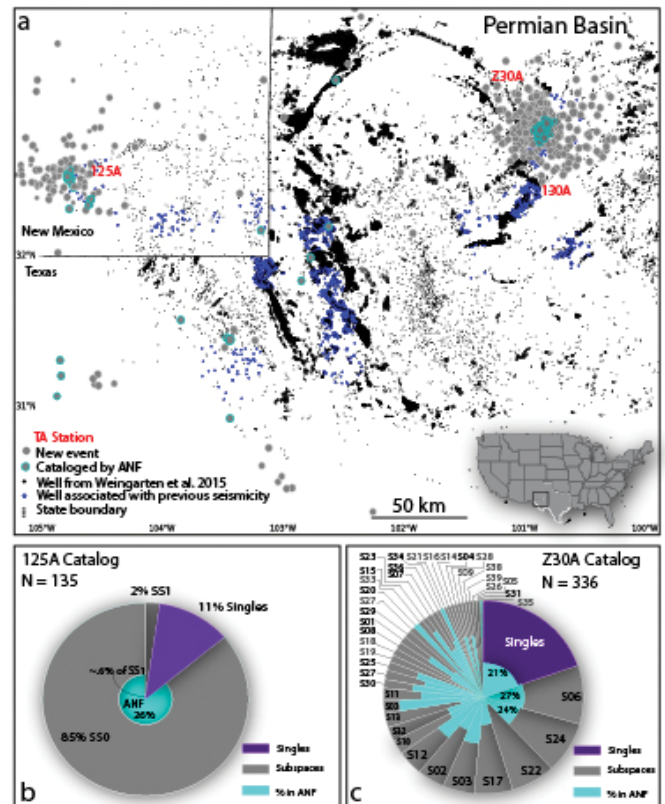
*Research Interests: Crustal seismology, earthquake triggering, and earthquake source physics. Diversity Interests: Improving how science is communicated to students and the public.*

**A frequency-domain approach to identify small earthquakes [Linville et al., work in progress].** We develop a frequency-domain, array-based detection algorithm, which exploits the gridded nature of the Transportable Array network (~400 stations), to detect and locate small ( $-0.25 \leq M < 2$ ) earthquakes. Applying our new method to data from three sedimentary basins in the Central United States, we can increase the catalog size three-fold (from 140 to 562 events). A majority of the newly detected seismicity in the Permian and Denver-Julesburg basins may be linked with induced seismicity, while in the Williston Basin there continues to be little evidence of induced sequences. We apply single-link clustering and sub-space detection methods to our data (Figure 20) and find some regions have very similar sources (i.e., a limited number of subspace families) while others are extremely variable (up to 38 subspace families). Because our method requires no preconceived assumptions about the source waveform characteristics, our algorithm can be used to successfully find signals of unknown source types.

**A Time-Domain Detection Approach to Identify Small Earthquakes within the Continental U.S. [Velasco et al., 2016].** We aim to detect small seismic events triggered by distant large earthquakes using the continuous data recorded by the EarthScope USArray network. We apply time domain short-term average (STA) to long-term-average (LTA) ratio algorithms to three-component data to create a catalog of detections. We apply this method to  $\pm 45$  hours and  $\pm 5$  hours of USArray data from the 2011 Japan magnitude 9.0 and the 2010 Chile magnitude 8.8 earthquakes, respectively. Our detection algorithm identified three regional earthquakes in the Coso region of California that were concurrent with the passage of the S- and surface-waves of the Chile mainshock at station R11A, as well as events in Texas following the Japan earthquake. These distant aftershocks are assumed to be triggered by dynamic stress changes caused by the mainshock's seismic waves.

## DIVERSITY ACTIVITIES (OCTOBER 2016—SEPTEMBER 2017)

**Sally Ride Science Summer Academy for Girls [SRS 2017]:** I was the Director of the 2017 Sally Ride Science (SRS) Summer Junior Academy, which took place at Mission Bay High School. In this capacity I was responsible for selecting and vetting the instructors and classes. The 2017 Academy ran for 4-weeks and included 59 classes (9-noon or 1-4PM). A total of 524 middle- and high-school age students enrolled in the classes, of which 46% of the students were awarded scholarships. Of the 19 instructors in our program this year, 10 were SIO affiliated.



*Figure 20. (a) Map of the Permian basin including known wells (black) and wells known to induce earthquakes (blue). Only ~25% of the earthquake catalog for the Permian basin (grey circles) were cataloged by ANF (cyan edges). (b) Venn diagram of events near station 125A (Dagger Draw, NM). Of the 135 events in our catalog only 26% are in the ANF catalog. Of the 135 events, 85% belong to a single subspace. (c) As in (b) for the 336 events between TA stations Z30A and 130A (Snyder, TX). For these data our clustering method identifies 35 subspaces (labeled S01, S02 etc.)*

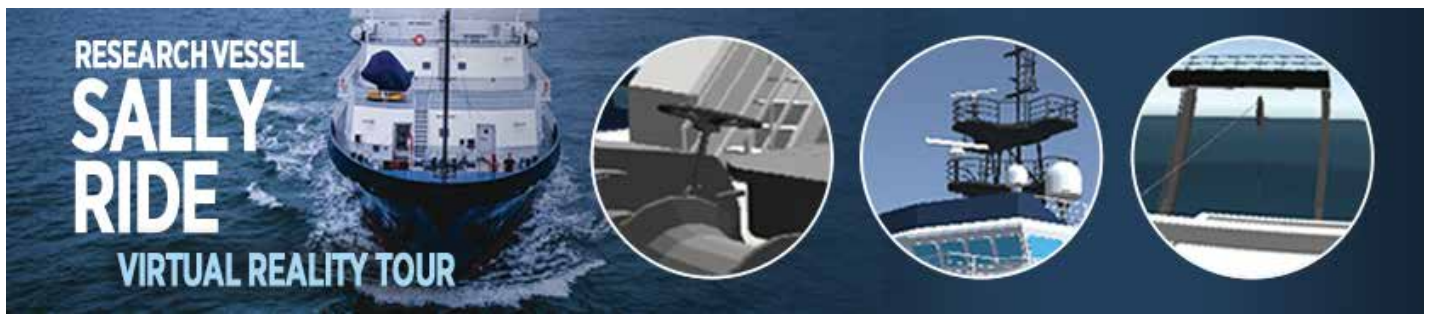


Figure 21. Promotional banner for the SIO GAMES free Virtual Reality Sally Ride app.

**Virtual Reality App of the Sally Ride Research Vessel [Yang et al., 2017; software app]:** Our SIO GAMES group created a free virtual reality app, which provides viewers a virtual reality tour aboard Scripps Institution of Oceanography's newest research vessel the R/V Sally Ride (Figure 21).

**Library NExT:** I am the Science Outreach Director of the Library NExT (Network of Education x Training) program, which is a partnership program between the San Diego Libraries and Sally Ride Science. The pilot program launched in January 2017, offering free classes for middle- and high-school students at 10 local libraries. To date the program has provided 207 hours of instruction to 557 students.

**The Great California Shake Out:** For the fifth year in a row, I partnered with the Birch Aquarium at Scripps to participate in their annual Great California Shake Out event. I was on site to discuss current seismology research at Scripps, real-time seismic data and earthquake preparedness.

**Invited speaker:** Point Loma Nazarene University Perspectives on Science lecture (December, 2106), La Jolla Women's Society (April, 2017) and San Diego Lion's Club (April, 2017).

**Outreach:** Day for Kids (Boys & Girls Club; presenter), STEM club (Ocean Knoll Elementary; presenter), Seismology Rocks! (Notre Dame Academy; presenter; 5 programs), Earthquake! (Ocean Air Elementary School; presenter), San Diego STEAM Maker festival (presenter), Science Nights (elementary schools; assisted; 5 programs).

## RECENT PUBLICATIONS

Sally Ride Science (SRS) Summer Academy for Girls [2017, webpage]: <https://www.sallyridescience.com/wp-content/uploads/2017/04/SallyRideSummerAcademy.pdf>

Velasco, A.A., R. Alfaro-Diaz, D. Kilb, K.L. Pankow [2016]. "A Time-Domain Detection Approach to Identify Small Earthquakes within the Continental United States Recorded by the USArray and Regional Networks", *Bull. Seism. Soc. Am.*, 106: 512-525, doi: 10.1785/0120150156.

Yang A., S. Shpigelman and D. Kilb [2016, Software App]. A virtual reality tour aboard Scripps Institution of Oceanography's newest research vessel, R/V Sally Ride. Available from the iTunes and GooglePlay stores: <http://siogames.ucsd.edu/vrsallyride.php>.

# GABI LASKE

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*Research interests: Regional and global seismology; surface waves and free oscillations; seismology on the ocean floor; observation and causes of seismic noise; natural disasters and the environment*

Gabi Laske's main research area is the analysis of seismic surface waves and free oscillations, and the assembly of global and regional seismic models. She has gone to sea to collect seismic data on the ocean floor. Laske's global surface wave database has provided key upper mantle information in the quest to define whole mantle structure. Graduate students Christine Houser and Zhitu Ma as well as students from other universities have used her data to compile improved mantle models.

**Global reference models:** Laske continues collaboration with Guy Masters and former graduate student Zhitu Ma to compile and distribute global crust and lithosphere models. CRUST1.0, A 1-degree crustal model, was released in 2013. Applications relying on CRUST1.0 are found across multiple disciplines in academia and industry. Laske maintains the distribution website and provides guidance to users.

**The PLUME project:** For the past decade or so, Laske has analyzed waveforms collected on ocean bottom seismometers (OBSs). She was the lead-PI of the Hawaiian PLUME project (Plume–Lithosphere–Undersea–Mantle Experiment) to study the plumbing system of the Hawaiian hotspot. Results from various body wave, surface wave and receiver function studies were published. In the past year, continued collaboration with Kate Rychert at the University of Southampton, U.K. led to a publication on the seismic structure and geodynamical implications of the mantle transition zone.

The PLUME dataset also provides the basis for PhD student Adrian Doran who studies seafloor compliance and ambient-noise Green's functions. His work will help constrain structure in the shallow sediments and crustal layers that were not resolved by previous work. Doran formulated the concept of horizontal compliance and published a first-ever application to real OBS data.

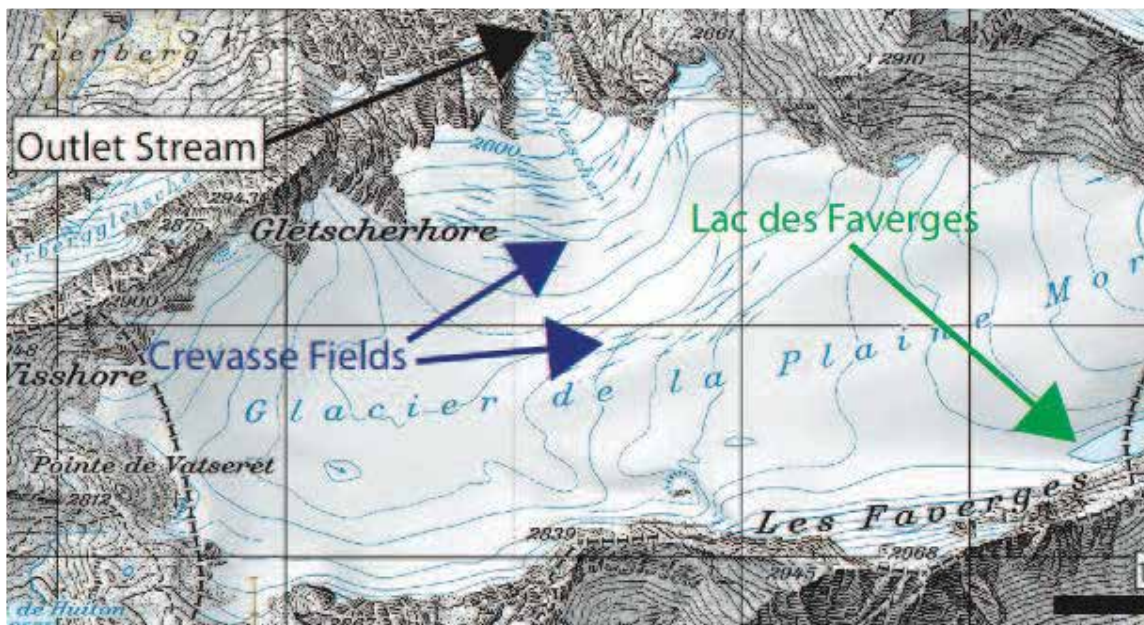


Figure 22. Map of Glacier de la Plaine Morte just south of Wildstrubel, Switzerland. The Rhone valley is to the south. Marked is the outlet stream at the toe of Rextli glacier that drains into the Simme river to the north. Arrows mark Lac des Faverges, a major glacier lake, and the two crevasse fields that Laske and Walter occupied with four arrays of short-period seismometers during the 2016 summer. The instruments were borrowed from the GIPP instrument pool at GFZ, Potsdam, Germany.



He also developed a new automated tool to determine OBS instrument orientations using Rayleigh waves, with little interaction by the data analyst.

A paper was published this year, and the Python computer code released for general use. Surface Wave Azimuthal Anisotropy: MS student Chenghao Shen finished his analysis of PLUME Rayleigh-wave azimuthal anisotropy. While shear-wave splitting results appear to be sensitive only to the fossil spreading direction "frozen" into the lithosphere, Laske and her students found a clear signal that is suggestive of plume-related flow in the asthenosphere. Shen's analysis included extensive forward modeling for local two-layer models which was presented at two international conferences. Laske has also collaborated with Donna Blackman to model flow-induced rock texture in the aging ocean lithosphere, and implications for seismic anisotropy. Results are summarized in a publication.

**The AnICEotropy project:** Laske has been collaborating with Fabian Walter at ETH, Switzerland to study ice quakes on the Glacier de la Plaine Morte, Switzerland. This plateau glacier that separates Cantons Berne and Valais develops a glacier lake, Lac des Faverges, during snow melt that frequently drains and floods the Simme valley to the north. Recent floods have become more frequent and larger, approaching the capacity of the flood control system. Last year, Laske and collaborators installed seismometers on the glacier and to identify precursory ice quake activity that helps improve early flood warning. As an academic by-product, the gathered seismicity allows a 'sandbox' azimuthal anisotropy analysis to test the hypothesis that seismic anisotropy is aligned with the crevasses on the glacier. Laske now co-mentors ETH graduate student Fabian Lindner, and a manuscript on azimuthal anisotropy is in preparation.

**The CABOOSE project:** The California Borderland Ocean Seismicity project (CABOOSE) is a collection of past present and future small OBS deployments to assess seismicity off-shore Southern California. For the ADDOSS (Autonomously Deployed Deep-ocean Seismic System) project, Laske collaborated with Jon Berger, John Orcutt, Jeff Babcock and Liquid Robotics Inc. to develop and test an untethered OBS system that is capable of providing near-real time data collected on the ocean floor. A wave glider towing an acoustic modem maintains a communications link to the OBS. The group has performed several tests in shallow (1000 m) and deep (3800 m) water. During the 3-month deep-water test about 300 km west of La Jolla, never-before seen seismic activity was observed in the Outer Borderland. Doran and Laske returned in the summers of 2015 and 2017 on UC ship fund cruises to continue investigation of the Borderland seismicity in more detail.

## RECENT PUBLICATIONS

Blackman, D.K., Boyce, D.E., Castelnuovo, O., Dawson, P.R. and Laske, G., Effects of crystal preferred orientation on upper-mantle flow near plate boundaries: rheologic feedbacks and seismic anisotropy. *Geophys. J. Int.*, 210, 1481–1493, 2017.

Doran, A.K. and Laske, G., Ocean-Bottom Seismometer Instrument Orientations via Automated Rayleigh-Wave Arrival-Angle Measurements. *Bull. Seismol. Soc. Am.*, 107, doi:10.1785/0120160165, 2017.

Agius, M.R., Rychert, C.A., Harmon, N. and Laske, G., Mapping the mantle transition zone beneath Hawaii from Ps receiver functions: Evidence for a hot plume and cold mantle downwellings. *Earth Planet. Sci. Lett.*, 474, 226–236, doi: 10.1016/j.epsl.2017.06.033, 2017

# GUY MASTERS

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The three-dimensional structure of the mantle tells us about how the Earth is moving to get rid of its heat and is central to the question of the nature of heat and mass transfer within the Earth. Three-dimensional images of the mantle have been extensively studied using travel time tomography. Shear (S) velocity images of the mantle agree well but the compressional (P) velocity and density structures are still controversial.

To address this, we focus on the analysis of Earth's normal modes and the development of a novel mathematical approach to better estimate the lateral variation of Earth structure with estimates of its robustness. Normal mode frequencies are sensitive to both velocity and density structures. Earth's normal modes sense different parts of the Earth depending upon the mode and type of vibration. Normal modes are visualized in the frequency domain and normal mode spectra, which would be single resonance peaks if the Earth were spherically symmetric, are split into a number of lines (known as singlets) due to rotation, ellipticity, and three-dimensional structure of the Earth. It is this splitting that we use to infer the 3D structure of the Earth.

The method we use (the "auto-regressive" method) was previously introduced by Masters and co-workers in 2000. The advantage of the method is that it needs no knowledge of the earthquake source and so can be used for the largest, most complex, earthquakes ever recorded. We first remove the receiver location information from the stack of complex spectra for all the available stations around the globe and produce spectra known as "receiver strips" (Masters et al. 2000, Figure 23). Importantly, this step allows us to visualize the excitation of singlets of a normal mode. For example, two inner core sensitive modes, 3S2 and 13S2, are excited differently by the same earthquake (Figure 23). The zero line in the case of 3S2 is noisy and signal is almost below the noise level while that for 13S2 is much better. The receiver strips can then be analyzed to recover "structure coefficients" which are linear functionals of 3D structure and which can be used to generate "splitting functions" which are the modal equivalent of phase velocity maps for surface waves. Here, we implement a fully non-linear parameter sampling approach to estimate the structure coefficients (Pachhai et al. 2016). The benefit of this approach is that it allows us to determine what aspects of 3D structure are actually required to fit the data.

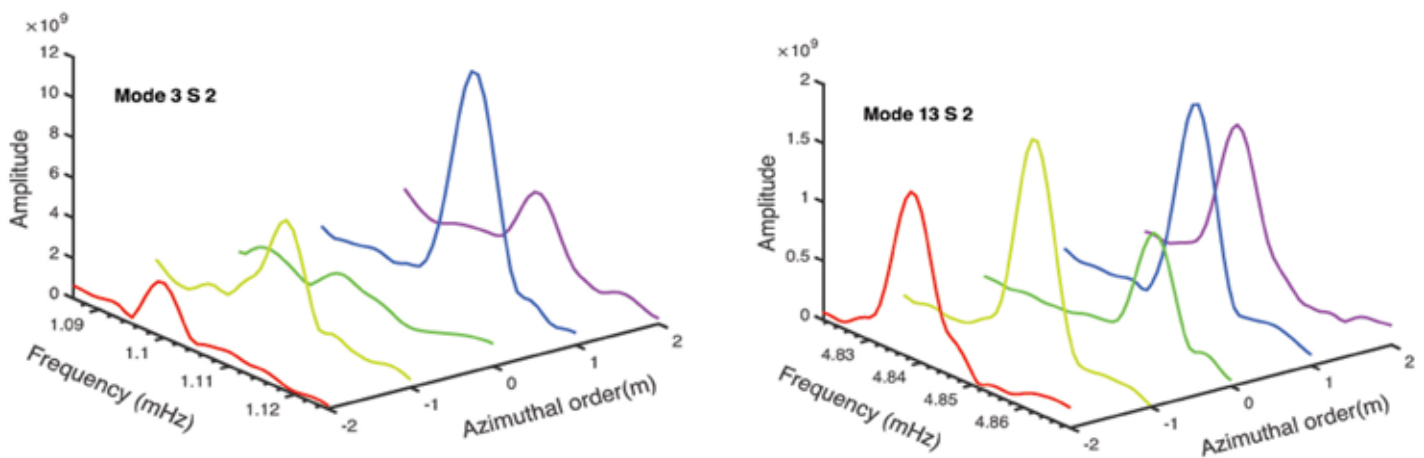


Figure 23. Amplitude spectra of receiver strips for, (left) 3S2 and (right) 13S2, inner core sensitive modes computed for Bolivia earthquake, 1994.

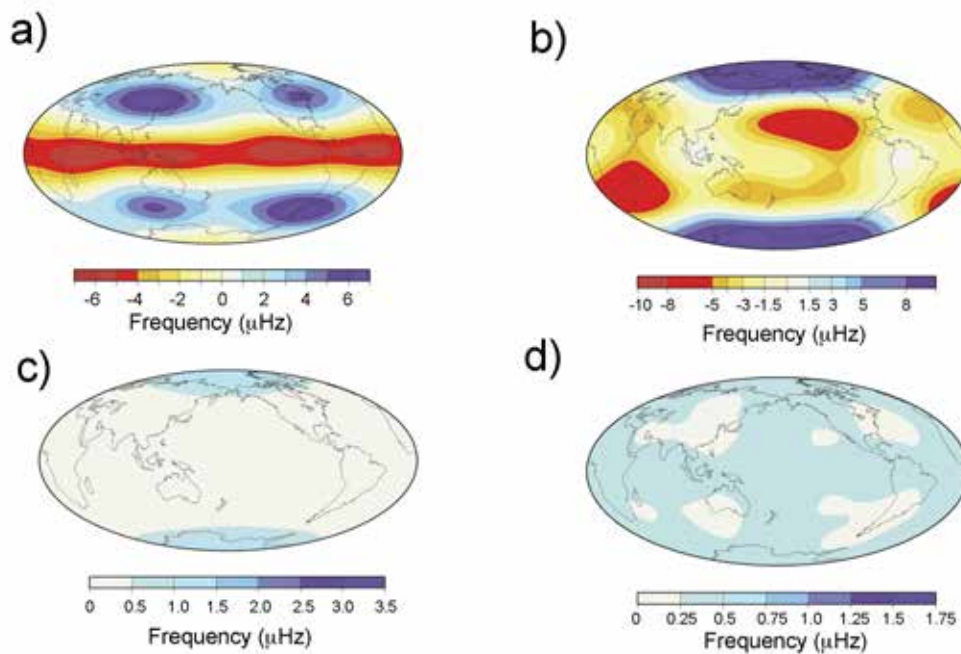


Figure 24. Measured splitting functions for (a) 3S2 and (b) 13S2 modes. Standard deviation of splitting functions for (c) 3S2 and (d) 13S2 modes. Since all the singlets are not excited equally well (as shown in Figure 1, we use more than one event to achieve well-constrained splitting function).

To have a better understanding on the robustness of estimated 3-D structures, we developed a probabilistic Bayesian approach. The Bayesian method combines a prior information (what we know beforehand) and the likelihood (which incorporates the data information). It follows a random search in which models are proposed randomly from a prior range. The proposed model is accepted or rejected based on the ratio of likelihood in the current iteration to that in the previous step. If the proposed model is accepted then the model is updated and is continued further. In contrast, if the proposed model is rejected then the old model is kept and the process is repeated. This algorithm is run for 100-thousands of iterations and the ensemble of models are collected. From this ensemble of models, we can evaluate the uncertainty of the 3-D structure.

After evaluating the applicability of this approach through synthetic experiments for different modes, we applied it to estimate the splitting coefficients for more than 20 inner-core sensitive modes. The estimated coefficients are visualized on the surface of spherical Earth through the splitting functions. Example of splitting functions and their uncertainties are shown in Figure 24 for two inner core sensitive modes (3S2 and 13S2). One of the most common features of these splitting functions is that the frequency is positive near the poles and is negative near the equator suggesting faster velocity along the polar direction and slower along the equator. This directional dependence of velocity is due to the presence of cylindrical anisotropy in the inner core. In contrast, the standard deviation of the splitting functions for 3S2 is much higher than that for 13S2, particularly near the poles. This is due to the noisy receiver strips and almost no excitation of the zero line in the case of 3S2 mode. Such an assessment would not be possible with a traditional approach.

## RECENT PUBLICATIONS

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- Pachhai, S., Tkalcic, H. & Masters, G. 2016. Estimation of splitting functions from Earth's normal mode spectra using the neighbourhood algorithm, *Geophys. J. Int.*, 204, 111-126.

# JEAN BERNARD MINSTER

Distinguished Professor of Geophysics

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*Research Interests: Seismology, Geodesy, Data Science and Policy*

As reported last year, I stepped down from my long-held role as chair of the ICSU World Data System (ICSU-WDS) Scientific Committee (SC) in July 2015. This did not end my participation, however, and I have attended all teleconferences and several meetings, chaired by Professor Sandy Harrison of the University of Reading.

As Chair Emeritus for WDS, I have served as liaison with the ICSU Committee for Data in Science and Technology (CODATA [www.codata.org](http://www.codata.org)). This is a completely different aspect of the emerging words of data policies and data sharing. I was elected to the Research Data Alliance (RDA: [www.rd-alliance.org](http://www.rd-alliance.org)) Council in early 2016, and have served since then. My specific assignments include:

- RDA Council
- Council Strategy
- Sustainability and Funding
- Engagement and Communications
- Operations and Coordination

A major event, first in history, took place in Denver, CO, on September 10-17 2016. It was called "*International Data Week*" (IDW: [www.internationaldataweek.org](http://www.internationaldataweek.org)). For the first time, several events were synchronized:

- The ICSU World Data System and ICSU CODATA held their international conference SciDataCon-2016, including business meeting, together with
- the WDS member forum,
- the CODATA Data Science conference
- The RDA plenary meeting (P#8) was held in the same venue immediately afterwards

An important component of IDW was held mid-week, labeled *International Data Forum* (IDF). It featured senior speakers from various governments, and agencies. As a member of the organizing committee, I spend innumerable hours on the phone coordinating the activities and obligations of three very different international organizations, based on different continents, all focused on data issues. This was surprisingly challenging, and convergence did not happen until very late in the planning process.

I organized and chaired a session entitled "*Data Stories*" that dealt with Citizen Science (such as Great Barrier Reef Coral bleaching survey and OpenStreetMap), and Health Science (*Doctors without Borders*). That session was extremely well received. Ultimately, the IDW and IDF were remarkably successful, and there is an emerging strong consensus to repeat such an event in a couple of years, probably on a different continent, with South America and Africa as serious contenders. I will surely participate.

A recent entrant on the international data scene is the *Research Data Alliance* (RDA). As a newly minted member of the RDA Council, I continue to be an active participant in a number of the innumerable RDA Working Groups and Interest Groups, in particular:

- Repository Audit and Certification DSA–WDS Partnership WG
- Libraries for Research Data IG
- RDA/CODATA Legal Interoperability IG
- RDA/WDS Certification of Digital Repositories IG
- RDA/WDS Publishing Data IG
- Digital Practices in History and Ethnography IG

Although I am a silent participant in most of these, I have been very active in a couple which have turned out to be very demanding. The two most demanding ones are the DSA-WDS, and the Legal Interoperability groups. In the former case, the task was to coordinate the criteria used by the World Data System and the Data Seal of Approval organizations to certify their respective data facilities. What looked initially like a simple process turned into a protracted discussion. A main difficulty arose because Humanities and Social Science data centers notion of data curation is to preserve the data exactly as submitted, whereas physical sciences and in particular, astronomy allow updating of the metadata records as more information (e.g. calibration) becomes available. After 18 months of effort, a common set of criteria was arrived at, that is undergoing the RDA process of adoption, and that is being presented at a variety of venues, notably the AGU meetings.

The Legal Interoperability Interest Group was the object of well over 65 teleconferences, involving primarily lawyers from several continents. Except for one librarian, I was the only non-legal participant and the only scientist. The main issues discussed involved intellectual property rights, and the licensing of scholarly works and the associated data. Profound differences existing between US laws and practices notably the *fair use* doctrine, the *European Database Directive*, which has been adopted by almost all EU members, and the Australian intellectual property laws. The final report was reviewed by no fewer than 20 reviewers. The six principles listed below were arrived at after considerable discussion. They seem to be uncontroversial, yet had to be reworded more than once in response to the reviews. The final document includes a lengthy attachment outlining implementation guidelines. Of special note is the recommendation that the Creative Commons CC-By license be used (instead of the oft quoted CC-0) in order to improve legal interoperability among various jurisdictions. Again the RDA adoption process is underway, and the material is being circulated among National Academies, Learned societies, and data facilities worldwide, with a target date of April, 2017.

Finally, I continue my service on the EarthCube Council of Data Facilities as well as my participation in the NASA planning and review activities surrounding two Low-Earth-Orbit geophysical missions planned for the end of the decade: ICESAT-2 and NISAR.

## RECENT PUBLICATIONS

Legal Interoperability of Research Data: Principles and Implementation Guidelines

<https://rd-alliance.org/rda-codata-legal-interoperability-research-data-principles-and-implementation-guidelines-now>

<https://www.rd-alliance.org/wds-and-dsa-announce-unified-requirements-core-certification-trustworthy-data-repositories-developed>

# WALTER MUNK

Research Professor

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*Research Interests: Ocean waves and sea level changes*

My research has again been divided between acoustics and physical oceanography. The focus is on wind drag on a roughened sea surface (wavelengths 2 cm to 1m), central to understanding the wind-driven ocean circulation, coastal upwelling, near-surface mixing, deep pressure fluctuations, etc., etc. These are classical problems, but some of current naval interest.

It is surprising that these classical problems are not well understood. Let me review what has been accomplished and what has NOT. In 1954 Cox confirmed that oil spread on the channel between Hawaii and Maui reduced not only the hf-roughness (understood since the old sailing days), but also the low-frequency higher waves. In 1963 Van Dorn demonstrated that soap on an open-air yacht basin greatly reduced the wind-induced surface slope.

The 1954 measurements were part of an experiment to photograph sun-glitter from the AFOSR B-17 photographic plane. Thirty images from wind speeds between 1 and 15 m/s yielded (i) a remarkably linear dependence on windspeed, and (ii) a remark-



Figure 25.



ably large cross-wind component of 59% the up-down wind component. These results were confirmed in 2006 by Breon and Henriot with almost 10 million satellite images taken globally. Attempts to explain these broad directional beams have not been successful. Ultimately they need to produce a balance between generation and dissipation, and the molecular dissipation of gravity waves is negligible compared to any reasonable model of wind generation.

Here we have taken a different approach. We boldly assume that the flow of the turbulent atmosphere over the sea surface is associated with random pressure points travelling at some velocity  $V$  and generating a non-directional wave system. The directional pattern is formed by the subsequent coherent addition of waves formed at different times. This is precisely the ship wake problem first reported by Kelvin in 1887. The wave direction varies from  $\alpha = -90^\circ$  at the starboard bow to  $0$  at the stern to  $+90$  at the port bow, accordance with  $C(k) = V \cos \alpha$  (Munk 2017, in preparation). Remarkably, some geometric features, such as the Kelvin cusps, are independent of the velocity  $V$  of the pressure points. The hypothesis requires further observations.

We are now engaged in trying to understand the other finding: (i) the linear dependence of mean-square slope on wind speed.

## RECENT PUBLICATIONS

W. E. Farrell, J. Berger, J.-R. Bidlot, M. Dzieciuch, W. Munk, R. A. Stephen, and P. F. Worcester (2016), Wind sea behind a cold front and deep ocean acoustics, *J. Phys. Oceanogr.* 46, 1705-1716, DOI: 10.1175/JPO-D-15-0221.1

W. Munk (2015) An oceanographic perspective, in Sustainable Humanity, Sustainable Nature: Our Responsibility Pontifical Academy of Sciences Extra Series 41 (Vatican City).



## JOHN ORCUTT

Distinguished Professor of Geophysics, Editor-in-Chief of AGU Earth and Space Science

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*Research Interests: Seafloor seismology and acoustics including applications to nuclear test ban treaty verification. Large scale data management and access.*

In close collaboration with Jon Berger, Martin Rapa, and Jeff Babcock and with an objective of increasing the fidelity of recorded data on the seafloor, we have developed a novel approach for burying seismometers in the seafloor, which could be readily extended to other sensors. Our rationale for seismometers, however, is to reduce current or flow noise around a sensor that simply sits on the seafloor as is the case for all current systems in use. In a large experiment we conducted years ago south of Hawaii, we tested a variety of seismometers to ascertain the gains that could be realized; e.g. Collins et al., 2001. Some sensors sat directly in the seafloor sediment, one was buried just below the surface and another was inserted into a cased borehole drilled earlier by the NSF Ocean Drilling Program (OSN-1). The quietest location turned out to be the sensor that was buried just below the surface.

Earlier this year, during science sea trials of the new R/V *Sally Ride*, we took advantage of the availability of the WHOI *JASON ROV* to test a remote burial system on the seafloor in 1000m of water. The system, inserted in the seafloor, is pictured in Figure 26. The burial system comprises three aluminum tubes arranged in a triangle with the seismometer in the center. The three tubes are attached to a manifold leading to a pump on *JASON* sucks the tubes into the seafloor (e.g. suction piles often used in seafloor anchoring). A movie of the operation (in real time) can be played from [https://www.dropbox.com/s/2rczz2lle1tk60q/Sucker\\_clip.mp4?dl=0](https://www.dropbox.com/s/2rczz2lle1tk60q/Sucker_clip.mp4?dl=0).

Once the *JASON* pumps are turned on, the system buries the tubes quickly (seconds) as well as well as the centrally mounted seismometer. Once inserted, the pumps can be reversed to blow the system back to the seafloor leaving behind the seismometer for long-term recording.

We subsequently named the tube assembly 'SPIDER' for *Seismometer Penetration and Internment Device for Embedment Realization*. A future assembly is shown in Figure 27. In the new design, each of the tubes has its own seawater pump and operation will be coordinated between the pumps to minimize the tilt of the assembly as the *SPIDER* is pumped into the seafloor. Each of the pumps has its own

*Deep Sea Power and Light* battery pack and the recording system and batteries for long-term operation (1-3 years) are attached to the *SPIDER*. The power and recording assemblies are released when *SPIDER* returns to the sea surface for recovery by a research vessel at the surface. We plan to add a camera and possibly LIDAR to the package to map the seafloor as the target is approached.

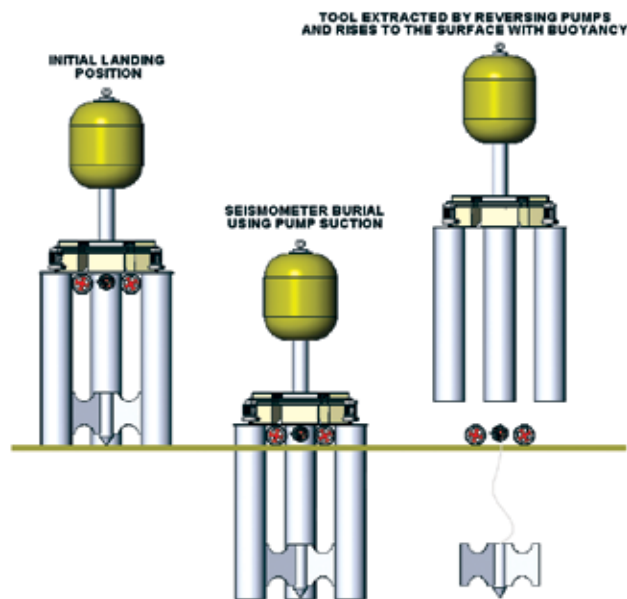


Figure 26. SPIDER inserted in seafloor using WHOI JASON



Figure 27. Operation of SPIDER with seafloor landing on the left, insertion in the center, and recover of SPIDER on the right leaving behind power, electronics and acoustic transponder on the right.



The data will be valuable for assessing the effects of seafloor morphology and constitution and, in time, using the knowledge for the artificial intelligence (AI) needed to ensure success with each drop.

Provisional Patent: 37866-613P01US/2017-198-1

## RECENT PUBLICATIONS

Collins, J. A., Vernon, F. L., Orcutt, J. A., Stephen, R. A., Peal, K. R., Wooding, F. B., et al. (2001). Broadband seismology in the oceans: Lessons from the Ocean Seismic Network Pilot Experiment. *Geophysical Research Letters*, 28(1), 49–52. doi.org/10.1029/2000GL011638

Berger, J., Laske, G., Babcock, J. and Orcutt, J., An Ocean Bottom Seismic Observatory with Near Real-time Telemetry, *Earth and Space Sci.*, doi: 10.1002/2015EA000137, 2016.

# ANNE POMMIER

Assistant Professor

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*Research Interests: Physics and chemistry of silicate melts; role of magma in planetary interiors, from the scale of volcanic magma reservoirs to planetary-scale magma oceans; evolution of planetary interiors from "deep time" (e.g., planet evolution) to the present.*

Research projects over the last year have mainly focused on (i) the experimental investigation of the core-mantle boundary systems of terrestrial planets (in particular, Mercury), (ii) the investigation of subduction zones by combining field and laboratory electrical measurements.

(i) Transfers of mass, heat, and electric currents between a silicate mantle and an underlying metallic core characterize the Core-Mantle Boundary (CMB) region of terrestrial planets. In particular, constraining the structure and chemistry of the CMB region of Mercury is crucial to understand its thermal state and unique magnetic activity. To probe the physical and chemical processes of the Hermean CMB, SIO Postdoctoral Researcher Zhou Zhang and I conducted an electrical study of metal-olivine

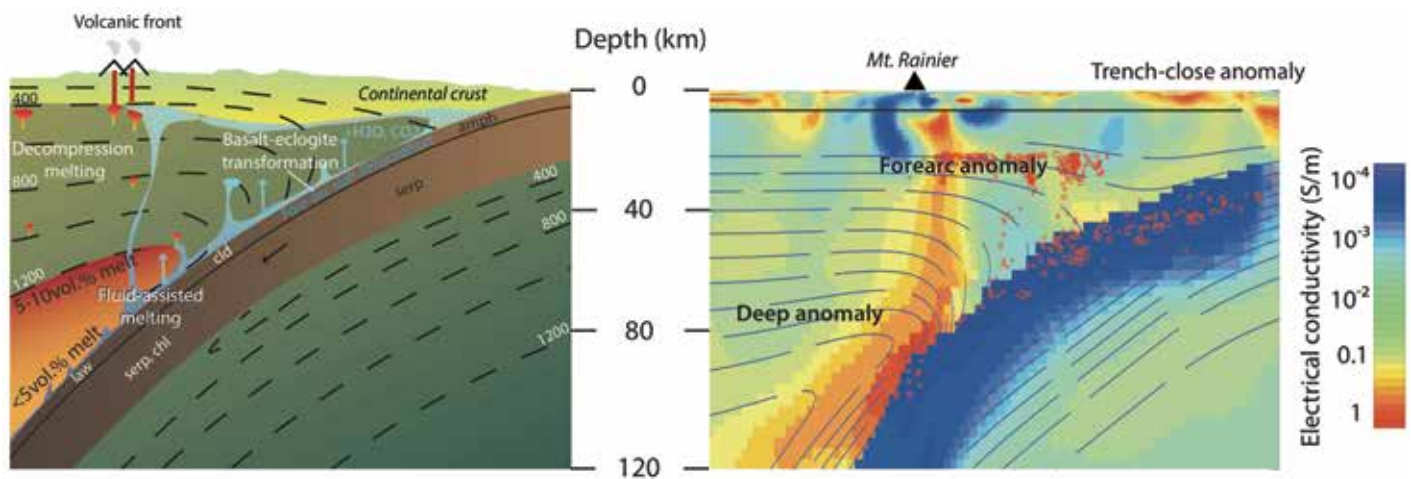


Figure 28. Detection of fluids using electromagnetic studies: comparison between the petrological view of a subduction zone (left: after Schmidt and Poli, 1998; Grove et al., 2012; Timm et al., 2014) and an electromagnetic profile (right: Cascadia, McGary et al., 2014). Labels in the slab correspond to stable hydrous minerals: amph: amphibole; cld: chloritoid; law: lawsonite; serp: serpentine; chl: chlorite. Figure from Pommier and Evans

systems at pressure, temperature, and chemistry conditions relevant to the mantle and CMB region of Mercury (Zhang and Pommier, in rev.). This is the first experimental study performed in the new Planetary and Experimental Petrology Lab in IGPP. Under funding from an SIO Postdoc Fellowship, a UC San Diego Academic Senate Research Grant, and NSF-COMPRES, we conducted electrical experiments in the multi-anvil apparatus at 5 and 7 GPa and up to 1675°C using the impedance spectroscopy technique. The samples are composed of one metal layer (Fe, FeS, FeSi<sub>2</sub>, or Fe-Ni-S-Si) and one polycrystalline olivine layer, with the metal:olivine ratio ranging from 1:0.7 to 1:9.2. For all samples, we observe that the bulk electrical conductivity increases with temperature from 10<sup>-2.5</sup> to 10<sup>1.8</sup> S/m, which is higher than the conductivity of polycrystalline olivine but lower than the conductivity of the pure metal phase at similar conditions. In some experiments, a conductivity jump is observed at temperature corresponding to the melting temperature of the metallic phase. Both the metal:olivine ratio and the metal phase geometry control the electrical conductivity of the two-layer samples. By combining electrical results, textural analyses of the samples, and previous studies of the structure and composition of Mercury's interior, we propose an electrical profile of the deep interior of planet that accounts for a layered CMB-outer core structure. The electrical model is in agreement with existing conductivity estimates of Mercury's lower mantle and CMB using magnetic observations from MESSENGER and thermodynamic calculations, and thus, supports the hypothesis of a layered CMB-outermost core structure in the present-day interior of Mercury. We propose that the layered CMB-outer core structure is possibly electrically insulating, which may influence significantly the planet's structure and cooling history.

(ii) Understanding the thermal and compositional state of our planet and in particular across subduction zones has been the focus of a collaboration with Dr. Rob L. Evans (WHOI) (Pommier and Evans, 2017). The cycle of fluids in subduction zones is a critical component of slab recycling and continental building processes. A better understanding of the role of melt and volatiles is therefore key to improving our knowledge of the geodynamic processes at work, shaped by mass transfer and energy release. It can also help us better assess volcanic and earthquake hazards in these contexts. We compiled electromagnetic studies of subduction zones to identify common and unique electrical signatures and based on electrical laboratory measurements, we interpreted them in terms of fluids and rheological constraints. This contribution is a novel synthesis in which we propose new explanations for electrical anomalies at 80-100 km depth that involve the rheology of the incoming seafloor (presence of fracture zones or seamounts) and its capability to store fluids. We hypothesize that regions where very strong conductive anomalies are observed in the mantle wedge at depths of about 80-100 km are related to the subduction of anomalous seafloor, either related to excessive fracturing of the crust (e.g., fracture zones), subduction of seamounts, or other ridges and areas of high relief. These features deform the seafloor prior to entering the trench, permitting more widespread serpentinization of the mantle than would otherwise occur. An alternative explanation is that the large conductors represent melts with higher contents of crustal-derived volatiles (such as C and H), suggesting in particular locally higher fluxes of carbon into the mantle wedge, perhaps also associated with subduction of anomalous seafloor structures with greater degrees of hydrothermal alteration. This research on subduction is supported by NSF-EAR Petrology and Geochemistry.

## RECENT PUBLICATIONS

- Z. Zhang and A. Pommier, Electrical Investigation of Metal-Olivine Systems and Application to the Deep Interior of Mercury, *JGR-Planets*, in rev.
- A. Pommier and R. L. Evans, Constraints on Fluids in Subduction Zones from Electromagnetic Data, *Geosphere*, 13 (4), doi:10.1130/GES01473.1, 2017.

# DAVID T. SANDWELL

Professor of Geophysics

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*Research Interests: Geodynamics, global marine gravity, crustal motion modeling, space geodesy*

**Students and Funding:** Research for the 2016-17 academic year was focused on understanding the dynamics of the crust and lithosphere. Our group comprises four graduate students Eric Xu, John DeSanto, Hugh Harper, Hiroki Arai, and one lab assistant Ben Tea. Brook Tozer will join our group as a postdoc in early 2018. Our research on improvement the marine gravity field is co-funded by the National Science Foundation (NSF) and the Office of Naval Research (ONR). The NASA Earth Surface and Interior Program as well as the Southern California Earthquake Center provides funding for our research on the strain rate and moment accumulation rate along the San Andreas Fault System from InSAR and GPS.

**Global Gravity and Bathymetry:** We are improving the accuracy and spatial resolution of the marine gravity field using data from three new satellite radar altimeters (CryoSat-2, AltiKa and Jason-2). This is resulting in a factor of 2-4 improvement in the global marine gravity field. Most of the improvement is in the 12 to 40 km wavelength band, which is of interest for investigation of seafloor structures as small as 6 km. The improved marine gravity is important for exploring unknown tectonics in the deep oceans as well as revealing thousands of uncharted seamounts (Matthews et al., 2016; Zhang and Sandwell, 2016; [http://topex.ucsd.edu/grav\\_outreach](http://topex.ucsd.edu/grav_outreach)).

**Integration of Radar Interferometry and GPS:** We are developing methods to combine the high accuracy of point GPS measurements with the high spatial resolution from radar interferometry to measure interseismic velocity along the San Andreas Fault system (Figure 29) associated with earthquake hazard (Xu et al., 2017). Over the past three years, three new InSAR satellites became operational. Sentinel 1A and 1B are the first of a series of European Space Agency (ESA) SAR satellites to provide an operational mapping program for crustal deformation along all zones having high tectonic strain. The third new satellite is ALOS-2, launched by JAXA. **These satellites have the measurement cadence and spatial coverage needed to revolutionize our understanding of earthquake cycle processes both globally and along the San Andreas Fault System (Figure 29).** The InSAR processing was performed with new geometric alignment software (Xu et al., 2017) which is now part of GMT-SAR developed at SIO (<http://topex.ucsd.edu/gmtsar>).

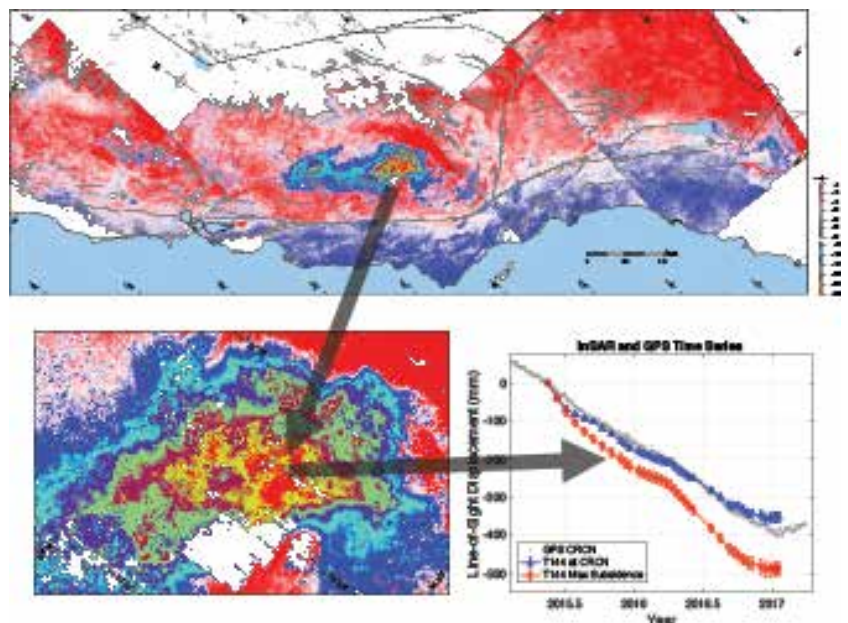


Figure 29. Crustal deformation map of California derived from the first 2.5 years of Sentinel-1 radar interferometry. The large subsidence signal in the Central Valley is caused by excessive pumping of groundwater during the 2014.5 - 2016.8 drought. Abundant precipitation in the winter of 2017 began to recharge some of the aquifers resulting in a pause of the subsidence.

## RECENT PUBLICATIONS

Matthews K. J., R.D. Müller, D.T. Sandwell, Oceanic microplate formation records the onset of India–Eurasia collision, *Earth and Planetary Science Letters*, 433, 204-214, 2016.

DeSanto, J. B., D. T. Sandwell, and C. D. Chadwell, Seafloor geodesy from repeated sidescan sonar surveys, *J. Geophys. Res. Solid Earth*, 121, 4800–4813, 2016.

Sandwell, D. T., and P. Wessel, Interpolation of 2-D vector data using constraints from elasticity, *Geophys. Res. Lett.*, **43**, 703-709, 2016.

Xu, X., D. T. Sandwell, E. Tymofyeyeva, A. Gonzalez-Ortega, and X. Tong, Tectonic and anthropogenic deformation at the Cerro Prieto geothermal step-over revealed by Sentinel-1 InSAR, *IEEE Trans. Geosciences and Remote Sensing*, **55**, 5284-5292, 2017.

Xu, X., D. T. Sandwell, D. Bassett; A Spectral Expansion Approach for Geodetic Slip Inversion: Implications for the Down-dip Rupture Limits of Oceanic and Continental Megathrust Earthquakes, *Geophysical Journal International*, in press, <https://doi.org/10.1093/gji/ggx408>, 2017.

Zhang, S., D. T. Sandwell, Retracking of SARAL/AltiKa radar altimetry waveforms for optimal gravity field recovery, *Marine Geodesy*, **40**, 40-56, 2017.

## PETER SHEARER

Distinguished Professor

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*Research Interests: Seismology, Earth structure, earthquake physics*

My research uses seismology to learn about Earth structure and earthquakes, using data from the global seismic networks and local networks in California, Nevada, Hawaii, and Japan. My work in crustal seismology has focused on improving earthquake locations using waveform cross-correlation, systematically estimating small-earthquake stress drops from P-wave spectra, and studying properties of earthquake clustering, especially swarms and foreshock sequences.

Graduate student Daniel Trugman applied an improved spectral decomposition approach to estimate stress drops within five regions of dense seismicity in southern California (Trugman and Shearer, 2017b). The results show that average stress drop increases with moment for each region, a clear break from earthquake self-similarity, but a result that depends upon the assumed high-frequency falloff rate. Daniel also refined and improved our earthquake relocation codes into the software package GrowClust (Trugman and Shearer, 2017a) and applied it to two recent earthquake swarms in Nevada, which yielded dramatically sharpened images of the seismicity (see Figure 30). Graduate student Wei Wang performed a comprehensive analysis of coda waves in southern California and showed how they can be modeled using a multiple-scattering Monte Carlo seismic phonon algorithm to determine the best-fitting 1-D model of scattering properties and intrinsic attenuation (Wang and Shearer, 2017).

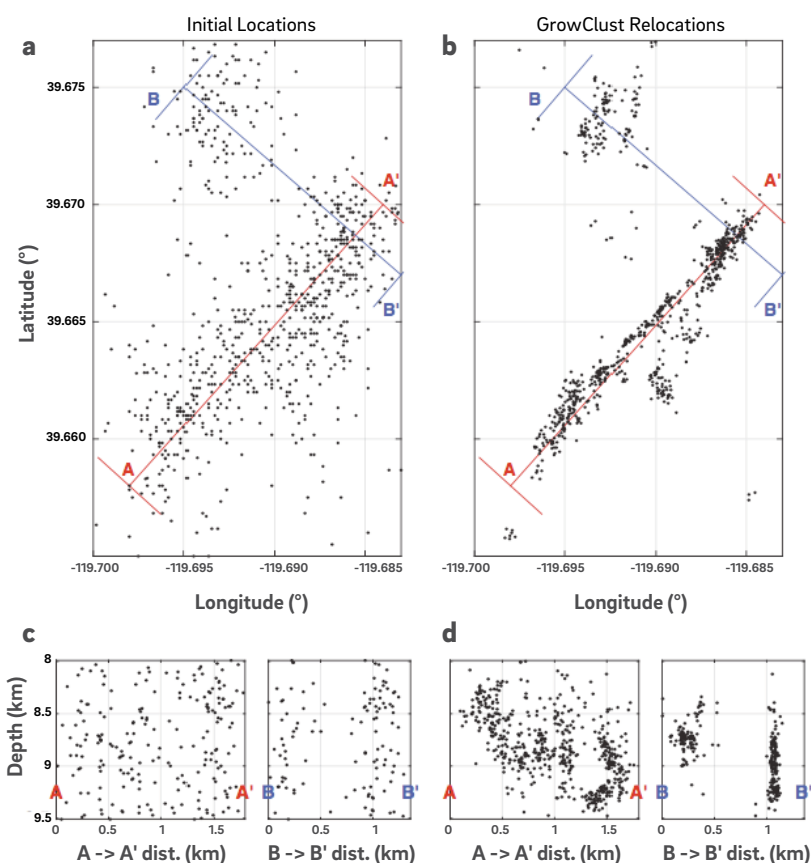
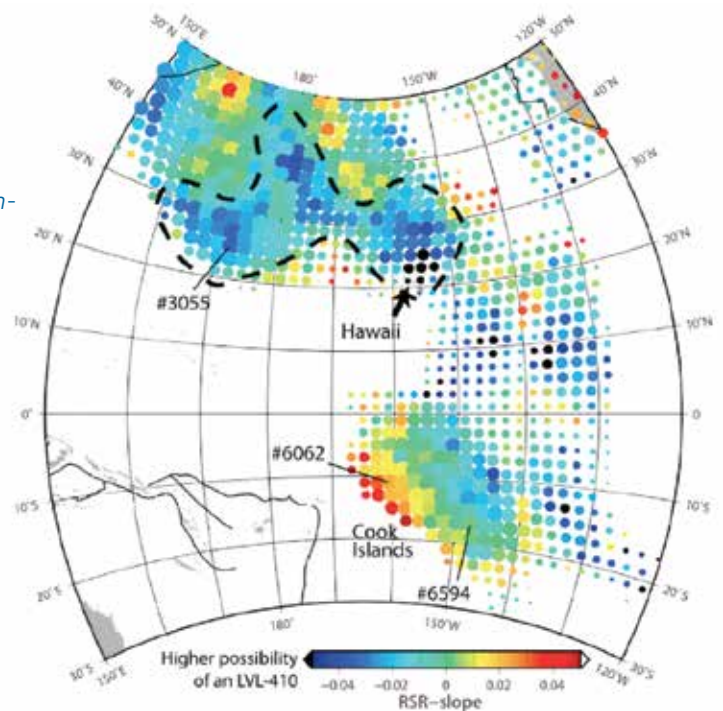


Figure 30. Comparison of initial catalog earthquake locations and GrowClust relocations for the 2012–2015 Spanish Springs, Nevada, sequence. (a, catalog) and (b, GrowClust) provide a map view comparison of the initial and relocated event positions. (c, catalog) and (d, GrowClust) provide a comparison of fault-parallel and fault-perpendicular cross.

Figure 31. A map of the western Pacific, showing the locations in dark blue where a low velocity layer (LVL) above the 410-km discontinuity is indicated by SS precursor observations.



On a more regional scale, postdoc Janine Buehler used Pn and Sn arrivals from the USArray experiment to resolve lateral variations in the upper-mantle velocity structure under the United States, including anisotropy, Vp/Vs ratios, and variations in the velocity gradient (Buehler and Shearer, 2016b). Her results indicate partially molten mantle beneath the Snake River Plain and the Colorado Plateau and changes in the orientation of azimuthal anisotropy with depth. Janine also used USArray data to quantify event location uncertainty across North America through the use of source-receiver reciprocity, i.e., by “relocating” seismic stations based on their travel-time residuals (Buehler and Shearer, 2016a).

Using global seismic data, Green Scholar and postdoc Shawn Wei studied SS precursor waveforms and identified anomalous reflections from the 410-km discontinuity that require the presence of a low-velocity layer (LVL) just above the interface, likely caused by partial melting due to dehydration of ascending mantle across the 410-km discontinuity, which is predicted by the transition zone water filter hypothesis (Wei and Shearer, 2017). This suggests partial melting with varying intensities across the Pacific and provides indirect evidence of a hydrous mantle transition zone with laterally varying water content.

## RECENT PUBLICATIONS

- Buehler, J. S., and P. M. Shearer, Characterizing earthquake location uncertainty in North America using source–receiver reciprocity and USArray, *Bull. Seismol. Soc. Am.*, 106, 2395–2401, doi: 10.1785/0120150173, 2016a.
- Buehler, J. S., and P. M. Shearer, Uppermost mantle seismic velocity structure beneath USArray, *J. Geophys. Res.*, 121, 1–13, doi: 10.1002/2016JB013265, 2016b.
- Trugman, D. T., and P. M. Shearer, GrowClust: A hierarchical clustering algorithm for relative earthquake relocation, with application to the Spanish Springs and Sheldon, Nevada, earthquake sequences, *Seismol. Res. Lett.*, 88, 1–13, doi: 10.1785/0220160188, 2017a.
- Trugman, D. T., and P. M. Shearer, Application of an improved spectral decomposition method to examine earthquake source scaling in southern California, *J. Geophys. Res.*, 122, doi: 10.1002/2017JB013971, 2017b.
- Wei, S. S., and P. M. Shearer, A sporadic low-velocity layer atop the 410 km discontinuity beneath the Pacific Ocean, *J. Geophys. Res.*, 122, doi: 10.1002/2017JB014100, 2017.
- Wang, W., and P. M. Shearer, Using direct and coda wave envelopes to resolve the scattering and intrinsic attenuation structure of Southern California, *J. Geophys. Res.*, 122, doi: 10.1002/2016JB013810, 2017.

# LEONARD J. SRNKA

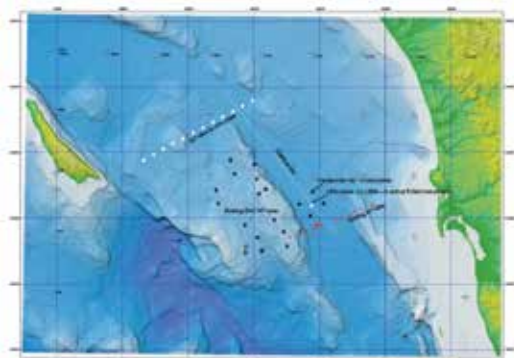
Professor of Practice

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*Research Interests: Land and marine electromagnetic (EM) methods; integrated geophysical data analysis and interpretation; inverse theory; energy outlooks and global change*



*Figure 32. Test of an airborne earth-field NMR system for detecting near-surface contaminants. Image courtesy of ExxonMobil.*



*Figure 33. Map of the 2006 San Diego Trough and Catalina Crater SIO seafloor electromagnetic research surveys. The SAIC MT sites were acquired for a separate project. Data from the red MT sites, deployed earlier, are not being used in the current research.*

In the fourth year of my SIO appointment, I completed my involvement in research started in 2006 whilst at ExxonMobil's Upstream Research Center on novel airborne Earth-field (~2.2 kHz) nuclear magnetic resonance (NMR) techniques for detecting contaminants in the shallow subsurface. I am first inventor on the 2013 US patent 8,436,609 that describes the method. Among other near-surface applications, this technology is particularly well suited for detecting oil under ice and snow, which is a crucial environmental need in the Arctic (Chavez et al., 2015) as the international hydrocarbon industry continues to evaluate the resource potential of the region. The research fits well in the SIO theme "Understanding and Protecting the Planet". The research led to a unique transmitter/receiver antenna design and signal protocol for T2 and T2\* relaxation responses to detect oils of various properties in the presence of the huge water-proton NMR signal. The work was done in conjunction with several geophysical service companies. A full-scale prototype using a helicopter-slung system was tested successfully in NE Canada in October 2016 (Figure 32) using a simulated Arctic environment. I did not directly participate in this latest test.

My research in seafloor electromagnetics continues on re-examining CSEM data acquired in the San Diego Trough in May-June 2006 in about 900m water depth using the R/V *Sproul* and R/V *New Horizon*. Novel electric field gradient measurements were taken using tandem long-wire electric (LEM) receivers pioneered by Professor Steve Constable. Nearby magnetotelluric (MT) measurements across the Catalina Crater, acquired for a separate project but whose data overlap the CSEM data in time, are being examined as candidates for use in pre-stack CSEM noise suppression methods similar to those used in the seismic reflection industry.

## RECENT PUBLICATIONS

Chavez, L., Altobelli, S., Fukushima, E., Zhang, T., Nedwed, T., Palandro, D., Srnka, L., and Thomann, H., 2015, Using NMR to detect Arctic oil spills. *Near Surface Geophysics*, 13 (4), 409-416. DOI: 10.3997/1873-0604.2015023

# FRANK VERNON

Research Geophysicist

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*Research Interests: Earthquake source physics and ground motion estimation. Time series analysis applied to terrestrial and space data. Development of instrumentation that improves the observation and understanding of seismic measurements. Realtime environmental sensor networks and wireless networking.*

I am the principal investigator for the ANZA Seismic Network that monitors local and regional seismicity in southernmost California. 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. The ANZA network is the foundation for the San Jacinto Fault Zone project in collaboration with Yehuda Ben-Zion to examine the dynamics associated with earthquake rupture. The studies being 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. In the late Spring of 2014, 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 vertical instruments in an area 600 meters by 600 meters, spanning the surface trace of San Jacinto Fault at Sage Brush Flats. Since then we have deployed 100 element three component linear fault crossing arrays at Blackburn Saddle (2015), Ramona Indian Reservation (2016), and Sage Brush Flats (2017).

My group operates the Array Network Facility for the USArray project Transportable Array. 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 is moved in a rolling manner to the east. At present, the ANF facility is already operating the largest broadband seismology system in the world. USArray finished up in the Lower 48 and is now deploying instruments in Alaska, creating a whole new set of challenges. USArray was the foundation of the Central and Eastern US Network, which is continuing to operate in the eastern United States.

The other major program I am involved in is the HPWREN program creating a largescale 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. HPWREN provides wide area wireless internet access throughout southernmost California including San Diego, 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. HPWREN is in the process increasing network capacity to support new innovative wildfire camera systems such as the AlertSDGECamera system.

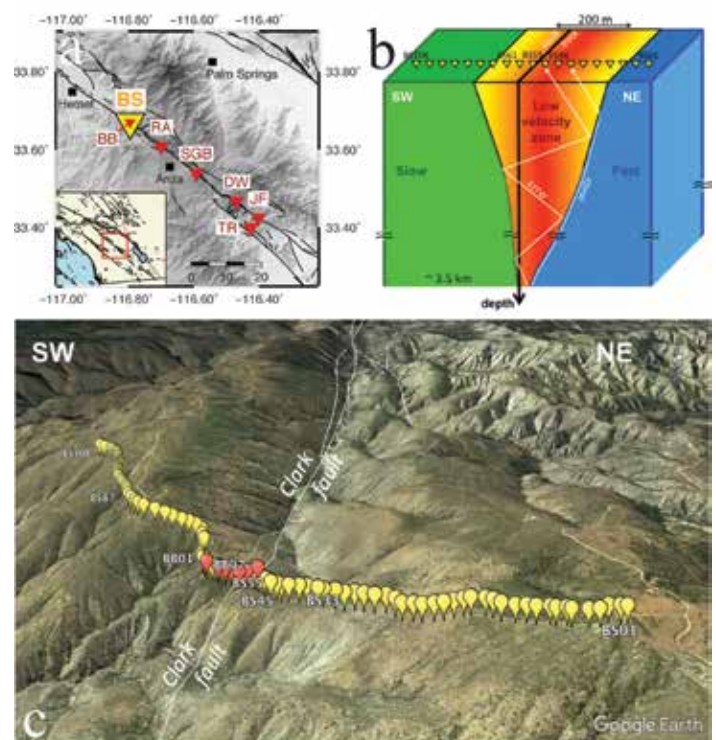


Figure 34.

## Recent Publications

- Jacques, A. A., Horel, J. D., Crosman, E. T., Vernon, F. and Tytell, J. (2016). The Earthscope US transportable array 1 Hz surface pressure dataset. *Geosci. Data J.*, 3: 29–36. doi:10.1002/gdj3.37
- Philippe Roux, Ludovic Moreau, Albanne Lecointre, Gregor Hillers, Michel Campillo, Yehuda Ben-Zion, Dimitri Zigone, and Frank Vernon (2016). A methodological approach towards high-resolution surface wave imaging of the San Jacinto Fault Zone using ambient-noise recordings at a spatially dense array. *Geophys. J. Int.* 206 (2): 980–992 doi:10.1093/gji/ggw193
- David J. Thomson and Frank L. Vernon (2016). Some Comments on the Analysis of “Big” Scientific Time Series. *Proceedings of the IEEE 104*, 11, 2220–2249. DOI:10.1109/JPROC.2016.2598218
- Z. E. Ross, M. C. White, F. L. Vernon, Y. Ben-Zion (2016). An Improved Algorithm for Real-Time S-Wave Picking with Application to the (Augmented) ANZA Network in Southern California. *Bulletin of the Seismological Society of America*, Vol. 106, No. 5, pp. 2013–2022, doi: 10.1785/0120150230
- Kerkez, B., Daniels, M., Graves, S., Chandrasekar, V., Keiser, K., Martin, C., Dye, M., Maskey, M. and Vernon, F. (2016), Cloud Hosted Real-time Data Services for the Geosciences (CHORDS). *Geosci. Data J.*, 3: 4–8. doi:10.1002/gdj3.36
- Zachary E. Ross, Yehuda Ben-Zion, Malcolm C. White and Frank L. Vernon. (2016). Analysis of earthquake body wave spectra for potency and magnitude values: implications for magnitude scaling relations, *Geophys. J. Int.* 207, 1158–1164 doi:10.1093/gji/ggw327
- Tanimoto, T., C.-J. Lin, C. Hadziioannou, H. Igel, and F. Vernon (2016), Estimate of Rayleigh-to-Love wave ratio in the secondary microseism by a small array at Piñon Flat observatory, California, *Geophys. Res. Lett.*, 43, 11,173–11,181, doi:10.1002/2016GL071133
- Alexander A. Jacques, John D. Horel, Erik T. Crosman, Frank L. Vernon (2017). Tracking Mesoscale Pressure Perturbations Using the USArray Transportable Array. *Monthly Weather Review*, 145, 3119–3142, DOI: 10.1175/MWR-D-16-0450.1





# PETER WORCESTER

Researcher Emeritus

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*Research Interests: Acoustical oceanography, ocean acoustic tomography, underwater acoustics.*

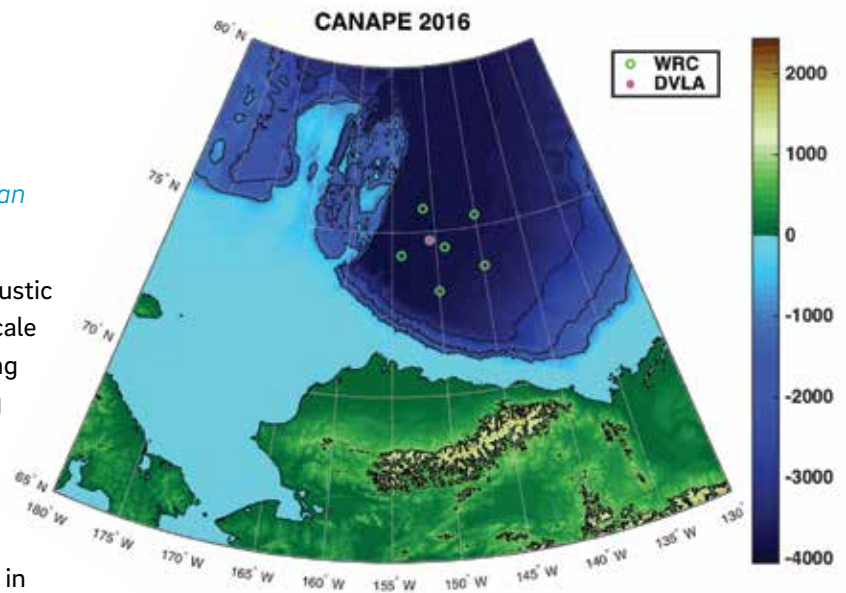
My research is focused on the application of acoustic remote sensing techniques to the study of large-scale ocean structure and on improving our understanding of the propagation of sound in the ocean, including the effects of scattering from small-scale oceanographic variability.

My recent research has been focused in the Arctic Ocean, which is undergoing dramatic changes in the ice cover and ocean structure. Changes in sea ice and the water column affect both acoustic propagation and ambient noise. This implies that what was learned about Arctic acoustics in the past is now obsolete. My group has conducted or participated in a series of experiments in the Arctic.

Thin-ice Arctic Acoustic Window (THAAW). A Distributed Vertical Line Array (DVLA) receiver mooring was deployed near the North Pole during April 2013. The mooring line parted above the anchor shortly after deployment, and the mooring drifted slowly south toward Fram Strait in the Transpolar Drift, providing a time series of ambient noise until it was recovered in September 2013 (Ozanich et al., 2017).

DAMOCLES, ACOBAR, and UNDER-ICE. My group participated in a series of ocean acoustic tomography experiments in Fram Strait that were led by our colleagues at the Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway (Geyer et al., 2016; Sagen et al., 2017).

Canada Basin Acoustic Propagation Experiment (CANAPE). CANAPE was designed to determine the fundamental limits to the use of acoustic methods and signal processing imposed by ice and ocean processes in the new Arctic. To achieve this goal, the CANAPE project conducted two experiments: (1) the short term 2015 CANAPE Pilot Study and (2) the yearlong 2016–2017 CANAPE experiment. The hope is that these first steps will lead to a permanent acoustic monitoring, navigation, and communications network in the Arctic Ocean. The specific goals of the CANAPE project include (1) understanding the impacts of changing sea ice and oceanographic conditions on acoustic propagation and fluctuations; (2) characterizing the depth dependence and temporal variability of the ambient noise field; and (3) measuring the spatial and temporal variability in the upper ocean throughout the annual cycle by combining acoustic and other data with ocean models.



*Figure 35. The 2016–2017 CANAPE experiment consisted of six Teledyne Webb Research acoustic transceivers (WRC, green) and a DVLA receiver (DVLA, red). The array radius is 150 km.*

For the 2016–2017 CANAPE experiment, six acoustic transceiver moorings and a DVLA receiver mooring were deployed north of Alaska during August–September 2016 and recovered during September–October 2017 (Figure 35). The experiment combines measurements of acoustic propagation and ambient noise with the use of an ocean acoustic tomography array to help characterize the oceanographic variability throughout the year in the central Beaufort Sea. The one-year deployment in a fixed geometry provides measurements in open water during summer, in the marginal ice zone (MIZ) as it transitions across the array during the spring and autumn, and under complete ice cover during winter. Processing and analysis of the data acquired during the 2016–2017 CANAPE experiment has just begun.

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- Farrokhrooz, M., K. E. Wage, M. A. Dzieciuch, and P. F. Worcester (2017), Vertical line array measurements of ambient noise in the North Pacific, *J. Acoust. Soc. Am.*, 141(3), 1571–1581, doi:10.1121/1.4976706.
- Geyer, F., H. Sagen, G. Hope, M. Babiker, and P. F. Worcester (2016), Identification and quantification of soundscape components in the Marginal Ice Zone, *J. Acoust. Soc. Am.*, 139(4), 1873–1885, doi:10.1121/1.4945989.
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- Ramp, S. R., J. A. Colosi, P. F. Worcester, F. L. Bahr, K. D. Heaney, J. A. Mercer, and L. J. Van Uffelen (2017), Eddy properties in the Subtropical Countercurrent, Western Philippine Sea, Deep Sea Research Part I: *Oceanographic Research Papers*, 125, 11–25, doi:10.1016/j.dsr.2017.03.010.
- Sagen, H., P. F. Worcester, M. A. Dzieciuch, F. Geyer, S. Sandven, M. Babiker, A. Beszczynska-Möller, B. D. Dushaw, and B. Cornuelle (2017), Resolution, identification, and stability of broadband acoustic arrivals in Fram Strait, *J. Acoust. Soc. Am.*, 141(3), 2055–2068, doi:10.1121/1.4978780.

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## MARK ZUMBERGE

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*Research Interests: Measurement of gravity and pressure in the marine and subaerial environments, development of new seismic instrumentation, optical fiber measurements of strain.*

## DISTRIBUTED ACOUSTIC SENSING WITH AN OPTICAL FIBER IN THE SAFOD BOREHOLE

(with William Ellsworth, Stanford University, and Martin Karrenbach, OptaSense)

There is a new sensing technology, Coherent Optical Time Domain Reflectometry, that is potentially transformative in geophysics. It allows strain along the length of a standard telecommunications optical fiber to be sampled at hundreds of Hz at thousands of intervals a few meters apart with a strain resolution below a nanostrain, far surpassing the capabilities seen in the older techniques. It converts a standard optical fiber cable into a dense, linear seismic array.

We tested the new OptaSense interrogator on an optical fiber that extends from the surface to 864 m depth in the San Andreas Fault Observatory at Depth (SAFOD) in central California. Soon after installation, a magnitude 1.4 earthquake occurred 10 km directly beneath the borehole. Figure 36 shows the resulting seismogram (processed by M. Karrenbach of Optasense). The instrument was configured for a 10 m gauge length and 1 m spacing, and about 80 m of cable exists between the recording unit and the wellhead. Therefore channel number 80 (labeled along the top axis of the figure) corresponds to the surface and channel 900 is at about 820 m depth.

## Phase mode: Two Pulse Rayleigh "Virtual Interferometer" → true strain measurement

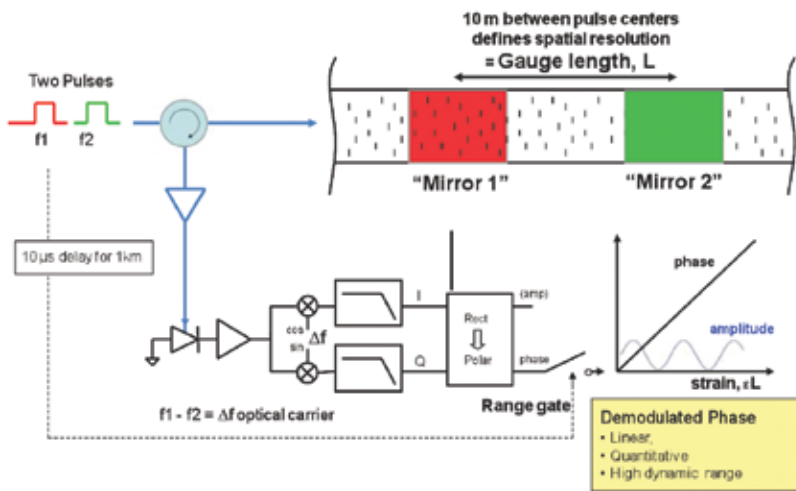


Figure 36. In this new transduction method, advanced by the commercial firm Optasense, two pulses closely spaced in wavelength, are injected in the fiber, separated by the desired length (i.e., time) of the virtual strain gauge sensors, say 10 m. Rayleigh backscatter from the two pulses interfere with each other, manifested at the optical detector as a self-demodulated signal at a frequency equal to the difference between optical frequencies of the pulses. The phase of this RF signal is the same as the difference in optical phase between the two scattering regions, which is a measure of the combined strain and index of refraction change in the virtual strain sensor between the two pulses. For each range bin (designated by time-division multiplexing), the system provides a measure of this phase for each optical pulse pair, and thus a calibrated phase-coherent time series for each virtual sensor every 1 m (or other desired "virtual" sensor separation) down the fiber. (Diagram provided by OptaSense).

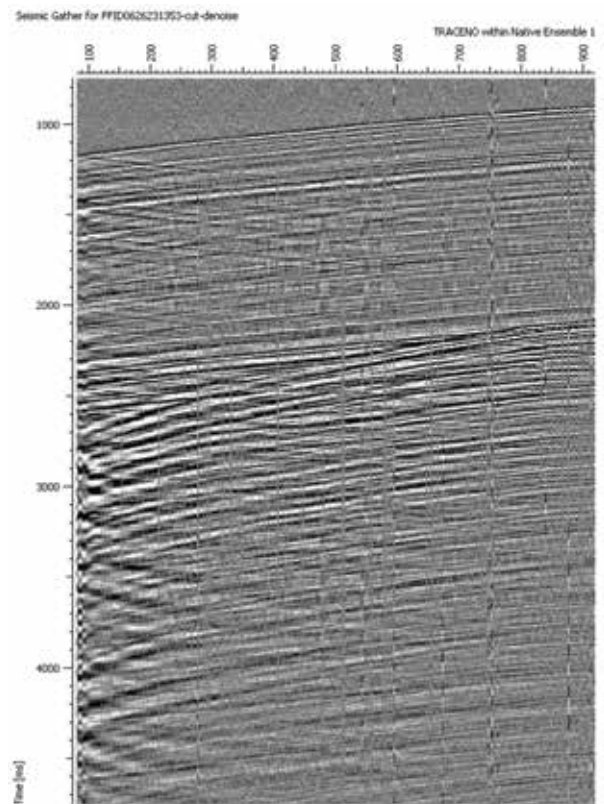


Figure 37. Each vertical slice of the figure is a seismogram with a duration of about a half second. The P and S waves, arriving at the lowest segment first, are clear, as are surface reflections. These data are collected from a single optical fiber.

## RECENT PUBLICATION

Ellsworth, W. L., Karrenbach, M. H., and M. A. Zumberge (2017), Full wave field recording of the vertical strain at SAFOD from local, regional, and teleseismic earthquakes. *EOS, Trans. Am. Geophys. Union*, abstract accepted for 2017 annual meeting.



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