celebrating 30 YEARS of INNOVATION for SCIENCE

UNAVCO

REPORT ON THE 2014 UNAVCO SCIENCE WORKSHOP: CELEBRATING THIRTY YEARS OF GEODESY INNOVATION FOR SCIENCE

OMNI INTERLOCKEN HOTEL
BROOMFIELD, COLORADO
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Overview

In 1984, UNAVCO began under the auspices of CIRES at the University of Colorado to enable pooling of community GPS receivers and technical expertise for deployment in studies of tectonic plate motion, earthquake cycle and volcano deformation. The universities that banded together to leverage these resources became UNAVCO consortium, which has held annual or biennial community science workshops to further the geosciences by application of frontier and foundational geodetic instrumentation and data sets, as well as their broader impacts.

In this context, the UNAVCO investigator community celebrated Thirty Years of Geodesy Innovation for Science at the 2014 UNAVCO Science Workshop, continuing the now biennial tradition of bringing the UNAVCO community together to share advances in geodesy-supported research and education.

The workshop centered on the theme of Celebrating Thirty Years of Geodesy Innovation for Science. The community organizing committee developed a workshop agenda that included a spectrum of geoscience and education topics: from plenary sessions on sea level rise and real-time observations, to short courses on hydrogeodesy and strainmeter data analysis.

Highlights also included a celebratory banquet that featured Byron Tapley's keynote address on the origins of space geodesy, an evening Ignite session focused on the origins and key transitions in UNAVCO's history, a field trip to image with lidar and study the 2013 Boulder flood sites, and an exhibit space dedicated to emerging geodetic technologies and geodesy education applications and demonstrations. Investigators engaged with students as part of an Expanding Networks through Mentoring (E-NET) Program. More than 240 participants attended from 24 different countries, including 19 students whose travel was supported by the UNAVCO GAGE Facility.

This report provides a synopsis of the science advances presented in plenary and poster sessions, a summary of the recommendations from technical and education Special Topics Sessions, and a brief on the celebration of UNAVCO's history and the origins of space geodesy.

http://www.unavco.org/community/meetings-events/2014/sciworkshop14/sciworkshop14.html

2014 UNAVCO Science Workshop attendees. (Photo/Travis Bildahl)

Science

PLENARY SESSIONS

Six plenary sessions focused on emerging areas of geosciences and examined recent scientific discoveries, future science directions, and education and broader impacts. Invited presenters spoke about coastal subsidence and sea level rise, large-scale computing, exploiting dense geodetic networks data, combining real-time geodesy and seismology for early earthquake detection, geodesy and the cryosphere, and regional response to great earthquakes.

Plenary Session I:

"Coastal Subsidence and Sea Level Rise"

This session focused on approaches and new results to assess the effects of sea level rise, fingerprinting, and vertical land motion at the coast, particularly in areas with potentially significant human impact. An important theme throughout the session focused on informing the public and communicating with city and regional managers on preparing to mitigate hazards posed by coastal land movement and rising sea level, particularly as the effects of storm surges and tsunamis can be amplified over time.

UNAVCO's facility capabilities support diverse work on this topic, at all spatial and temporal scales for a variety of geodetic techniques. At the global scale, Woppelman's presentation highlighted the subtle effects that the reference frame can have on estimated vertical land motion when comparing the northern to southern hemisphere, and on sea level variation inferred by satellite altimetry. Continued UNAVCO support for the global reference frame is therefore critical to assess the long-term variations in global sea level. At the regional scale, Hill's presentation showed how large segments of coastline can be strongly affected by tectonics, particularly the earthquake cycle, thus coastal hazards can change significantly in time. At the shortest time scale, tsunamis are devastating. Thus both the long-term regional monitoring of tectonics and real-time GPS near coastlines in tectonically active regions must be supported. Special attention must be given to large population areas that are at risk. Horton and Wang focused on two such case studies: New York City and Houston. Horton showed the importance of assessing not only the long term change in sea level and coastal subsidence, but also on how these long term changes can amplify the resulting devastation of storms.

Wang focused on the need to characterize subsidence in high population centers, using dense networks – as spatial variability can be high and difficult to model. Woppelman made clear that InSAR is capable of capturing that spatial variability, while GPS is needed to capture temporal variability and to resolve the slowest changes. He showed that there remain significant technological challenges when attempting to derive a consistent picture spanning all relevant spatio-temporal scales of vertical land motion and sea level rise measured by tide gauges and satellite altimetry.

PLENARY I

Costal Subsidence and Sea Level Rise

Session Chairs: Geoffrey Blewitt (University of Nevada, Reno), David Phillips (UNAVCO)

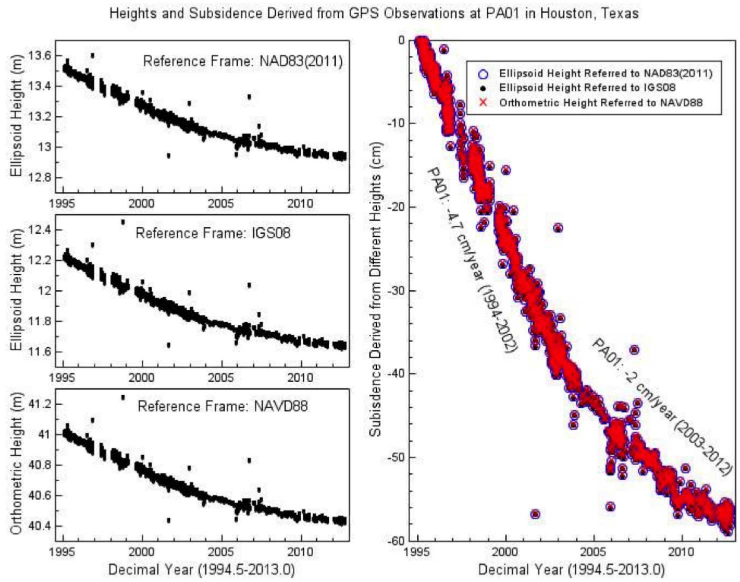
Guy Woppelman (University of La Rochelle)
Challenges in using GPS data to address sea level rise issues at the global and local scales

Emma Hill (Earth Observatory of Singapore)
The dynamic nature of relative sea level in Southeast Asia: tectonic effects and human impacts

Radley Horton (Columbia University)
Anticipating future sea level rise and coastal storms in New York City

Sonia Stephens (University of Central Florida)
Building sea level rise narratives through interactive visualizations

Bob Wang (University of Houston)
Land subsidence using GPS in the area of Houston, Texas: 1993-2012



Land subsidence in Houston, Texas, as measured at continuous GPS station Pa01. The left plots show the time series of ellipsoid and orthometric heights; the right plot illustrates the relative heights (subsidence) derived from the different heights shown in the plots on the left. (Wang and Soler, 2014)

In summary, the hazards posed by sea level and coastal subsidence is a complex topic of research that continues to benefit from UNAVCO facility support for investigators performing basic research in the underlying techniques, and support for effective monitoring systems such as permanent GPS stations and the associated technological infrastructure.

The UNAVCO facility has played a significant role in supporting geodetic techniques at all the spatial and temporal scales needed to address this important problem to society.

Plenary Session II: "Large Scale Computing Constrained by Geodesy"

Geodesy contributes unique constraints to characterizing and understanding geodynamics at all scales, including the global scale. Sauber's presentation explored the spectrum from historical observations of the interactions between active tectonics and changes in the cryosphere at human time scales as short as region-specific annual ice mass loss and large variable seasonal and inter-annual mass fluctuations. Beyond these shorter term effects on temporal and spatial scales in a region of upper crustal faulting and folding associated with collision and accretion of the Yakutat terrane. Numerical models at a variety of scales – from simple elastic models, regional finite element modeling with PyLith to global normal models – constrained by laser and radar altimetry, GPS and satellite data, and GRACE-derived mass change, reveal geodynamic drivers at a variety of temporal and spatial scales.

Lohman focused on ingestion and interpretation of large geodetic imagery data sets such as InSAR, that support both focused hypothesis testing and global discovery mode interrogation of contemporaneous surface deformation, enabled by current and developing global SAR capabilities

PLENARY II

Large Scale Computer Constrained by Geodesy

Session Chairs: Louise Kellogg (University of California, Davis), Fran Boler (UNAVCO)

Jeanne Sauber with contributions from Scott Luthcke, Shin-Chan Han, and Dorothy Hall (Goddard Space Flight Center)
Measurement and Modeling of Cryosphere-Geosphere Interaction

Rowena Lohman (Cornell University)
Ingestion and interpretation of large sets of geodetic imagery - computational needs and ancillary data sets

Atreyee Ghosh (Indian Institute of Science)
Numerical models of plate-mantle coupling: constraints from geodesy

Scott King (Virginia Tech)
Large-scale mantle dynamics computations constrained by geodesy: Past, present, and future radar satellites

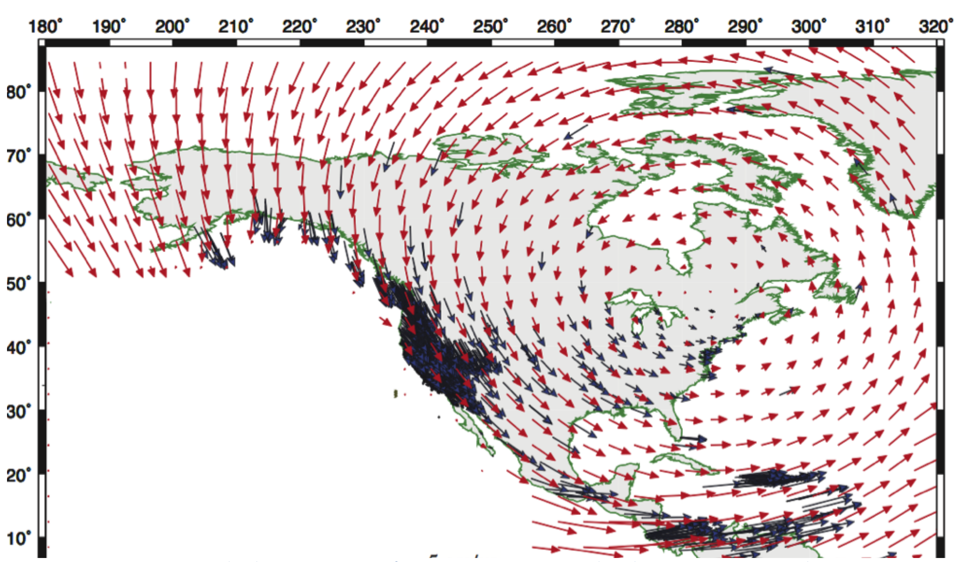
and large-scale computational capabilities. Recent and planned SAR missions will expand these capabilities and data sets, promising an emerging set of new geoscience problems that will require furthering large-scale computing capabilities in order to be solved.

Ghosh demonstrated powerful global scale numerical geodynamic models that integrate the geodetically constrained surface deformation field with seismic tomography to reveal how density driven convection couples with the lithospheric plates, with implications for the lithospheric stress field, whether the stresses originate from density buoyancy driven mantle convection or whether these are associated with topography and lithosphere structure, and the nature of coupling between the plates and the mantle. The Earth's long wavelength hydrostatic geoid, determined from satellite geodesy, further constrains mantle convection models and the strength of lower mantle slabs.

Lastly, King presented a vision for geodetically constrained modular computations of large-scale mantle dynamics by integration flow solvers, plate information, mineral physics and tomography-based regional and global models, dynamic topography, geoid and sea level history and trends.

Jeanne Sauber, plenary II Measurement and Modeling of Cryosphere-Geosphere Interaction. (Photo/Travis Bildahl)

Rowena Lohman, Cornell University, speaks to ingestion and interpretation of large geodetic imagery data sets such as InSAR. (Photo/Travis Bildahl)



Modeled dynamic velocities (red) plotted on top of kinematic GPS velocities (blue) over North America. (Ghosh, 2014, modified from Ghosh & Holt, 2012)

Plenary Session III: “Exploiting data from dense geodetic networks”

This session was designed to highlight some of the potential challenges and opportunities enabled by the ongoing explosion in dense geodetic observations associated with large networks of continuous GPS stations and interferometric synthetic aperture radar (InSAR). By “dense”, we imply both spatial and temporal resolution and globally extensive coverage that were not previously achievable. The density of observations in general increases with time as exemplified by the recent and upcoming launches of NISAR capable satellites in the next 6 years (i.e., ALOS-2, Sentinel-1a/b, Radarsat Constellation Mission, CSK 2nd generation, NISAR). Thus, on one hand, we must consider how do we extract as much information as possible from these systems, to achieve the next quantum leap in the our ability to detect and quantify geophysical phenomena, while at the same time, explore the range of new applications not previously contemplated.

The first presentation focused first on the impact of ionspheric delays on InSAR observations – primarily in terms of phase shifts, image defocussing, and geometric distortions. It then discussed ways to mitigate these impacts using signatures in polarimetric data (Faraday rotation) and/or split spectrum (i.e., multi-frequency) estimates as done commonly with L1/L2 combinations in GPS. These effects are greatest at very high latitudes and near the equator. It is important to note that the underlying physics is well understood, what currently is lacking are the data (with polarimetric image and/or large bandwidth) with characteristics allowing for routine correction. Of course, one person’s noise is another’s signal and there will be opportunity to use estimates of ionospheric activity found in InSAR data to inform models of ionospheric dynamics.

The second presentation focused on using estimates of GPS-derived column water vapor to improve our understanding of monsoons and improve our ability to predict associated large precipitation events. The current ability to predict these catastrophic precipitation events is limited by a lack of observations of tropospheric water vapor with sufficient spatial and temporal resolution. Examples both in Mexico and southern California suggest that we need to exploit the possibility of routine assimilation of GPS-derived water vapor estimates into our weather models. Suominet, TLALOCNet and COCONet all provide key networks that can and should be used for such developments, thereby making these networks useful additions to climate modeling and monitoring efforts at time scales spanning hours to years. While not explicitly discussed in this presentation, we also note that spatial and temporal variation in water vapor are a limiting noise source in use of InSAR data. Thus, improved regional weather reanalysis products that exploit dense GPS observations is expected to be an important contributor to improving our ability to detect tectonic signals in InSAR data.

The third presentation highlighted selected challenges and opportunities in the use of dense GPS and InSAR observations. As satellite InSAR data becomes more

PLENARY III

Exploiting Data from Dense Geodetic Networks

Session Chairs: Mark Simons (Caltech), John Braun (UCAR)

Franz Meyer (University of Alaska, Fairbanks)
SAR and the ionosphere: Challenges and opportunities

Yolande Serra (University of Arizona)
Use of total column water vapor measurements for forecasts of the North American monsoon precipitation

Mark Simons (California Institute of Technology)
Troposphere, tides, tomography, transients and tectonics

Sang-Ho Yun (Jet Propulsion Laboratory)
Super typhoon Haiyan’s damage in Tacloban area, Philippines, imaged by X-band COSMO-SkyMed radar satellites

ubiquitous, we will be able to detect fault slip on faults distributed around the globe independent of the presence of ground-based observations. While much of the effort using InSAR has focused on inter-seismic, co-seismic and post-seismic processes, an example was shown from the North Anatolian Fault of how we can now detect aseismic transients on faults that may not have ground-based observations nearby. Dense time series also allow us to detect a variety of subsurface hydrological processes, including both secular and seasonal changes associated with exploitation of shallow aquifers. These uses of InSAR data require us to address the various "corrections" needed as touched on by the previous two presentations. In particular, tropospheric delays are probably the most challenging problem. Progress has been made using weather reanalysis products to estimate and correct for elevation dependent delays – but these corrections are only as good as the models. Therefore, we need to participate and advocate for weather models that are best suited for our needs (temporal and spatial resolution) and that integrate all available constraints (e.g., GPS-derived water vapor estimates). The sheer volume of data involved as we go forwards puts us into the class of "Big Data". We will need tools to automatically extract or at least isolate key observations. For instance, we will need automatic transient detection algorithms that will flag regions experiencing fault transients or volcanic unrest. Such tools will rely intimately on rigorous error models.

The fourth presentation highlighted recent advances in using repeat InSAR for rapid disaster response. Radar has a distinct advantage over optical data in that radar works regardless of whether it is day or night or if it is cloudy or hazy. This presentation focused on the use of temporal changes in InSAR coherence (specifically, increases in decorrelation) to provide synoptic views (100 km scale) with high spatial resolution (10 m pixels) of devastation associated with natural disasters. The examples shown described the results and associated timeline to the response to Super typhoon Haiyan' that hit the Philippines in 2013. Validation of these devastation estimates showed accuracy at the level of individual homes. Other applications not highlighted within the presentation include automatic mapping of tsunami run-up, post-earthquake devastation, and extent of volcanic ash cover during ongoing eruptions. With the decreasing latency expected to image a given part of the world after a disaster, it becomes increasingly viable to automatically map devastation in order to improve emergency response and to inform meso-term and long-term recovery planning. Full exploitation of this capability requires: low latency access to archive and post-disaster radar imagery from common viewing geometries, an automatic processing system that is triggered to produce the damage proxy map, and tools designed to distill such results and make them understandable and knowledgeable end users who can act on this information.

Plenary IV:

"Mixing it up: Multi-sensor systems for hazards applications (geodesy, seismology, and real-time monitoring)"

The session showcased the exciting state-of-the-art approaches and advances in real-time or near real time hazard applications through the joint use of multi-sensor data such as seismology, high-rate GPS, satellite InSAR and in-situ measurements. Important recent advances have been made among the community in this field on several fronts:

1. Development of new algorithm or novel source inversion approach for real-time determination of earthquake magnitude, finite fault slip and tsunami early warning using high rate GPS and other sensor data,
2. New techniques and related data product such as combination of seismo-geodesy displacement waveform for source inversion, SAR based damage proxy map for the rapid damage assessment,
3. Automated end-to-end geodetic data assimilation and analysis system for natural hazard monitoring & response, and
4. Exploitation of the potential of the crowd-sourced observations from the sensors on smartphones, tablets, etc., for earthquake early warning and rapid response around the globe.

Rapid determination of an earthquake source model together with timely and accurate forecast of near-field tsunami intensity after rupture initiation remains a challenging problem. Dr. Melgar from UCSD used GPS/strong motion/GPS buoy and ocean bottom pressure data from the 2011 Tohoku earthquake to test source models obtained from newly developed geodetic moment tensor inversion algorithm. The work demonstrates the ability of such source models using land-based coseismic data from the combination of GPS and strong-motion sensors to forecast near-source tsunamis. It also demonstrates the potential to rapidly ingest offshore shallow water (100–1000 m) wave gauge data to substantially improve the earthquake source and tsunami forecast. Towards the same challenge of real-time source and tsunami forecast, Dr. Minson from USGS presents a Bayesian based inversion approach that use real-time high-rate GPS data to simultaneously determine both fault geometry and finite fault slip model in real-time. The work also illustrates the potential of employing crowd sourced consumer electronics sensors (e.g, smart-phone, ipad etc.) to improve and expand existing earthquake early warning systems around the globe.

PLENARY IV

Mixing it up: Multi-sensor systems for hazardsapplications (geodesy, seismology, and real-time monitoring)

Session Chairs: Zhen Liu (JPL), David Mencin (UNAVCO)

Sarah Minson (California Institute of Technology)
Potential of real-time high-rate scientific, consumer, and crowd-sourced GPS for earthquake early warning and rapid response

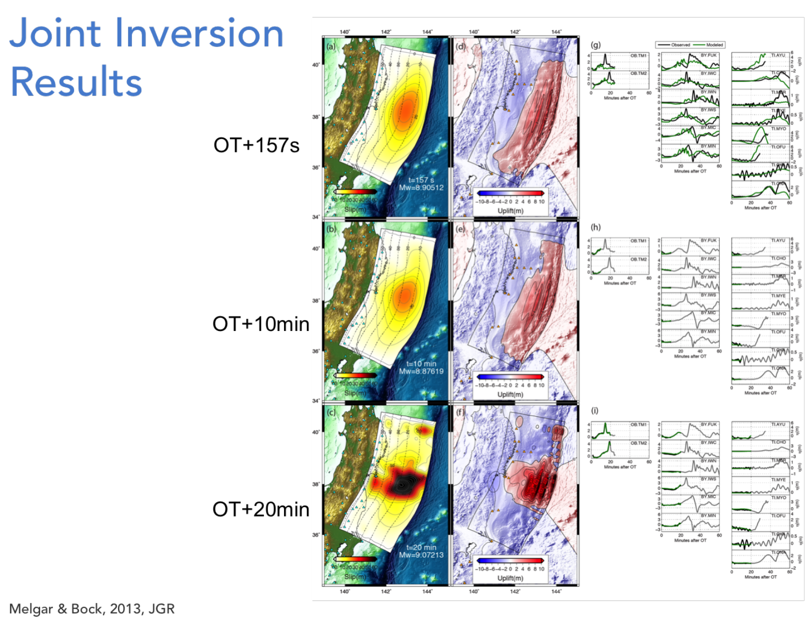
Diego Melgar (University of California, San Diego)
Earthquake and tsunami early warning: A multi-sensor approach

Susan Owen (Jet Propulsion Laboratory)
Integrating SAR, high-rate GPS, and seismology for natural hazard monitoring & response: Applying geodetic science to improve situational awareness

Anne Egger (Central Washington University)
Teaching with a 21st-Century toolbox: Opportunities and challenges

In response to the increasing data volumes from dense GPS and seismic network and existing and new SAR missions, advances are taking place to automate the data analysis and modeling as exemplified by JPL/Caltech ARIA (Advanced Rapid Imaging and Analysis) effort presented by Dr. Owen from JPL/Caltech for natural hazard monitoring and response. The new damage proxy map derived from satellite InSAR is also part of this end-to-end hazard information system.

The recent advances in real-time source inversion and tsunami forecast and high-level data product for hazard response are crucially dependent on facility infrastructure support in terms of data collection, archiving, processing and streaming, which facilitate real/near-real time application. Continuous maintenance and improvement of such infrastructure is fundamental for new breakthroughs in hazard application and rapid response using multi-sensor data.

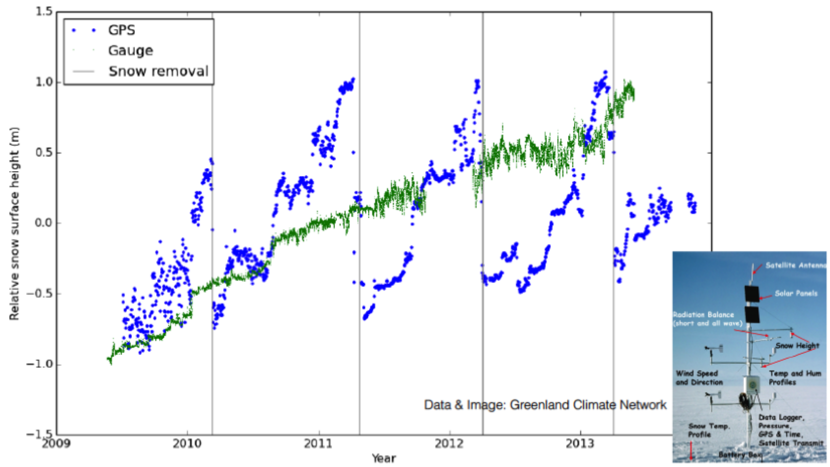


Rapid earthquake source Inversion and predicted ocean floor uplift for 2011 Tohoku earthquake at 157s, 10min, and 20min after the earthquake origin time. The inversions are of the joint data set.(g)–(i) Comparison between observed (black) and synthetic (green) data for the wave gauges. The orange portion of the waveforms is the input for the inversion. (Melgar, 2014)

Lastly, Anne Egger challenged the community to find inroads with students to engage with authentic and credible geoscience data by framing their relevance: "Natural hazards like earthquakes/hurricanes affect us, here. What do we know about them? How can we find out more in order to be prepared?" She developed this approach in the context of guiding documents that set new direction for science literacy, next generation science standards, and how to effectively tailor instruction to engage students, regardless of their career aspirations. And she concluded with a brief assessment of who learned about a new educational tool and who could help further the toolbox for students.

Plenary V:
Geodesy for the cryosphere

Hardy and Larson use reflected GPS signals to chart changes in snow height at Summit Station, in the middle of the Greenland ice sheet. This innovative application of GPS reflectometry discriminates changes in surface conditions. This study establishes GPS multipath reflectometry as a useful tool to record the snow surface over time, adding an important constraint to optically obtained snow cover mapping. It further established that environmental sensing using GPS should be explicitly considered during station location.



Snow accumulation and removal at Summit Station, Greenland. Blue shows snow surface determination from GPS reflections, snow-gauge determined snow accumulation from a nearby meteorological station in green, and vertical gray bars note annual crew removal of snow to prevent station burial, coincident with lowering of the GPS-determined snow surface height. Both data sets show a long-term increase in the snow depth, as less snow is removed than accumulated. (Hardy and Larson, 2014)

Khan studied mass balance of the Greenland Ice Sheet over the period 1900-2012, relying on a mix of techniques over a century of observations. The Greenland Ice Sheet loses mass through surface meltwater runoff and discharge from marine terminating outlet glaciers. The spatial variability and magnitude of these processes have been studied and described in detail for the past decades. Here, they combine the mass loss between the Little Ice Age (LIA) to 2012. They used high quality aerial stereo photogrammetric imagery recorded between 1978 and 1987 to map morphological features such as trim lines and end moraines marking the maximum ice extent of the LIA, which enables them to obtain vertical point-based differences associated with former ice extent. These point measurements are combined with contemporary ice surface differences derived using NASA's Airborne Topographic Mapper (ATM) from 2003-2012, NASA's Ice, Cloud, and land Elevation Satellite (ICESat) from 2003-2009, NASA's Land, Vegetation, and Ice Sensor (LVIS) from 2010, to estimate mass loss throughout the 20th and early 21st Century. The mass balance estimates of the GrIS since retreat from maximum LIA for the period for three intervals, LIAmax (~1900) - 1978/87, 1978/87 - 2003, and 2003 - 2012. Collectively these techniques provide powerful constraints on changes to the cryosphere and Glacial Isostatic Adjustment (GIA), with the largest signals coming from the rapid melting of glaciers that fringe the ice cap itself.

Eric Ivins presented Century-scale continent-to-ocean ice mass transport and measurement of lithospheric thickness and mantle viscosity using GPS uplift data, a robust correction for GRACE mass balance between 2003-2014, to derive new estimates for two active slab windows. Results from Patagonia and the West Antarctic Peninsula

PLENARY V

Geodesy for the Cryosphere

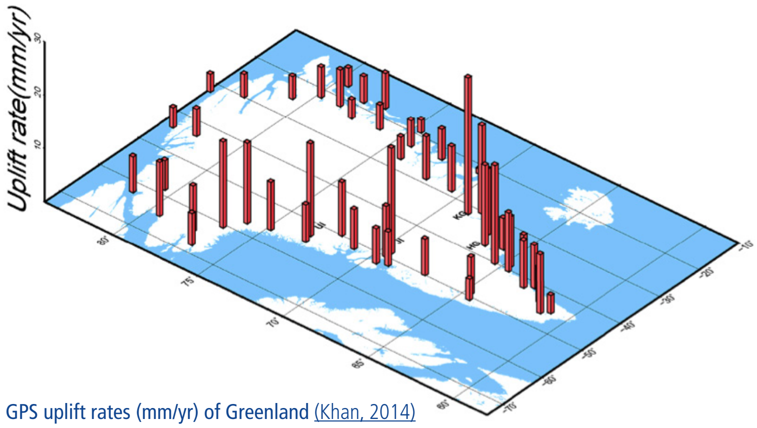
Session Chairs: Tonie van Dam, (University of Luxembourg), Joe Pettit (UNAVCO)

Ryan Hardy and Kristine Larson (University of Colorado, Boulder)
GPS Snow Surface Height Measurements at Summit Station, Greenland

Abbas Khan (Danish Technical University)
Mass balance of the Greenland ice sheet during 1900-2012

Erik Ivins (Jet Propulsion Laboratory)
Century-scale continent-to-ocean ice mass transport and the measurement of lithospheric thickness and mantle viscosity using GPS

Falk Amelung and Wenliang Zhao (University of Miami)
Estimating ice sheet mass balance from InSAR and elastic loading



GPS uplift rates (mm/yr) of Greenland (Khan, 2014)

substantiate an upper mantle viscosity consistent with the large slab window postulated in previous studies. Using uplift constraints in combination with the ice mass loss constraint, Ivins derived a 10-15 Gt/yr GIA correction for mass balance, and mantle viscosity values of 0.6 – 3 x 1019 Pascal seconds, consistent with Pollitz and Nyst (2005).

Lastly, Falk Amelung applied InSAR to determining ice mass change through time, with a focus on the effects of global warming on sea level including results from Iceland, Baffin Island, Northern Greenland, and Antarctica. The results demonstrated the power of InSAR in the detection of ground uplift due to ice mass loss. Given these results and the expanding InSAR data sets (TerraSAR-X, Sentinal, and the planned NISAR), ongoing InSAR observations are a key part of the global observation strategy.

The role that UNAVCO has played in facilitating these scientific results was strongly stated in this session. The UNAVCO community has established international leadership in polar research, and support for SAR interferometry. UNAVCO provides an umbrella for community science planning and innovative technical solutions, that have progressively improved resolution of subtle signals that provide insight into GIA, the Earth's viscosity, and present day changes in ice mass. In addition to this plenary, there was a special topic session *Science opportunities in extreme environments, technical requirements & logistical constraints* to discuss current capabilities and future requirements for geodetic based polar science.

Plenary VI:

Regional effects of great earthquakes: Triggering, lithospheric response, post-seismic slip and other transients.

The session conveners invited four presentations that considered the geodetic community response to four significant earthquakes. Each presenter was asked to discuss topics including the scope and scale of the geodetic response and community engagement following the events, as well as the novel science outcomes resulting from these investigations.

The first presentation, by Roland Bürgmann from UC Berkeley, showcased the diverse set of geodetic and seismic observations made in the leading up to and following

PLENARY VI

Regional Effects of Great Earthquakes: Triggering, Lithospheric Response, Post-Seismic Slip and other Transients

Session Chairs: Simon McClusky (Austrailian National University), Freddy Blume (UNAVCO)

Roland Bürgmann (University of California, Berkeley)
Time-dependent crustal deformation and slip following the 2011 Tohoku earthquake

Sarah Stamps (Massachusetts Institute of Technology)
Education and Community Engagement in Response to the 2010 Haiti Earthquake from a Young Investigator's Perspective

Simon McClusky (The Australian National University)
The 1999 M7.6 Izmit/Duzce Turkey Earthquake sequence - Lessons learned from 20 years of geodetic observations

Ben Brooks (United States Geological Survey)
Regional response to the 2010 Maule, Chile great earthquake

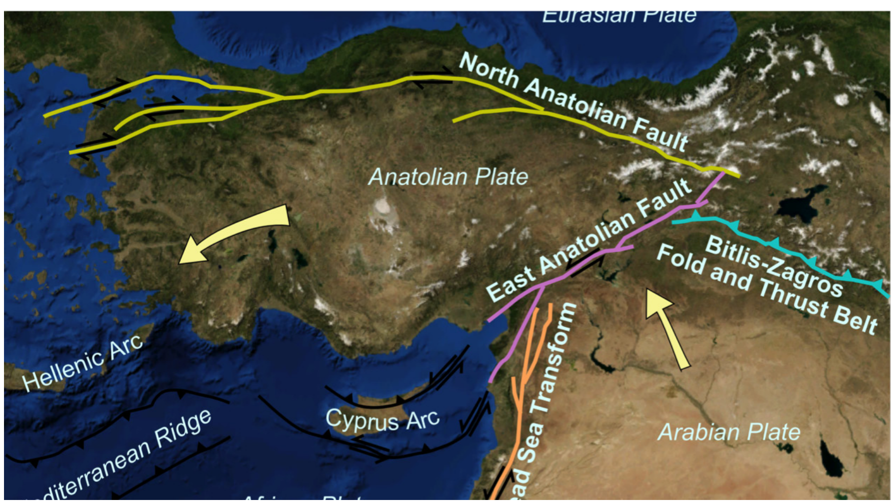
the Mw 9.0, 2011 Tohoku earthquake in NE Japan. This presentation highlighted the extraordinary potential of dense, large scale, continuous, real-time, high rate geodetic observations. A combination of land-based and state of the art seafloor geodetic techniques as well seismic observations reveal in exquisite detail the inner workings of the NE Japan Megathrust in the decades leading up to the 2011 Mw 9.2 Tohoku earthquake (inter-seismic phase), the seconds after rupture initiation (co-seismic phase), and the days months and years following the earthquake (post-seismic phase). Inter-seismic geodetic observations of deformation showed the ability of precise geodetic observations to illuminate the spatial and temporal distribution of coefficients of locking along megathrust interfaces indicating regions of greater or heightened seismic hazard. High rate observations of co-seismic deformation following the initiation of the earthquake rupture observed by the dense onshore GNSS network, and novel seafloor measurements close to the seduction trench illustrate the details of rupture evolution providing detailed estimates of the spatial distribution of slip on the megathrust interface. Integration of geodetic observations of deformation resulting from post-seismic relaxation of earthquake induced stresses and seismic observations of characteristic earthquakes on the megathrust interface enabled separation of the relative contributions of rheologic structure of the lithosphere, asthenosphere and upper mantle and the mechanical or frictional properties of plate boundary faults.

Presentation highlights included:

- Seafloor geodetic data and seismic observation of repeating earthquakes on the megathrust provide unique constraints on competing after slip, poro-elastic and visco-elastic deformation processes.
- Understanding the 3D rheological structure is of first-order importance for interpreting post-seismic relaxation.
- Viscoelastic relaxation will dominate deformation and stress fields around NE Japan, Sumatra and other recent megathrust ruptures and will influence seismic hazard, for decades to come.
- New seafloor geodetic and geophysical measurements (GPS-Acoustic, pressure, cabled observatories, interferometric multi-beam bathymetry, OBS, etc.) using lower cost autonomous vehicles and buoys will revolutionize or understanding of megathrusts.
- Integration of geodetic observations, seismic source imaging, and rock mechanics for better characterization of structure, processes and rheology.
- Modeling and careful exploration of parameter space and model tradeoffs with increasingly physical models (e.g., rate-state friction, power-law flow, poro-elastic response etc.) will lead to greater understanding of the earthquake cycle and seismic hazard assessment.

The second presentation, by Sarah Stamps, discussed the geodetic response of a team of geodesists and geophysicists deployed to the field to investigate the devastating 2010 Haiti earthquake using GPS measurements. This presentation focused on the process of community engagement, outreach and education (ECE) undertaken by team members at different social and political levels ranging from interactions at schools, broadcast radio programs, to advising the Haitian government, relief agencies and the United Nations on response issues. The presentation discussed outreach contributions, commenting on issues relating to the impact of such activities in the short, medium, and long-term outcomes. The presentation offered ideas and guidance for around developing a practical ECE framework to be used by geodetic and geodynamic scientific investigations in the aftermath of other major disaster.

Simon McClusky discussed the lessons learned from 20 years of geodetic observations before and after the 1999 M7.6 Izmit/Duzce Turkey Earthquake sequence (Mw=7.4, 7.2), the last in a 20th Century series of westward migrating, M>7 seismic events that broke an approximately 1000 km section of the North Anatolian Fault (NAF). A remaining seismic gap lies under the Sea of Marmara, in close proximity of the center of Istanbul, now considered vulnerable with



The North Anatolian Fault (NAF) is an active right-lateral strike-slip transform fault in northern Anatolia separating the Eurasian Plate and the Anatolian Plate. The fault extends ~ 1500 km westward from a junction with the East Anatolian Fault at the Karliova Triple Junction in eastern Turkey, across northern Turkey and into the Aegean Sea. It runs about 10 km south of Istanbul city center, under the Sea of Marmara. The North Anatolian Fault is similar in many ways to the San Andreas Fault in California USA. Both are continental transforms with similar lengths and slip rates. (McClusky, 2014) an estimated 35-70% probability of generating a similar event over the next 30 years. An extensive and dense GPS velocity field for the Marmara region based on data that were painstakingly collected from 1994-2013 informs the kinematic context of these events. By co- and post-seismic motions for the 1999 earthquake sequence, the velocity field forms the basis of estimate for secular strain accumulation on mapped, active faults within the western extent. For the Izmit and the Ganos segments, the estimated slip deficit accumulation rate reported here (~ 20 mm/yr) is consistent with earlier geodetic results and with the occurrence of M >7 historic earthquakes on both segments, during 1999 and 1912 events. The first direct observations of strain accumulation on the Princes Islands (PI) segment within the eastern Marmara directly south of Istanbul indicates a slower slip deficit rate to 10 - 15 mm/yr, with larger uncertainty due to the limited GPS coverage near the fault trace. Meanwhile the central segment of the MMF shows negligible strain deficit accumulation, at < 2 mm/yr. Despite uncertainty about the precise location of pre-instrumental earthquakes, the geodetic results are consistent with historic earthquake studies that report multiple M>7 events on the PI segment, the last large event occurring in 1766, while only two M>7 events have been reported in the past 2000 years on the central MMF. Estimated slip deficits point to the Princes Island segment as the most likely to generate the next M>7. This study points to the value of long-term geodetic time series for resolving subtle changes that discriminate between earthquake cycle models and to forecast likely temporal patterns of future events.

The last presentation, by Ben Brooks from the USGS, discussed the regional response to the 2010 Maule, Chile great earthquake. Static offsets produced by the February 27, 2010 Mw= 8.8 Maule, Chile earthquake were measured by GPS and InSAR, providing constraints on the coseismic slip along a section of the Chilean subduction zone along 650 km strike length and 180 km width. Campaign and continuous GPS and InSAR data sampled the deformation field. Inversions of distributed slip show a slip maximum ~15 m at ~15–25 km depth on the megathrust offshore Lloca. Seismic slip was largest north of the epicenter, and propagated bilaterally. A secondary slip maximum occurs at ~25 km depth on the plate interface. Coseismic slip is negligible below 35 km depth. Estimates of the seismic moment based on different datasets and modeling approaches vary from 1.8 to 2.6×10^{22} N m. This first analysis of the static displacement field using a layered spherical Earth model obtained a seismic moment estimate of 1.97×10^{22} N m, corresponding to a moment magnitude of 8.8, similar to that obtained by previous work.

POSTER SESSIONS

A total of 76 poster abstracts were submitted in eight geodesy-related categories including Atmosphere, Cryosphere, Environmental and Hydrogeodesy, Human Dimensions, Ocean, Solid Earth, Technology, and Other. Those submitted as “other” are summarized with similar topics in this segment. Two evening poster sessions offered meeting participants time for one-on-one interaction on topics of current work in geodetic science, technology, and education.

Poster contributions covered a diverse range of compelling science questions from the water cycle in California to surface flow characteristics of glaciers in Alaska. There were presentations on applied science for society, such as the effect of the rise of sea level on NASA facilities and a seismogeodetic earthquake early warning system for the Pacific Northwest. Advancing technology topics included distributed, coaxial-cable-based strainmeter for onshore and seafloor geodesy and shaketable assessments of GPS and MEMS accelerometer for real time observations seismic effects on manmade structures.

Presenters and session attendees discuss a wide range of geodetically supported science topics at the Workshop poster sessions. (Photo/Travis Bildahl)

Atmospheric Science Posters

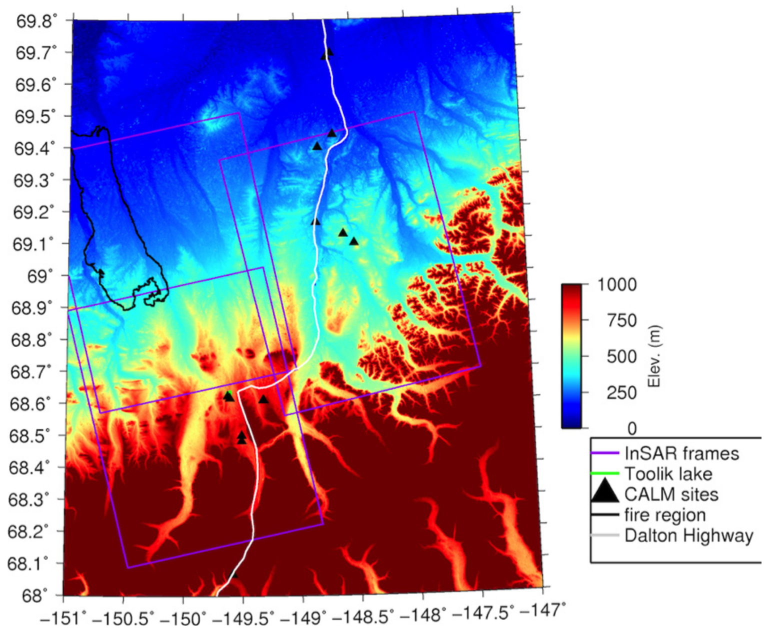
Atmospheric science contributions focused on the distortions to SAR that are introduced by the ionosphere (Franz et al. 2014), operational uses of real-time GPS in NOAA weather models (Moore et al., 2014), and a detailed analysis of the impact of the 2012 Mw 7.8 Haida Gwaii thrust earthquake and tsunami on the ionosphere (Rolland et al., 2014).

Cryosphere Science Posters

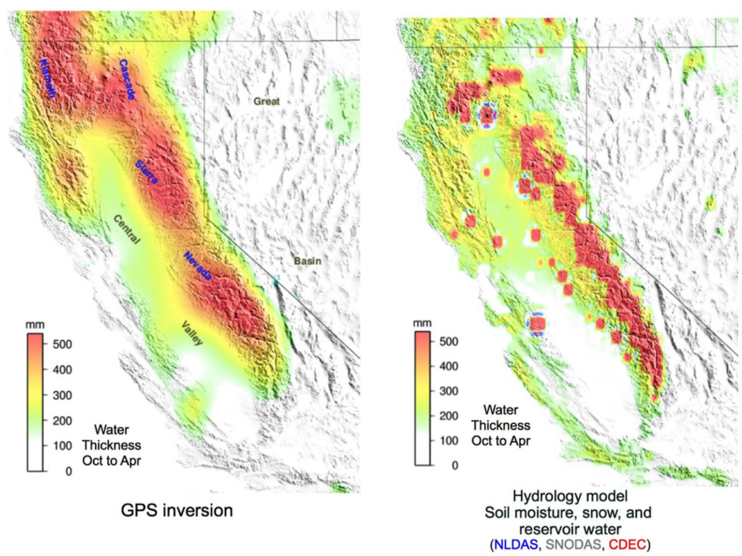
Contributions in this category included applications of InSAR to permafrost studies (Chen et al., 2014), and satellite observations of glacier surface flow (Elliott et al., 2014), both of these in Alaska. Greenland studies focused on the application of GPS reflectometry to snow surface height at Summit Station (Hardy and Larson, 2014) and a comprehensive ice sheet mass balance analysis since the Little Ice Age (Kahn et al., 2014).

Environmental Geodesy and Hydrogeodesy Posters

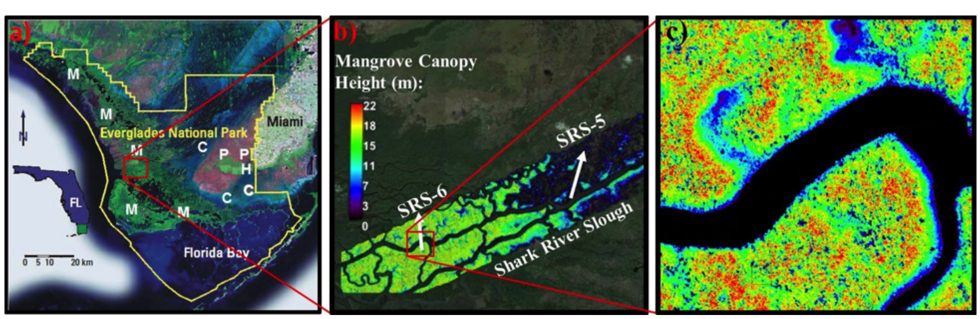
Several hydrogeodesy posters focused on the Plate Boundary Observatory and HoustonNet, including analyses of regional uplift sensitive to the loss of surface and groundwater load (Fu et al., 2014; Argus and Fu, 2014; Puskas et al., 2014), subsidence of 2 – 4 cm/year related to the 2011 Houston drought (Jiang, 2014), and a broader suite of PBO H2O water cycle observables from GPS and reflectometry (Larson et al., 2014, presented by Chew). Two innovative applications of InSAR by students from the University of Miami (Oliver-Cabrera and Wdowinski, 2014; Feliciano et al., 2014) focus on biomass and human impacts on tidal circulation in the fragile Everglades wetlands. Multi-instrument geodetic monitoring of a nuclear power plant in Korea informs site characterization, early warning for hazards, and long-term predictions of changes in site condition and stability (Lee et al., 2014). Lowry et al. (2014) report high resolution displacement monitoring of a slow velocity landslide using ground based radar interferometry.



Toolit Station InSAR study area. (Chen et. al., 2014).



Water thickness in California modeled from GPS measurements of vertical surface motion in response to seasonal water storage. (Argus and Fu, 2014)



a) Everglades National Park boundaries. b) Zoom-in to the Airborne LiDAR Shark River Slough transect showing mangrove canopy height. Height was derived by subtracting the Digital Terrain Model from the Digital Surface Model. C) Zoom-in to SRS-6 site showing canopy height and water (black). (Feliciano, 2014)

Human Dimensions Posters

The Human Dimensions contributions were particularly engaging and diverse, exploring curriculum innovation (Douglas et al., 2014; Lamb and Bennett, 2014; Cronin et al., 2014a, 2014b), and interactive learning and tailored public communications related to hazards and science (Olds et al., 2014; Stamps et al., 2014; Pratt-Sitaula et al., 2014; Stephens, 2014; Bartel and Charlevoix, 2014).

Participants in the Cascadia EarthScope, Earthquake, and Tsunami Education Program (CEETEP), a multi-institutional project to mitigate the effects of these potential disasters through collaboration building and professional development for K-12 teachers, park and museum interpreters, and emergency management outreach educators in communities along the Oregon and Washington coast. (Pratt-Sitaula et al., 2014)

Ocean Science Posters

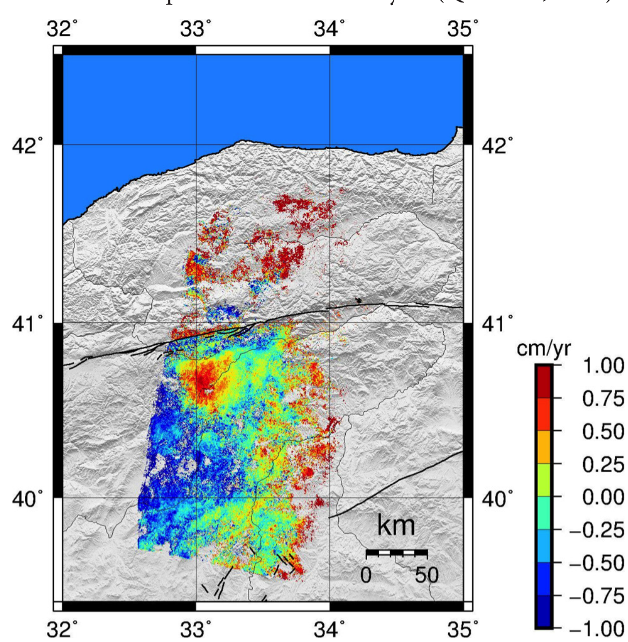
Submissions to Ocean Science focused on different aspects of coastal and near shore geodesy. Three studies explored relative sea-level change or its potential impact on infrastructure: in the remote Aleutians (Tweet et al., 2014), at local and global scales indicating differences the northern and southern hemispheres (Wöppelmann, 2014), and site characterization of coastal NASA facilities at Kennedy Space Center using TLS and GPS, and a proposal to establish a Coastal Hazard Supersites for GEOSS to facilitate fundamental research on coastal land subsidence (Nerem et al. 2014). Song et al. (2014) detailed early tsunami detection and magnitude estimation. Wei et al. (2014) described a novel coaxial cable Bragg grating (CCBG) sensing technology for seafloor geodesy; potentially providing high temporal resolution at a moderate cost, high accuracy (micro-strain) and with an unprecedented spatial (~10 m) resolution over 10s of km length.

Solid Earth Science Posters

Solid Earth Science contributions dominated the poster sessions, accounting for 40 of the 76 total contributions. These can be broadly grouped into six subcategories: (1) Time variant and/or interseismic deformation, (2) vertical deformation and interactions with the hydrosphere, (3) deformation during earthquakes as well as earthquake early detection and warning, (4) mantle geodynamics, (5) volcano or magma-induced deformation, and (6) regional networks for deformation and local reference frame.

1. Time variant interseismic deformation

Thirteen posters examined interseismic deformation, including long-term slip and creep, transient deformation events such as post-seismic deformation, episodic tremor and slip, and the culmination of the seismic cycle. Long-term deformation rates from active back-arc deformation across the southern Subandes of Bolivia (Weiss et al., 2014), the Ballenas transform fault (Fattahi et al., 2014) and the Yakima fold and thrust belt (McCaffrey et al., 2014) illuminate the structural style of these evolving orogens. Fault creep studies focus on the Alto Tiberina fault, central Italy (Bennett et al., 2014), the Ismetpasa segment of the North Anatolian fault zone (Havazli et al., 2014 a, b), and steady and unsteady creep on the San Andreas fault southeast of Parkfield (Agnew et al., 2014). Post-seismic transients such as after-slip and viscoelastic relaxation are reported from the 1992 Landers and 1999 Hector Mine earthquakes (Pollitz, 2014), the 2010 7.2 El Mayor Cucapah earthquake (Rollins et al., 2014), and the 2011 Mw 9.0 Tohoku-oki earthquake (Zhang et al., 2014). Other transient deformation events include Cascadia episodic tremor and slow slip (Roelloffs and Beeler, 2014), comprehensive studies of the entire seismic cycle in Costa Rica (Kyriakopoulos et al., 2014), and a decade-long record of slip evolution in time and space in Sumatra, where multiple large and great earthquakes on various segments reveal different parts of the seismic cycle (Qiu et al., 2014).



Velocity field derived from InSAR showing the creeping Ismetpasa segment of the North Anatolian fault zone. (Havazli et al., 2014)

Mavrommatis et al. (2014) develop the first GPS-determined acceleration map, revealing a spatially systematic and statistically significant crustal acceleration field during the decade leading up to the 2011 Tohoku-oki earthquake.

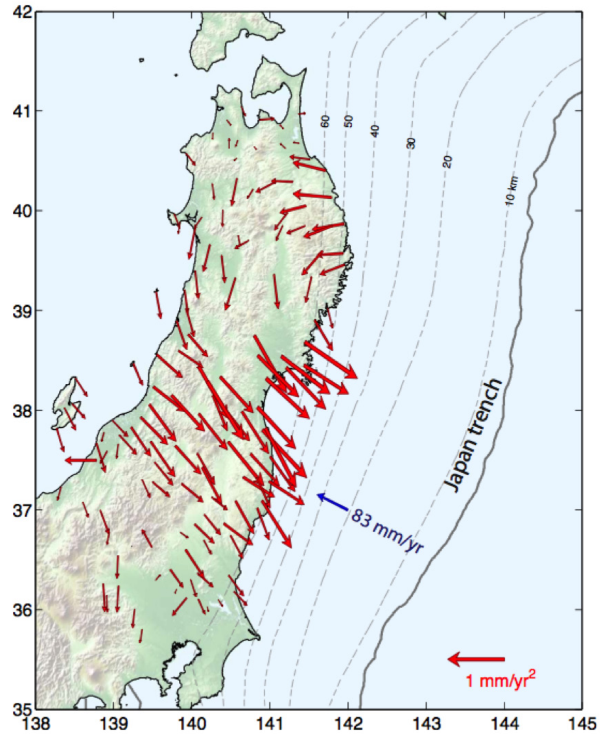
2. Co-seismic deformation and earthquake early detection

Seven contributions addressed co-seismic deformation or anticipation of capturing a significant earthquake. D'Anastasio et al. (2014) report the GeoNet response to three recent M > 6 earthquakes in New Zealand, events that they are using to further development of early detection capabilities. Seismogeodesy characterization of the 2013 ML 6.4 Wanrung, Taiwan earthquake indicates the usefulness of 10-Hz GPS and double-integrated accelerometers within the 15 km epicentral distance in detecting S waves and surface waves. An international collaboration is laying the groundwork to "Catch a Big One" on the megathrust in Ecuador (Mothes et al., 2014). Wei and McGuire (2014) report on a study of the Mw 6.5 Offshore Northern California Earthquake of January 9, 2010, one of the first oceanic strike-slip earthquakes captured by GPS. Its epicenter was at 29 km rupturing through the strongest portion of the mantle lithosphere, apparently without melt weakening, at odds with lab experiments on peridotite. To test the hypothesis that much of the slip associated with small earthquakes is aseismic, Hawthorne et al. (2014) investigate co- and post-seismic strain changes associated with M 2 to 4 earthquakes on the San Andreas fault, concluding that the ratio of aseismic to seismic slip is independent of earthquake size. Funning et al. (2014) compile source parameter information from over 130 published studies of 101 individual earthquakes (Mw 4.7-9.0) studied using InSAR, in order to evaluate end-member scaling models for earthquake self-similarity, a conclusion that was not favored by their results.

Another three posters specifically focused on implementation of earthquake early detection, in support of early warning efforts. Grapenthin et al. (2014) and Johanson and Grapenthin (2014) report on different strategies for developmental early detection schemes for the Bay Area Regional Deformation network (BARD) that relies on UCB, USGS and PBO operated GPS stations, with collocated accelerometers. J. Haase reported results from seismogeodetic monitoring system based on GPS technology for real-time observations of large earthquakes that can also be used for structural monitoring (Bock et al., 2014).

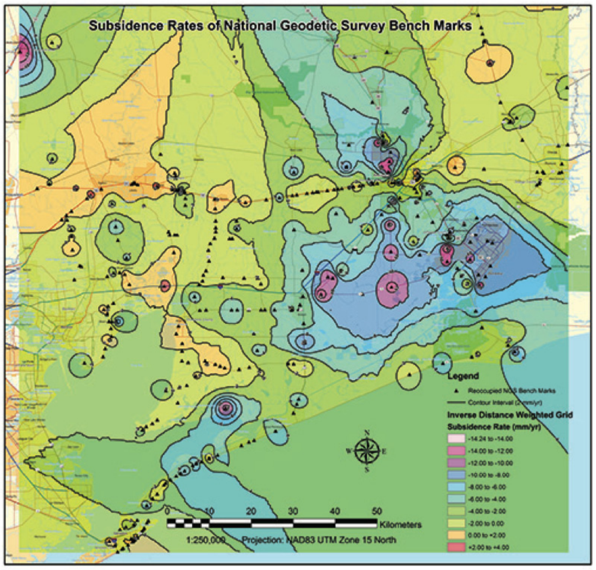
3. Vertical deformation and interactions with the hydrosphere

Perhaps the most exciting and provocative posters were among the 11 investigations of vertical deformation that reflect a variety of new GPS-detectable phenomena, in some studies used in conjunction with InSAR. Vertical deformation along the U.S. west coast is constrained by a network solution for tide gauges, satellite altimetry, GPS, and leveling, varying by up to 6 mm/yr along the U.S. Cascadia margin and 3 mm/yr along the California transform margin, with heterogeneity that is not predicted by GIA models (Burgette et al., 2014). Hill et al. (2014) also explore the interactions among tectonic deformation, the geoid, and relative sea level in Southeast Asia. During earthquakes, coastlines may suddenly uplift or subside by many meters, exposing a growing coastal population to inundation.



Acceleration field in northern Honshu, Japan, for the time period 1996 to 2011. Accelerations are corrected for postseismic transients from large earthquakes before 1996. (Mavrommatis et al., 2014)

Five studies focused on land subsidence in metropolitan areas. Of these four were in the Houston-Galveston area of SE Texas using up to 20 years of cGPS (Yu et al., 2014; Kearns et al., 2014), and integration of cGPS extended with a century of historical leveling stations (Wang et al, 2014; Kruger, 2014). The fifth study uses InSAR to detect land subsidence in several metropolitan areas of South America (Solano-Rojas et al., 2014), including Bogota and Sao Paulo, but not in Lima or Buenos Aires, inviting speculation that coastal cities subside less as salt-water incursion replaces fresh water reservoir extraction.



Subsidence rates in Southeast Texas in mm/yr. (Kruger, 2014)

Schmalzle and Wdowinski (2014) compare, evaluate and merge cGPS solutions for Plate Boundary Observatory from a variety of processing centers, yielding a final refined vertical velocity field of 1,292 velocities with uncertainties better than 4 mm/yr. Choe et al. (2014) focus on the Rio Grande Rift, evaluating vertical deformation after GRACE-, LDAS-, and TWS-constrained removal of water loading signals, noting subtle, sub-mm/yr subsidence of the north and uplift in the south. Hammond et al. (2014) evaluate vertical combining GPS and InSAR, across active fault systems in California, yielding rates that vary between -5.0 and 2.6 mm/yr. Localized uplift near the junction of the San Andreas and San Jacinto faults are consistent with a viscoelastic earthquake cycle model that improves agreement with geologic slip rates.

4. Mantle geodynamics

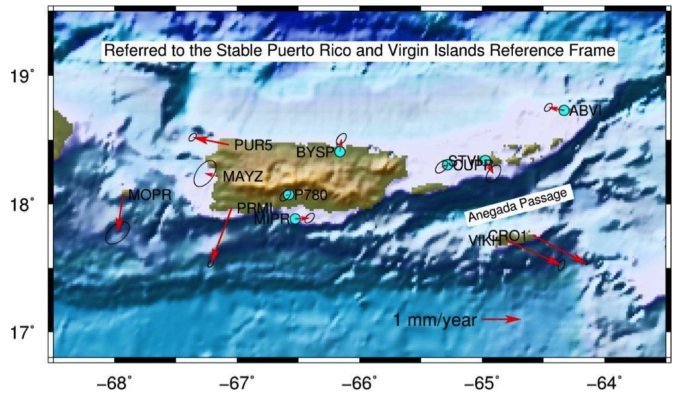
Two posters report innovative approaches to sensing mantle geodynamics. Ghosh (2014) reports global-scale models based on GPS and seismic data that explore density-driven convection coupling with the lithospheric plates. Martens and Simons (2014) exploit periodic loading by ocean tides that generate 5 – 10 cm deformation in order to constrain the density and elastic structure of the Earth's crust and upper mantle.

5. Magma-induced deformation

Two studies focused on magma-induced deformation. Morales Rivera and Amelung (2014) reported the results of volcano deformation and modeling in the Northern and Central Andes from ALOS InSAR time-series confirming co-eruptive inflation, post-eruptive deflation, and possible inflation southeast of Cerro Auquihuato in Peru. Adem and Lewi (2014) report deformation associated with dyke intrusion events in the Afar Depression, noting cm-scale displacements.

6. Regional networks

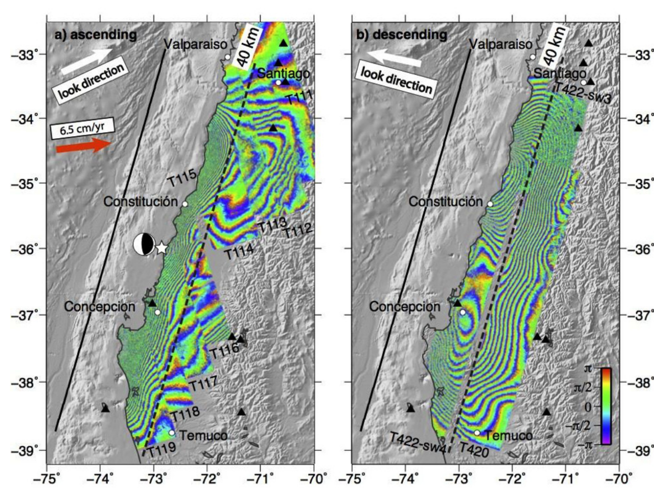
Three posters featured important advances in cGPS/GNSS networks and reference frames, including GEORED in Colombia (Mora-Paez, 2014), PRVI in Puerto Rico and the Virgin Islands (Liu and Wang, 2014), and enhancements and performance metrics for the Plate Boundary Observatory southwest region (Walls et al., 2014).



GPS-derived velocities of sites in the Puerto Rico and Virgin Islands region in the Stable Puerto Rico and Virgin Islands Reference frame (SPRVIRF). (Liu and Wang, 2014)

Technology Posters

Technology posters sampled advances in seismogeodesy for Cascadia early earthquake detection and warning (Crowell et al., 2014), as well as software solutions for a network approach to GPS uncertainty estimation (Dmitrieva and Segall, 2014), for internationally federated GPS seamless archives (Fernandes et al, 2014) and enhancements to GMTSAR for InSAR data processing (Sandwell et al., 2014). Goldfarb et al. (2014) presented a detailed comparison of GIPSY PPP and GAMIT double-differenced daily solutions, for better understanding of common-mode errors.



ScanSAR interferogram of the Mw8.8 2010 Maule, Chile earthquake, produced using GMTSAR, an open source InSAR processing system. (Sandwell et al., 2014)

TECHNICAL SESSIONS AND RECOMMENDATIONS

Special Topics Sessions (STS)

Twelve STS breakouts in four sessions focused on topics that complemented the plenary sessions and provided the opportunity to explore recent advances, emerging technologies and science or education topics, and the technical and facility requirements for advancing new directions. Each STS was asked to report out on these topics, with specific recommendations for priority. These reports vary from narrative to bulleted, and while the format has been edited for continuity, the reports themselves are not edited, in the interests of preserving the intent of those who participated in each STS.

STS 1.1 Coastal subsidence, ice loss, glacial rebound and sea level change

Falk Amelung (University of Miami), Sarah Doelger (UNAVCO)

What are some exciting recent science contributions and technical advances?

What are the compelling emerging science directions?

This session focused on the interrelated topics of the movement of water between the hydrosphere and cryosphere, land subsidence and uplift in coastal areas, and broader issues of sea level change. Improved satellite observation capabilities, such as InSAR, diurnal flood stage characterization, and coastal GPS observations contribute to recent science contributions and technical advances. These include characterizing subsidence in Venice and Jakarta, localized coastal subsidence or tectonic uplift, and progress on understanding post-glacial rebound. Near term progress is anticipated from emerging work on delta subsidence in non-urban areas and the location of the depth of sediment compaction resulting from groundwater loss (extensometer).

What are the technical and facility requirements to advance these new science directions?

Recommended areas for further development of technical and facility capabilities:

Data repository needs:

- Establish a data clearinghouse for data relevant to subsidence, including online extensometer data
- Enable water-level data dissemination

Remote Sensing Data Needs:

- Develop drone lidar capabilities with 5 cm vertical resolution.
- Continuity and expansion of InSAR acquisition
- Coastal altimetry (CoastAlt)
- Optical observations
- Use GPS to connect tide gages to the global reference frame through PSInSAR

In-Situ data needs:

- Coastal GPS networks
- Characterization of delta versus non-delta environments
- Extend extensometer observations

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

Proposed initial and long-term goals for supersite locations for the study of coastal subsidence:

Initial Supersites:

- New Orleans, Jakarta, Guangzhou, Bangladesh (pseudo-S.: Rotterdam)

Potential Supersites:

- Alexandria, Manila, Dakar
- Hai Phong, Ha Noi, Shanghai, Manila, Dongying, Bangkok, Bogale, Mekong, Lagos, Karachi-Indus

STS 1.2 Science powered by WInSAR – Achievement and opportunities of accessible InSAR data

Eric Fielding (Jet Propulsion Laboratory), Chris Crosby, Scott Baker (UNAVCO)

What are some exciting recent science contributions and technical advances?

What are the compelling emerging science directions?

WInSAR present plans for 2014:

- Spend $45k on new acquisitions and data purchase for TSX
  1. San Francisco Bay area
  2. Volcanoes in the lower 48 states
  3. Florida Sinkholes
  4. Subsidence in California Central Valley
  5. Newberry geothermal site
  6. Nevada geothermal sites
  7. North Texas earthquakes
- Data access through NGA (National Geospatial Intelligence Agency)

- Software: ROI_PAC wiki is available again thanks to UNAVCO:
- temp: http://aws.roipac.org/cgi-bin/moin.cgi%20 will replace http://roipac.org
- InSAR short courses
- Elections for officers starting in October

What are the technical and facility requirements to advance these new science directions?

Community suggestions:

- Suggestion to convert ROI_PAC wiki to general InSAR wiki
- Coordination with EROS on access to NGA data? They are set up to access data post-event, especially very high-resolution optical images
- Add training on new data mode of Sentinel-1 SAR (TOPS) use and issues - do this as part of a future short course.
- Duplicate copies in the archive when searching with API are frustrating - can that be resolved?
- Archive question: do we want to maintain the swaths or go back and reorder everything as frames?
- Electro-optical data? Do we want to expand into that area? Differencing services for optical data?
- Large amounts of Landsat and commercial EO platforms (WorldView etc) that could be madebetter available. Someone needs to develop a service for federating access. Can EROS take lead? Could WInSAR move into that area and replicate SSARA approach?
- How can WInSAR and UNAVCO cooperate with the European Helix Cloud computing initiative?

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

Future plans:

- Standard InSAR data products—SSARA prototype products at ASF.
- InSAR product archive at UNAVCO developed under SSARA project. User contributed for now.
- InSAR processing at UNAVCO or elsewhere like GPS data products?
- Connect to European Helix Cloud computing community to share data and analysis methods.

STS 1.3 Loading & transient deformation on a variety of timescales: weekly to decadal

Jeff Freymueller (University of Alaska, Fairbanks), Chuck Meertens, Christine Puskas (UNAVCO)

What are some exciting recent science contributions and technical advances?

Scientists have been using geodetic data to study both tectonic and non-tectonic deformation. Tectonic studies have focused on the earthquake cycle, where GPS instruments recorded coseismic offsets and post-seismic changes in velocities, where time series have been used to study stress changes after earthquakes due to viscoelastic flow and rheologic changes. Non-tectonic studies have focused on hydrology, seasonal surface loading from soil moisture, snow, etc., and glacial dynamic. Study of transients has been of particular interest, as a variety of transients have been recorded. Slow slip, episodic tremor and slip, and long-term deformation changes at subduction zones may be related to seismic hazard. The physics of such periodic events are not completely understood, and effects of tidal modulation, dynamic triggering, and transients preceding great earthquakes (2011 Tohoku, 1960 Chile, 1964 Alaska) are all being investigated. Strain transients have been observed at the San Andreas fault, volcanic deformation has been observed at Hawaii and other active volcanoes, and transient deformation has even been recorded following Hurricane Sandy landfall.

Ongoing research is investigating how heterogeneous the lithosphere is, what are the spatial and temporal variations, and if the heterogeneity effects observed deformation. People attending the session expressed the need for combining different observation types such as gravity (from GRACE) and GPS. Studies of transients and long-term deformation could be improved through improved resolution, with better coverage of all instrument types (GPS, BSM, in all areas). Of particular interest is the ocean floor, where seafloor geodesy can potentially constrain subduction zone physics, but seafloor geodesy instruments and techniques must first become affordable and robust.

What are the compelling emerging science directions?

Attendees identified a number of emerging issues and trends that would require longer term planning and operations on the order of 10-15 years into the future. These issues are climate change, hydrology, improving seismic hazard evaluation, new frontiers in space, and unusual future events. For climate change, assessing sea level rise and coastal subsidence will require new technology and new analysis methods. Hydrology is a broad subject, with multiple possibilities for applying geodetic data. Hydrologic signals are already observed in the GPS time series and the GPS data can be combined with GRACE observations to measure the evolution of aquifers in response to groundwater changes from pumping/drilling. Hydrologic models will be integrated into solid earth models, and models for seasonal processes will be developed and integrated into future reference frames. Applications to cryosphere and atmospheric studies are also being developed. Geodetic data will contribute to the field of natural hazards, providing data on short time scales to be used in realtime monitoring for earthquake and tsunami early warnings. GPS data in particular can be combined with paleoseismology and the historic seismic record to develop useful and realistic forecasts. Well-monitored areas are only recently starting to get models for the earthquake cycles, and geodesy will help capture the full range of uncertainties in the data and model. Geodetic data will further be used to constrain lithospheric viscosity models from post-seismic deformation. Related to hazards, it is likely that an unforeseen event such as a great earthquake or large volcanic eruption can spur new discoveries and attract public attention and funding. On a broader and more ambitious scale, satellite-based geodetic methods can be exported to other planets and moons, and may someday allow geodesists to measure deformation on Mars or Europa.

What are the technical and facility requirements to advance these new science directions?

The value of the PBO data set lies in its long time series, and the geodetic community representatives would like to maintain expanded recording, with long-term GPS and InSAR observations. To support ongoing network operations, UNAVCO should look for ways to decrease or share costs. This might include reaching out to stakeholders and facilities in other communities such as hydrologists and surveyors, and enlist their aid. Monumentation and maintenance are now the largest part of GPS costs, and there needs to be coordination between remote and easily accessible, densely instrumented regions to maintain maximum geographic coverage.

Workshop attendees identified a number of priorities that should be addressed in the face limited logistical, budget, and other resources. Seafloor geodesy is a developing field that can constrain deformation across subduction zones and other offshore areas of interest, but is expected to have very high costs. Realtime GPS data are in demand, especially as telemetry and data streams improve and become more reliable. There is demand for having realtime data available on a larger scale; currently only a fraction of PBO station are realtime. New funding streams will be required to expand realtime networks. As the new GNSS constellations come online and expand, there is interest in integrating the new signals into GPS processing. GNSS has already proven useful in kinematic processing and is expected to improve resolution and reduce noise in daily processing. High-rate gravity methods are/will be developed to measure mass changes at to-be-identified sampling. The integration of InSAR and GPS is also a promising method for recording deformation.

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

In conjunction with developing new technologies, methodologies, and expanding current capabilities, there was an emphasis on sharing and integration. For daily GPS, there are private and government networks that are not necessarily public, and sharing data from these networks would improve geographic coverage. Furthermore, it should be possible to share models and computer code associated with published papers beyond what is available at journal web sites. A shared repository of code, models, and data will enable study results to be reproduced, and code to be reused.

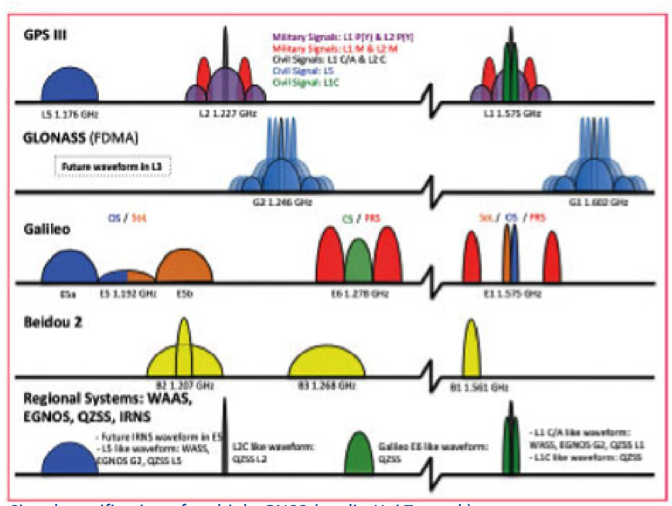
There was some discussion of strainmeters. Strainmeters have low noise and resolution up to three orders of magnitude greater than GPS, but manufacturers are retiring and there is the risk of losing institutional knowledge. Current research is looking at rainfall effects on strain, and these near surface effects can be tied to hydrologic research. Other research in grouting and borehole technology should lead to improved performance at new boreholes.

STS 2.1 Cyberinfrastructure & EarthCube: meeting challenges with CI; DOI

Susan Owen (Jet Propulsion Laboratory), Bill Hammond (University of Nevada Reno), Fran Boler, Chuck Meertens, David Phillips (UNAVCO)

What are some exciting recent science contributions and technical advances? A few examples (not a complete list!):

- Many scientific contributions showing contemporary changes in solid Earth shape, movements of ice, water, and their loads on the solid Earth, e.g. accelerations of elastic rebound owing to ice loss in Greenland.
- Demonstration of GPS-based estimation of elastic, density properties down to 300 km depth using response to tidal forcing.
- Published improvements in understanding of western US crustal deformation rate, pattern and style, estimates of fault slip rates throughout the western United States and their contribution to improved seismic hazard models. Rio Grande rift, Pacific Northwest, Southern California, Pacific Northwest, Basin and Range, Wasatch, Yellowstone.

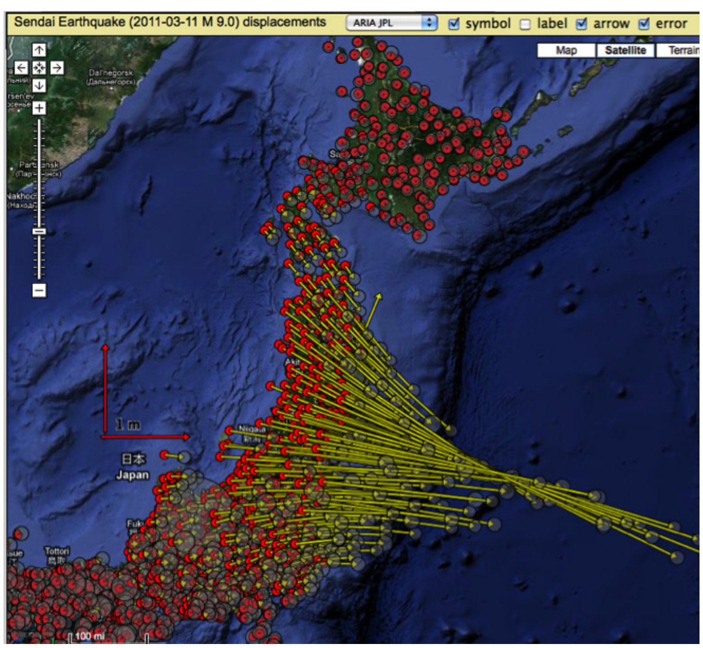


Signal specification of multiple GNSS (credit: Hai Ta et al.).

- Detection and further understanding of transient deformations associated with ETS, ongoing debate about transients in the Basin and Range.
- Demonstrations of impact of water cycle and human activity on vertical uplift of Sierra Nevada, California Great Valley, Pacific Northwest, effect of drought on vertical land motion, and possible effects of these on modulation of seismicity on major faults.
- Efficient processing strategies developed for processing of mega-networks of GPS stations globally distributed.
- Improvements in processing methods and time series analysis of SAR data, new missions recently launched and planned (ALOS2, Sentinel, NISAR).
- Improvements in readiness (e.g. READI) for rapid estimation of earthquake parameters during next large earthquake
- Other emerging and novel applications of GPS including atmospheric disturbances, snow depth, moisture sensing, volcanic plumes
- Laser imaging of faults, earthquake deformation, landslides.

What are the compelling emerging science directions?

- Effect of hydrosphere on solid Earth deformation
- Mantle flow and dynamics
- Global change broadly investigated, integrating across different scientific domains.
- Transient deformation detection and interpretation, physical understanding of these processes.
- Application of geodesy to seismic hazard analysis



Coseismic displacement from the 2011 Tohoku earthquake through the Real-time Earthquake Analysis for Disaster Mitigation Network (READI).

- Application of geodesy geophysical event response, e.g. earthquakes, tsunamis, landslides, floods. Incorporate improvements in real-time analysis, parameter estimation, sharing of information at high volume with low latency, to rapidly inform society and formulate science response.
- Mechanics of ice, ice streams, glaciers and response to climate forces.
- Dynamical modeling with data assimilation as an overarching category
- Improvement of characterization of data and model uncertainties
- Model ensembles/system level models that incorporate geodesy, multi-scale integration of complementary displacement data sets/data fusion
- Attribution for models and codes, with version numbers (difficult to do with DOI)
- More effective utilization of Big and Growing Datasets

What are the technical and facility requirements to advance these new science directions?

- More effective utilization of Big and Growing Datasets
- Facilities for sharing data and model products
- Implementation of policies and machinery that support data attribution, DOIs, record data provenance, ease discovery.
- Repositories
- Community earth models, including elasticity, density, stress, strain, strain rate, seismicity, temperature, faults, etc.
- SCEC has uniform fault representation for SoCal, could be extended to include a broader geographic scope. Will enable system scale science (SCEC on EarthScope scale).
- Useful to converge on a standard geometry/reference
- Reproducible/validated results for models.
- Easily accessible processed interferograms and time series.
- Standardized formats and services for InSAR products
- Software that will enable better education of next generation of geodesists, e.g. the Earth Science workbench, e.g. QuakeSim and GeoGateway. This includes, but may not be limited to front-ends, GUIs that drive processing, modeling codes e.g., EarthKit.
- Smoother transition between different levels of coding expertise.
- Visualization facilities/software that is easy to acquire, configure, use, share products.
- Cloud based modeling to make it easy to acquire, configure, use, share products.

- Sharing models and code (a la CIG).
- International collaborations, geodesy is a global science.
- Need continued support for the stable flow of essential data from networks that support the science goals also supported by geodesy cyberinfrastructure.
- Transition and continued support to real-time data streams for existing networks.

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

- Figure out a way to plug EarthScope into EarthCube, continue with EarthCube strategic plan and workshops.
- Extend usefulness of CIG products and organization for EarthScope users.
- Broaden reach of EarthScope by working with other communities (e.g., hydrology, atmospheric sciences).
- Define products that would be transformatively useful for integrating disciplines, e.g. solid Earth and hydrological sciences.
- CI workshop (or sequence of workshops) is needed to coordinate with future community planning that will be used to define EarthScope post 2018.
- Further connections with hydrology community... plan workshops, products that facility research on this front.
- Host code sprint/hackathon/workshop to share ideas, similar to the way that CIG has workshop/tutorials with "tinker time".
- Agency coordination to bolster support for networks essential to hazard mission.

STS 2.2 GNSS, network modernization, and other emerging technologies

Felipe Nievinski (Sao Paulo State University), Freddy Blume (UNAVCO)

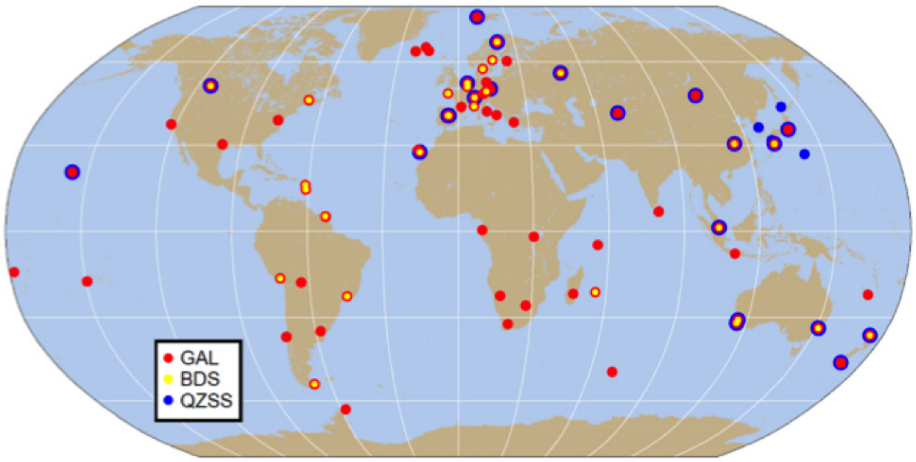
This special topic session (STS) started with an introductory presentation by Felipe Nievinski. Legacy GPS satellites and signals (~ 30 satellites and two carrier frequencies) were compared and contrasted to modernized signals and entire new constellations. It was emphasized the prospects for, in less than 10 years time, having more than 100 GNSS satellites broadcasting in multiple carriers and modulations.

Four background presentations were given by invited speakers. F. Nievinski, UNESP, presented "Reflectometry using modernized GNSS signals". It was acknowledged that positioning remains the main PBO product today, while reflectometry (GNSS-R) is an emerging technology (pioneered by K. Larson at CU Boulder). It exploits multipath for soil moisture, snow depth, and vegetation biomass monitoring. Modernized signals, such as L2C and L5, proved superior for GNSS-R, compared to the lower power and shorter codes of legacy signals. The availability of multiple frequencies also opens up the possibility of new methods. Modernized GPS and new GNSS are fostering innovations in GNSS-R, which brings its own data collection requirements to the tracking network.

The second background presentation was "Triple frequency Precise Point Positioning (PPP)", by J. Haase, UCSD (on behalf of J. Geng, UCSD). Support for L5, the third carrier frequency, had been incorporated to the standard L1/L2 PPP processor. A simulation was carried out to compare triple- and dual-frequency ambiguity resolution (AR). It is possible to cascade AR with triple-frequency signals, from a large wavelength (5.86 m) to the final shorter combination (0.1 m) through an intermediate value (3.4 m). This cascading accelerates PPP AR convergence, from tens of minutes down to just a few minutes.

Related to the topic of network modernization, F. Blume, UNAVCO, presented "Stability of GNSS Monumentation". It was remarked that, if monuments are not representing the bedrock movement, then any addition of new signals or processing methods may not be of any use for precise positioning applications. Five styles of monuments in various geologic settings (bedrock vs. soil, etc) were contrasted. Multi-monument locations were analyzed to assess stability. The ideal experimental setup was a 10-m equilateral triangle. Results from different data processing methods were analyzed. Excellent agreement was found between deep-drilled braced monuments (DDBM) and shallow-drilled/driven braced monuments (SDBM) and also between DDBM and mast/pillar directly into exposed bedrock; less agreement was found when using pillars in unconsolidated soil sediments. These findings are relevant for PBO and also for the UNAVCO-maintained NASA Global GPS Network (GGN) as well as the International Association of Geodesy (IAG) Global Geodetic Observing System (GGOS), which will be installing triple-monument sites to allow continuous inter-comparison.

The final short presentation was "IGS-MGEX: Preparing the ground for multi-constellation GNSS science", by F. Nievinski, UNESP (on behalf of O. Montenbruck, DLR/GSOC). The MGEX initiative was launched by the International GNSS Service (IGS) in 2012. It has almost 100 stations worldwide, contributed by 27 agencies from 16 countries. The tracking data is openly and freely available in the latest RINEX version 3. The heterogeneous equipment environment is sought for cross-validation of equipment performance and improved tracking robustness. The analysis products (ephemerides and clocks, etc.) produced depend on the funding priorities of the various participants – some agencies are processing GALILEO only, while others are doing truly multi-constellation GNSS. New products include inter-frequency and inter-system differential code biases as well as the monitoring of system time offsets. MGEX needs spacecraft



The IGS Multi-GNSS Experiment (MGEX) includes approximately 90 stations.

information (antennas, attitude, solar panels, etc.) which is sought from system providers.

What are some exciting recent science contributions and technical advances?

In the second half of the STS we had a group discussion, guided by four seeding questions. For each question it was offered structured remarks and the audience was asked for positive as well as negative feedback about the propositions. The first question was: "What are the exciting recent science contributions and technical advances?" It was noted that, after ten years in the air, the first modernized GPS signal (L2C) did yield breakthroughs in reflectometry (e.g. PBO H2O) but it is still not used routinely in high-precision positioning. A member of the audience, J. Braun (UCAR) pointed out that L2C has been found superior for GPS Radio Occultation (GPS-RO) applications as well. K. Hudnut (USGS) inquired how is PBO acquiring and using these new signals. Clarification was offered by noting that all Trimble NetRS receivers track L2C but it is not used in standard PBO processing; and that any user can request L2C data, although RINEX version 2 will only allow one phase observable per frequency, thus RINEX version 3 is necessary to hold phase from both L2C and L2P(Y). As for L5 tracking (unavailable in NetRS), all UNAVCO-operated receivers that can track L5 (e.g., Trimble NetR9) are configured to do so and these data are made available in the RINEX 2.12. J. Freymueller, (University of Alaska) recalled that care needs to be exercised with manufacturers' definition for L2C carrier phase zero offset as some introduce a ¼-cycle correction; he further stressed the desire to have a single data file containing all the observations recorded – thus the need for RINEX 3 . As for network modernization, T. Song (JPL) asked about plans for upgrading PBO sites in Alaska to real-time telemetry; Glen Mattioli (UNAVCO) answered that this cannot be done given the level of current core NSF funding for PBO.

What are the compelling emerging science directions?

The second seeding question, "What are the compelling emerging science directions?", was initiated by the STS facilitators noting that high-rate epoch-by-epoch kinematic-type GPS positioning (for seismology) has emerged in the last five years as a new usage that complements the more established daily time-series (for tectonics) (Hammond et al., 2010). The question was then posed to the audience: When and how are these two recent developments expected to come together – epoch-by-epoch GNSS positioning? Mike Lisowski (USGS) indicated that GLONASS works well for volcano deformation, with noticeable improvement in hourly solutions over GPS-only processing. In contrast, the increased observation redundancy brought by multi-constellation tracking data does not seem to benefit as much long-arc post-processing solutions. A proposition was put forth, that daily solutions might benefit from non-sidereal orbital periods, as it would randomize repeatable errors (e.g., spurious draconitic harmonics). Additional observations should improve such systematic mismodelings. The discussion went on to tracking network issues, such as RF interference with Iridium out-of-band transmissions (used for telemetry at remote sites) and the recent threat of LightSquared. UNAVCO has done some tests with different GNSS receivers and antennas – either or both can be susceptible to interference –, and some manufactures are starting to include adaptive frequency filters. Jennifer Haase (UCSD) mentioned that we should see great improvement in ground-based GNSS-Meteorology as well as spaceborne GNSS-RO with multi-constellation observations. GPS-Reflectometry is likely to continue to reap further benefits as well.

What are the technical and facility requirements to advance these new science directions?

Further discussion was seeded with the third question, "What are the technical and facility requirements to advance these new science directions?" Three broad topics emerged: hardware, software, and archival. It was noted that existing choke-ring antennas can be retrofitted for triple-frequency operation and also for improved filtering of RF interference. The question was raised if it is time to upgrade NetRS to NetR9 – or wait for more mature technology? It was recalled that obsolete instruments will not be able to be repaired and still need to be replaced despite the utility and application of new observations. A cost-benefit analysis was deemed critical given the budget-constrained environment. As for the second topic, it was hoped to hear the developer's perspective on positioning software (GIPSY, GAMIT, etc.) supporting the latest GPS signals and new GNSS constellations but the multiple STS running in parallel might have dispersed participants. The topic of data archival formats further indicated the future adoption of RINEX version 3, although doubts remain with regard to options for pre-processing and quality-control software (teqc, GPSTk, etc).

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

The STS finally advanced to the last seeding question, "Is community currently planning to support new directions, or are further activities needed?" Unfortunately the debate had to be stopped at the time allotted for all the parallel STS to reconvene. No consensus was reached on recommendations. A recurring theme worth of special notice was RINEX 3, both the expressed need for it and the concern for what would be entailed by its adoption. Other open questions were: When should PBO start tracking constellations other than GPS? Should data collection start before data processing capability is ready?

STS 2.3 Undergraduate geodesy curriculum

Bruce Douglas (Indiana University), Beth Pratt-Sitaula, Shelley Olds UNAVCO)

What are some exciting recent science education contributions and technical advances?

During the STS, we presented an overview of the current undergraduate curriculum development project funded by NSF, GEodesy Tools for Societal Issues (GETSI), the process of module development, and specifics about the two modules currently in development: Ice/Sea Level (intro level) and Imaging Active Tectonics (majors level). We then provided a brief tour of education resources using geodesy already available for undergraduate teaching. Most of the session focused on the resources the community would like to see developed. Fifteen community members (non-UNAVCO ECE staff) participated in the session discussion.

In response to what types of teaching resources, topics, and data sets would serve undergraduate students best, the session participants responded with a broad interest in different geodesy topics and applications (GPS to gravity to water resources); they expressed that there needs to be an emphasis on incorporating open source or other easily accessible software; and that locally-relevant (or tailor-able) data sets would make concepts more relevant to students.

Session participants discussed and shared exciting recent contributions and advances in geodesy undergraduate education:

- Animations on variety of topics produced by IRIS EPO
- Cornell isostasy interactive tool

GETSI (GEodesy Tools for Societal Issues) module, Ice and Sea Level Changes, authors Leigh Stearns and Becca Walker brainstorm module components during the February 2014 Materials Development Workshop.

- Visible Geology structural geology interactive
- Upcoming user tools for Google Maps.

What are the compelling emerging science education directions?

- Additional topics or educational products needed in the coming years included:
- Improved and more focused interactive online tools (less complexity is more useful at the undergraduate level).
- Easily accessible and processed InSAR time series.
- Easily accessible and processed High Rate GPS and Earthquake Early Warning Systems material.
- LiDAR imagery for educational purposes (not just research, ex. NCALM is open to doing field camp areas).
- UNAVCO hosting software licenses (ex. LiDAR processing software).

What are the technical and facility requirements to advance these new science education directions?

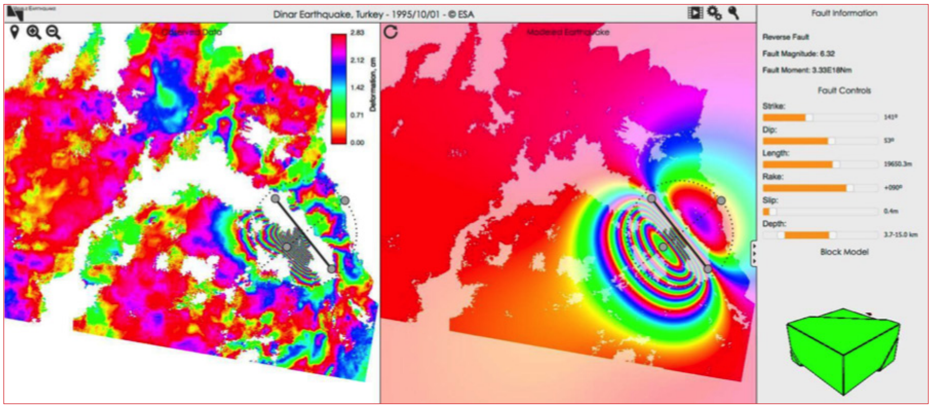
To advance in these directions, the technical, human, and financial requirements needed include:

- Support for including innovative Broader Impacts into research proposals.
- People to create/maintain interactive tool development.
- People to create more accessible data sets systematically (not just one-offs).

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

To achieve these goals, ideas on additional community planning or input included:

- UNAVCO could host blog or wiki discussion forum for



VisibleEarthquake interactive InSAR Tool (beta version) for understanding earthquake ruptures as measured by InSAR. FYI - Further development is near completion through UNAVCO support and collaboration with 3point-Science and Gareth Funning of UC Riverside, a GETSI co-author.

these topics (with guest writers).

- UNAVCO would continue to collaborate on broader impact components with PIs
- UNAVCO could send out reminders about upcoming deadlines for proposals and reminders of available educational resources prior to the beginning of each semester.

STS 3.1 Science questions at a hemisphere scale: towards federation of geodetic networks across the Americas

Pete La Femina (Pennsylvania State University), Glen Mattioli (UNAVCO)

What are some exciting recent science contributions and technical advances?

Geodetic imaging – OpenTopography and WinSAR for the Americas – maybe UNAVCO needs to expand the federation concept beyond traditional geodetic observations (GNSS, BSM, etc).

GPS-A or other sea-floor geodetic technologies MUST be developed if we are to understand plate interactions.

GRACE – new features are now being seen in data and may be related to solid earth processes and deformation – need to partner with this group – attend GRACE meetings.

What are the compelling emerging science directions?

- Hourly TEC product already assimilated into NOAA Ops – High quality, ionospheric scintillation needs >50Hz but SNR data only.
- ZWD/PWV observations provide useful constraints on regional, hourly NWS simulations now and it greatly improves these predictions.
- Entire global water vapor cycles every 7 days – current GCMs do not assimilate these data – may want global network – necessary spatial density not clear at this time.
- GIA – need more eastern NAM and arctic coverage – superposition of many processes – this can also drive loading and crustal processes – examine different time and length scales.
- Understand the interplay of orographic and climate interactions in the Andes today – how can this inform understanding about the past?

What are the technical and facility requirements to advance these new science directions?

- Problems with anti-American sentiment and national political constraints on partner agencies in many countries.
- Sensitivity to "publishing" GPS/GNSS data – need to get appropriate national approval at the highest level.
- High-rate, low-latency (different rates for different processes).
- Do we need at least one GPS-A (sea floor) site per plate?
- Processing more data together in a unified schema – also investigation of transients in a coherent way.
- Encourage vendors to include scintillation capabilities into receivers.
- Can we use cheap consumer electronics to our advantage? If so, how?

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

- Develop plans to have a workshop to define the problems and obtain additional funding.
- Much of the GIA and its impact on current and past processes have not been fully realized in EarthScope Science Plan and PBO.
- PBO ACs/ACC are now processing >1800 stations in NAM and CAR. Entire data set has been reprocessed in ITRF08 from 1996 onward. This will leverage

additional science, including GIA.

- More sites are going into Canadian Arctic – also regional/provincial networks are becoming more open for raw data files.
- For whom are we collecting these data? Human resource development – need to include local and regional scientists and students to help transfer technology and knowledge – PUT PEOPLE FIRST!

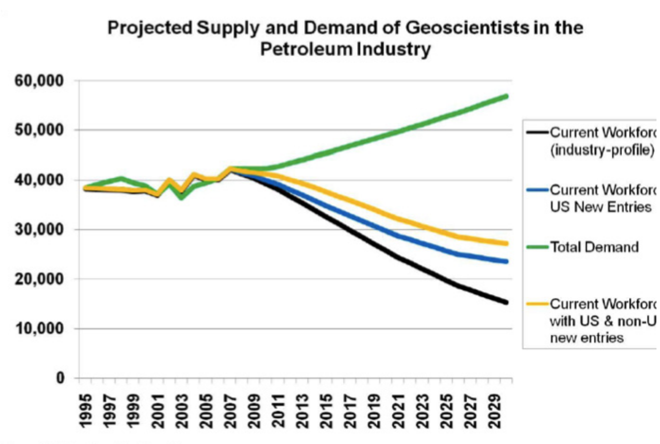
STS 3.2 Geoscience/geodesy workforce development and training

Bob Wang (University of Houston), Aisha Morris, Donna Charlevoix (UNAVCO)

An inaugural Special Topics Session focused on Geo-workforce development and training was convened at the 2014 Science workshop with the goals of community discussion and guidance on (1) identifying geo-workforce paths related to geodesy and (2) guiding UNAVCO in anticipating new directions and prioritizing resources to support the next generation of geoscientists and geodesists. The eighteen participants in this session represented faculty at research and teaching universities, graduate students, post-doctoral associates, NSF program officers, and UNAVCO staff.

What are some exciting recent workforce development contributions and advances? What are the compelling emerging workforce development directions?

NSF, in its Strategic Plan (2014-2016) asserts "The nation must maintain a robust science, technology, engineering and mathematics workforce." (p3). The work UNAVCO has undertaken with respect to workforce development aligns with the NSF performance goals Target 2 "Prepare and engage a diverse STEM workforce motivated to work at the frontiers." (p7). Shared NSF and UNAVCO core strategies for accomplishing this include integrating research and education to build capacity, and broaden participation in the STEM fields.



The demand for geoscientists in the petroleum industry alone is motivation for providing more support to aspiring scientists. (From: Tracking the Dynamics of the Geoscience Workforce (PowerPoint presentation), AGI, http://www.agiweb.org/workforce/reports.html

The demand for trained geoscientists is projected to increase through 2030. Geodesy is a toolkit for interdisciplinary geoscience work and as students become trained and well versed in geodetic content, instrumentation and data they build their skills base, increasing their marketability.

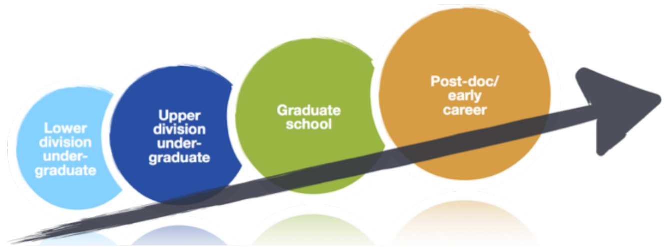
What are the technical and facility requirements to advance these new workforce development directions?

UNAVCO, as both a facility and a community of scientists, is uniquely positioned to contribute to training and support of the next generation of geodesists and geoscientists. UNAVCO currently has a broad infrastructure with which to deliver such support. UNAVCO supports geo-workforce development of the next generation of scientists through intentional preparation and talent development of populations traditionally underrepresented. This will create an infusion of necessary new perspectives and people into the workforce. UNAVCO's framework engages students from their first entry into higher education through their early career positions.

The participants in this Special Topics Session provided a variety of recommendations for UNAVCO to move forward on this initiative. The community participants spanned a wide range of experience including private industry and academia.

The community suggests that:

- UNAVCO could serve as a bridge between undergraduate education and technical needs of companies and employers (more broad experience than academic institutions or private industry/sector).
- UNAVCO is strongly encouraged to partner with professional societies and leverage the work they are doing with respect to supporting students and early career professionals.
- UNAVCO is uniquely positioned to complement training efforts of universities in non-theoretical (practical) areas such as cutting edge technology and, surveying. Universities have limited capacity to work these and related topics into the curriculum.
- UNAVCO should consider working with publishers of textbooks to strengthen the geoscience content and add a geodetic focus whenever possible.
- UNAVCO should consider providing other resources for learning material targeted to students and early career, videos in particular.
- UNAVCO should consider making visible or providing training on logistics planning for field research campaigns.
- UNAVCO should consider providing resources for developing "soft skills" for students and early career professionals. Soft skills, such as communications, were



The framework of the UNAVCO Workforce Development Initiative. UNAVCO serves community college and lower division undergraduate students through their entire academic career and into early professional positions through a series of internship programs, support systems and online resources.

recently deemed as very important by the geoscience education community at the Summit on the Future of Undergraduate Geoscience Education (January 2014, http://www.jsg.utexas.edu/events/future-of-geoscience-undergraduate-education/).

- UNAVCO should consider how they can help support development of quantitative reasoning skills and programming skills, as they are applied to geodesy.

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- UNAVCO should consider how they can help support development of quantitative reasoning skills and programming skills, as they are applied to geodesy.

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

In addition to providing recommendations, participants expanded the discussion to include areas of consideration they caution UNAVCO to consider as a more detailed plan and projects are identified and implemented.

Considerations to make as UNAVCO moves forward include:

- *Learning styles.* Individuals ingest and process information differently. How best will students learn this non-theoretical information? What would be the best delivery mechanism for such content?
- *Consuming information.* Attention must be given to how information is provided and where the user is most likely to access and interact with it. Effort should be taken to identify where students truly consume information and ensure that materials being provided are aligned.
- *Communication methods.* The role of social media and communication is powerful and thoughtful use of such channels has a potential to reach a broad audience.
- *Professional societies.* Many geoscience professional societies have efforts underway focused on workforce development or broadening participation. UNAVCO should examine those initiatives and leverage their expertise so as to build capacity.
- *Workforce pathways.* Only roughly 25% of STEM undergraduates go on to graduate school. Preparing students for the workforce is equally important to providing pathways to graduate programs.
- *Comprehensive skillset.* Success in the workplace relies on a diverse set of skills including computing skills, data literacy, scientific content knowledge and critical thinking.

STS 3.3 Using borehole and long baseline data to detect transient deformation

Rick Bennett (University of Arizona), Kathleen Hodgkinson (UNAVCO)

The goal of this special topic session was to further planning for existing and emerging science related to the use of borehole and long baseline strainmeters for detection of transient deformation. Session participation among community members was strong, although the precise number of participants was not recorded. Brief presentations were delivered by Duncan Agnew, Kathleen Hodgkinson, David Mencin, and Lawrence Murdoch.

Group discussion following the presentations addressed the following questions:

What are the exciting recent science contributions and technical advances?

It was noted that the Chinese have constructed (or are in the process of constructing) a new 200-station BSM network, which is larger than the PBO BSM network. UNAVCO has signed an agreement with that group to share data. Moreover, the two groups have begun discussing the possibility of co-locating PBO and Chinese BSM instruments. These developments should significantly increase the volume of BSM data sets available the UNAVCO community, as well as providing new insights into BSM technology, error sources and error mitigation methods, and overall performance of the instruments.

A number of recently published or forthcoming works illustrating the utility of BSM technology were discussed. These include studies of (1) strain associated with crustal loading driven by lake seiches, with implications for partial melt beneath the Yellowstone Caldera (e.g., Mencin et al., 2012; Lutrell et al., 2012), (2) high-time resolution records of creep on both the San Jacinto fault near Anza, and the San Andreas fault near Parkfield (e.g., Hodgkinson et al. 2013), and (3) combination of broadband seismometers and strainmeter instruments for seismic wave detection and "seismic wave gradiometry" (e.g., Langston and Liang, 2008; Blum et al., 2010; Barbour and Agnew, 2012).

A particularly intriguing application of BSM, presented by Murdoch, discussed hydrological applications of BSM instruments, particularly with regard to the effects of rainfall. Strain signals associated with rainfall were analyzed using hydrological models. Such models have the potential to reduce the level of "noise" in BSM time series for studies of crustal deformation, while at the same time constraining hydrological model parameters such as trans evaporation rates.

Finally, the group discussed the ongoing effort to transfer knowledge of BSM manufacturing to UNAVCO in collaboration with researchers at the Carnegie Institution of Washington.

What are the compelling emerging science directions?

The question was raised as to whether strainmeters might produce useful data for the carbon sequestration monitoring, and whether the UNAVCO community might have any interest in helping expand the role of strainmeters into this area. It was noted that UNAVCO has been approached by commercial operations (Newberry) to install BSMs.

Comments included the suggestion that (1) improvements could/should be made in our ability to record the smaller scale transients along the faults using strainmeter technologies and (2) the technology appears to be underutilized for volcanological research, although it was noted that strainmeter networks are currently running at magmatic systems in Italy, the Caribbean, Iceland, and Hawaii.

Another emerging area involves seafloor fluid-pressure strainmeters, which have been installed and are returning interesting data. Finally, it was suggested that decades-long data sets (from existing stations) might provide information on the effects of climate change, though no specific signals expected to result from climate change were reported in the summary materials.

What are the technical and facility requirements to advance these new science directions?

- Several recommendations were voiced in regard to the technical and facility requirements to advance emerging science directions. These include:
    1. reduce the cost of strainmeter instruments
    2. development of long-baseline fiber strainmeters,
    3. improve installations at volcanic sites in order to lower the noise levels associated with these sites,
    4. develop the data sets required to analyze long-term hydrological signals, precipitation, and possibly soil moisture,
    5. install shallow vertical strainmeters close to existing strainmeters to compare observed and modeled vertical strain
    6. develop low-cost removable borehole strainmeters for campaign style measurements,
    7. continue efforts to develop the Facility's ability to build and possibly redesign strainmeners
    8. keep existing creepmeters running.
- It was noted that long-baseline strainmeters are removable.

Is community planning to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

It was noted that NSF has recently funded a project in Turkey to study aseismic creep using borehole strainmeters. The need to develop a capacity to build BSMs and LSM in the long term was emphasized. In addition, the group agreed that a workshop dedicated to formulating a plan for the future development of the strainmeter data program was needed to more completely assess community needs. Finally, it was noted that software development is required, particularly for high sample data streams.

References for STS 3.3

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STS 4.1 High rate, real-time GPS for studies of earthquakes, volcanic eruptions and other major events

Ingrid Johansen (UC Berkeley), David Mencin, Freddy Blume (UNAVCO)

1. G-larmS: Real-time GPS at UCB - Ingrid Johanson, UC Berkeley
2. Kinematic Evaluation ofTrimble RTX Real-Time Positioning Systems – Henry Berglund, UNAVCO
3. Real-time GPS PPP(AR) Assists Earthquake Early Warning; ShakeAlert & Field Deployment - Ken Hudnut, USGS Pasadena

What are some exciting recent science contributions and technical advances?

G-larms (UCB) - UCSD multi-sensor - USGS EEW PPP-AR - Trimble RTX PPP (receiver- and server-based)

What are the compelling emerging science directions?

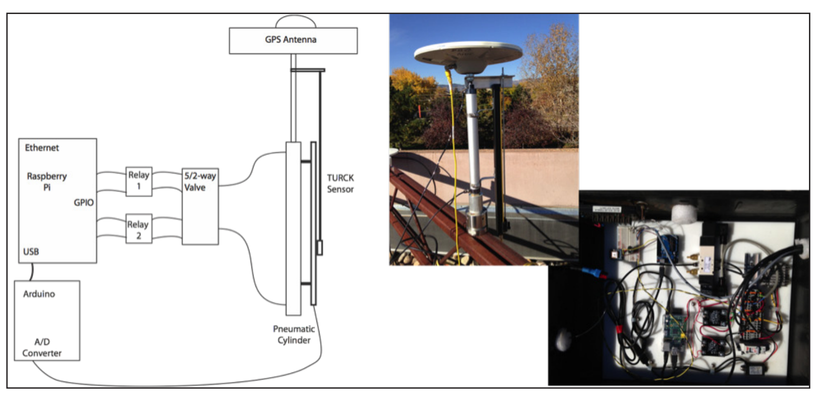
- Functional GPS and multi-sensor EEW systems ready for implementation - UCB G-larms - CISN ShakeAlert (USGS et al.) - UCSD multi-sensor
- Trimble/RefTek prototype GPS-accelerometer integration - Multi-constellation and modernized GPS signals in real-time positioning - Building monitoring to improve earthquake-resistant structural design - Other hazards (volcanoes, landslides)

What are the technical and facility requirements to advance these new science directions?

- Robust (including failover) and affordable data communications solutions - Continued UNAVCO and collaborative testing of RTX and PPP-AR solutions - Need for benchmarking and validation techniques in the field
- Deploy UNAVCO-designed low-cost kinematic antenna tests in PBO?
- Deployment of low-cost MEMS accelerometers at PBO field stations - Data format standardization for streams and position outputs - Guidelines for system deployment for end-users - NEED SCENARIOS AND MODELS TO TEST ! ! ! ! !
- Purchase 1 Hz Geo-Net earthquake data-sets (per prefecture) - Need funding for more real-time stations in high-hazard areas.

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

Testing of RTCM 3.2 stream which contains more information than BINEX in compact format (reduced bandwidth requirements)



Low cost kinematic anntena actuator for evaluation of real-time, high rate GPS.

>4 institutions testing and developing positioning algorithms independently and collaboratively.

Need to act now while attention is focused and window of opportunity is open. - Global theme: need new and stable funding sources for EEW infrastructure.

STS 4.2 Science opportunities in extreme environments, technical requirements & logistical constraints

Leigh Stearns (University of Kansas), Joe Pettit (UNAVCO)

What are some exciting recent science contributions and technical advances?

What are the compelling emerging science directions?

Many questions remain about the sensitivity of processes in the polar regions to atmospheric and oceanic variability. Reliable observations, at high temporal resolution are needed to constrain process-based models describing these processes. Recent improvements in the ability of GPS receivers to acquire data year-round in polar regions has been particularly important for estimates of ice sheet motion, snow depth and isostatic rebound.

Our group identified five main emerging science directions within the UNAVCO polar community:

- ice-ocean interactions
- ice sheet surface mass balance
- isostatic rebound
- satellite calibration
- soil moisture

These are by no means inclusive, but represent the experience of those attending the workshop.

What are the technical and facility requirements to advance these new science directions?

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

For UNAVCO to continue playing a large role in these polar disciplines, a number of improvements to the current observational platforms must be made. These recommendations were mentioned in the Science Workshop, and also in other polar technology conferences (2012 and 2014 PNSC Workshops, 2011 Automatic Polar Observing Systems Workshop).

Main recommendations include:

- Identifying a new polar GPS receiver, either through a competitive bid of private companies, or an MRI aimed at creating one in-house. Emphasis was placed on the unique needs of a polar receiver, whose development should be separate from that of non-polar receivers.
- Increased emphasis on research and development of the next generation of polar receivers, batteries, communication systems and enclosures. The polar community needs instruments that are more reliable and use less energy, and are powered by systems that create more power and are lighter than the current setups.
- Increased support for UNAVCO polar engineers to test and troubleshoot the current instrument pool. Problems are often found in the field, which comes at a huge cost to data acquisition.
- Development of a low cost/high risk GPS receivers that can be deployed near the terminus
- Incorporating near-situ observations (GBRI, TLS, time-lapse cameras) into the UNAVCO data pool.

There was consensus in our group that UNAVCO could facilitate cooperation amongst polar researchers by advertising the potential for co-located instruments. Funding agencies are increasingly interested in saving cost by building 'super-sites' where many instruments are co-located. The major limitation in this arrangement is that data communication is expensive and variable across instrument type.

UNAVCO polar engineers are often over-tasked by constantly preparing for large seasons and also helping individual researchers learn how to use equipment. Updated website forums and more short-courses will hopefully reduce the burden on the UNAVCO polar staff so that they can dedicate more time to product development and testing.

STS 4.3 Near-Field Geodetic Imaging: the Now and the Future

Ed Nissen (Colorado School of Mines), Ben Brooks (United States Geological Survey), Jim Normandeau (UNAVCO)

What are some exciting recent science contributions and technical advances?

We are witnessing an explosion of interest within the geoscience community in the use of near-field geodetic imaging to map landscapes and topography and to map and monitor Earth surface processes and deformation. Much of this interest is focused around laser (light detection and ranging (lidar)) scanning, whether airborne (ALS), terrestrial (TLS) or mobile (MLS); close-range photogrammetry including Structure-from-Motion (SfM); and terrestrial radar interferometry. Interest in these techniques has come about through the confluence of several factors, including wider coverage of ALS through collections by academic and state and local agencies (much of the data is freely accessible through portals such as OpenTopography); improved access to TLS equipment and support (including scanners deployed and operated by UNAVCO); the development of mobile technologies that incorporate hand-held devices or unmanned aerial platforms; and the increasing availability of

The 2014 UNAVCO Science Workshop field trip on the September 2013 flooding, TLS, and structure from motion. Wednesday, March 5, 2014. (Photo/Linda Rowan)

open-source software for imaging, processing, and analyzing such data. There is growing appreciation of these new technologies within geoscience education (e.g. deployment of UNAVCO's pool of TLS instruments at geology and geophysics field camps) as well as in research. UNAVCO is already heavily involved in TLS deployments but there is room for improved support in complementary or alternative technologies. UNAVCO needs to be especially carefull to consider these communities needs given the rapid growth of interest in this area.

What are the compelling emerging science directions?

Starting in about 2012, there has been rapid take-up of Structure from Motion (SfM) as an affordable and accessible way of generating topography using from unstructured sets of overlapping photographs captured on cheap digital cameras. This technology can map landscapes with resolutions of 100s to 1000s of pts/m2 (i.e. similar to those achieved by TLS) (Johnson et al., 2014), with the caveat that there are not yet any easy ways to strip vegetation from the scene. Often SfM photosets are collected using low-cost aerial platforms such as Unmanned Aerial Vehicles (UAVs) – including ones that fly pre-programmed routes autonomously – helium balloon/blimps or even poles. Point clouds at even higher density can be generated using mobile laser scanning (MLS) deployed from a blimp or backpack, though at much greater cost than SfM (Brooks et al., 2013). Portable structured light 3-D scanners such as Microsoft Kinect can be used to generate point clouds at finer scales and in real-time (Mancoff et al., 2013), and these will soon be available on handheld devices (e.g. Occipital Structure, Google Tango). These mobile and portable technologies are being used to map urban environments and even natural cavities such as volcanic conduits, reaching targets for which traditional ALS or TLS mapping is poorly suited.

The ease at which terrestrial and mobile imaging technologies can be deployed expedites rapid response or repeat mode applications. For example, MLS and SfM are being used to map fine-scale faulting offsets along the recent South Napa earthquake rupture before these are repaired or naturally degrade and subsequent deployment will attempt to capture post-seismic deformation. TLS instrument deployments are being used to capture rich time-series datasets for monitoring snow pack levels, permafrost melting, land-sliding, post-wildfire erosion, and for studying the dynamics of glaciers and lava lakes.

The widespread coverage of ALS data has enabled topographic time-series studies over much wider spatial apertures, though usually at coarser resolutions and precisions. To date, many of these differential lidar studies rely on early "legacy" datasets which are lower resolution than modern ALS surveys and which were never optimized for unanticipated science applications (Glennie et al., 2014). Nevertheless, repeat ALS data have been used to monitor or map dune migration, riverbank erosion, debris flows, and earthquake surface deformation. In the latter instance, deformation can be mapped in three dimensions (3-D), complementing the line-of-sight or horizontal displacements measured by "traditional" satellite geodetic measurements (InSAR and optical image correlation) and providing new insights into earthquake source physics.

What are the technical and facility requirements to advance these new science directions?

Is community planning needed to support new directions current (e.g., existing recommendations from recent workshop reports), or are further activities needed?

There is rapid growth in demand for UNAVCO's pool of TLS instruments and technical help, and the facility must be mindful of becoming capacity-limited. Scanning technologies are continuously improving and UNAVCO needs to ensure that its instrumentation pool is modern and captures a spectrum of capabilities from short- to long-range. Recommendations from the "Charting the Future of Terrestrial Laser Scanning" workshop (Phillips et al. 2012), are still generally valid in these regards. The use of TLS in field education is a great opportunity to engage students and showcase UNAVCO's capabilities, but it has some challenges, including peak demand during the summer period when instrumentation is also need to support research. Separate funding allocated to TLS instrumentation and curriculum development should be pursued. SfM also has the potential to be used in an educational setting and could relieve some pressure on TLS resources.

SfM is an emerging tool that is better suited in some situations than TLS (e.g. where rapid deployment is vital, where vegetation is sparse or low-lying, and where centimetric rather than millimetric precisions are sufficient). Yet few research groups are aware of these opportunities and UNAVCO should be positioning itself to support the community with SfM short courses and community demos (such as the one at the UNAVCO 2014 Science Workshop). The cameras and aerial platforms used for SfM mapping are affordable to most researchers and better uptake within the geoscience community could reduce the "strain" on UNAVCO's pool of TLS instruments.

There is a parallel need for improved community access to hardware, software (e.g. Keck Caves at UC Davis, 3-D TVs, and open source software such as CloudCompare, LAStools, Point Cloud Library, MicMac), and training that enable the visualization, manipulation and measurement of 3-D data. The greatest limiter to the successful scientific application of these imaging technologies is still the data processing and analysis required. UNAVCO should support a clearinghouse for software and workflows (leveraging existing resources available through OpenTopography), workshops, and training courses on best practices in 3-D data processing and analysis.

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COMMUNITY ACTIVITIES

In addition to the science and technical sessions, the 2014 UNAVCO Science Workshop celebrated UNAVCO thirty years of geodesy innovation for science – since its origins in 1984 at CIRES, University of Colorado. Community activities also included a keynote by Byron Tapley on the origins of space geodesy, short courses, enGAGE interactive space, student mentorship, a choice between a field trip to a 2013 Boulder Flood site and a UNAVCO tour, history interviews recorded on video, and an Ignite session.

Events Celebrating UNAVCO's Anniversary: Thirty Years of Innovation for Science

History. UNAVCO's history was a major theme of the 2014 UNAVCO Science Workshop, in celebration of the consortium's 30th anniversary. On Tuesday night, keynote speaker Byron Tapley, Director of the Center for Space Research and Professor of Aerospace Engineering at the University of Texas at Austin, provided a historical narrative of satellite geodesy intertwined with a history of the space program that provides support for the GPS satellite constellations.

Professor Tapley reviewed the ambitious origins of satellite geodesy and NASA in the late 1950s that relied on the use of artificial satellites to determine the form and dimensions of the Earth, the location of points on its surface and the nature of the gravity field associated with Earth mass. With time and improved technologies, this definition has been expanded to include repeat measurements that determine the temporal changes in these properties – Earth rotation, crustal deformation, sub-annual temporal changes in the gravity field, and tidal forces. More than 50 years after those origins, the geodetic capabilities that UNAVCO provides to the academic science community are deeply rooted in this history. Tapley's talk culminated with a glimpse into the

Keynote speaker Byron Tapley, Director of the Center for Space Research and Professor of Aerospace Engineering at the University of Texas at Austin, provided a historical narrative of satellite geodesy intertwined with a history of the space program that provides support for the GPS satellite constellations. (Photo/Travis Bildahl) future, and the emerging technologies that will sustain this renaissance: satellite bus capability, constellation control, nanometer ranging, sub-millimeter positioning, and a new generation of atomic clocks. Ultimately these will provide improved temporal and spatial observations of the changing Earth and high fidelity ocean, climate, and weather models that describe the interactions among its enveloping hydrosphere, cryosphere and atmosphere.

Throughout the Workshop, UNAVCO External Affairs collected 11 video interviews about the early days of UNAVCO and geodetic GPS for future use. Participants were invited to view and edit a timeline of UNAVCO's history and submit stories and photos from their experience with UNAVCO.

On Wednesday evening, an Ignite session, The origins and key transitions in UNAVCO's history, featured many investigators who been members of the UNAVCO community from the earliest days of campaign GPS. Nine presenters spoke for five minutes each about the importance and history of UNAVCO and geodesy. Follow the link for a fast-paced, multi-voiced tour of UNAVCO—past, present, and future.

Ignite UNAVCO Session
Wednesday, March 5, 2014

Ignite UNAVCO

In keeping with the theme of the 30 Years of Innovation for Science, the Ignite! UNAVCO session nominally focused on: The origins and key transitions in UNAVCO's history. Most of the speakers interpreted this rather loosely making for a fun, fast-paced and varied event. Nine presenters spoke for five minutes each about the importance and history of UNAVCO and geodesy. Follow the link for a fast-paced, multi-voiced tour of UNAVCO—past, present, and future.

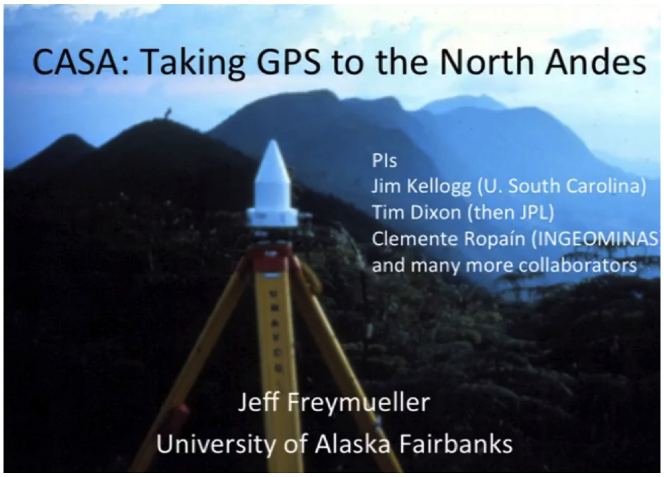
Leading with "The UNAVCO Community," Becky Bendick challenged our notion of the UNAVCO community, arguing that it should extend outward to encompass all of mankind. All people stand to benefit from our studies and adventures: Those who experience profound threat or risk from geologic and natural hazards - such as in the Kashmir of Pakistan, or who rely on the fragile web of ecosystem services provided by the hydrosphere in the very shallowest part of the solid earth about which we know surprisingly little, or like all humans intensely sensitive to the interactions between oceans, atmosphere and earth for weather. All people belong to this community of stakeholders. They rely on UNAVCO to make sense of the physical world. We owe them a duty of explanation about the importance of the science, an even greater duty of explanation to the skeptics to make accessible the patterns practices and premises of science. To the people we encounter, we are people who ask questions that allow them to think in a different way about the natural world. Bendick made the case that the face of the UNAVCO community is not the people who were in the room listening, rather it is a global community who benefits from our results and learning about what science is for in in the community of all mankind.

Roger Bilham led with the questions "Earthquakes vs. People: Who is Winning?" and more fundamentally "Can geodesy save lives?" as the jumping off point to explore the culprit – shoddy construction practices – focusing on vulnerable populations who live in unreinforced dwellings. Bilham asserted that earthquakes are "interested in" the weakest buildings, noting how little choice the poorest populations have when seeking shelter. Earthquake resistance adds 10% to construction costs, while the corruption that deflects governments from adopting and enforcing appropriate building codes to protect its people escalates building costs by 15%. In this global assessment, 85% of the deaths from recent notable earthquakes occurred in poor countries where construction practices have lagged behind modern standards.

Geoff Blewitt's "Becoming a Geodesist: 30 Years in 5 Minutes" opened with Talking Heads "How did we get here?" - here being the 1,100+ station Plate Boundary Observatory, 400 MAGNET stations in the Carson Sink, and openly available GPS data from more than 10,000 stations around the world. He then took a capricious (and nonlinear) walk through the key developments that led to the establishment of UNAVCO as we know it, including the North Liberty monument inscription "Blewitt and Clark Space Geodetic Pioneers", his role as first chairman of the board for UNAVCO in its current realization, together with Founding President Jim Davis, and board members Roland Burgmann, Bill Holt, Ken Hudnut, Meghan Miller, Paul Segall, and Wayne Thatcher; while producing his simultaneous lab notes on his reflections on loading and frames. Notably, he believes that Jim Zumberge deserves a medal for developing PPP as he and colleagues like Yehuda Bock were planning for the coming GPS data explosion. He ended with challenging the next generation of geodesists in the room to forget the textbook definitions of geodesy. Instead, redefine geodesy.

In "CASA: Taking GPS to the North Andes" Jeff Freymueller reviewed the colorful early history of observations – in Central and South America (CASA) including scaling a ladder and a cliff to get to the only (island) station on the Nazca plate. TI 4100 could observe 4 satellites at once, and had to be told when to switch satellites. It then took one CPU day to run a daily solution, for a 300-km baseline that had about ~1cm scatter – comparable to 1 second kinematic solution today. But yes, then as now, NSF reviewers demanded a demonstration study before recommending funding, so he went after big signals – plate motions, like Cocos – South America convergence (then 71±4 mm/year, now 69±2 mm/year). He ended with recognizing UNAVCO's role - providing equipment, training, customs, "everything."

Tom Herring posed the question about "Where are we

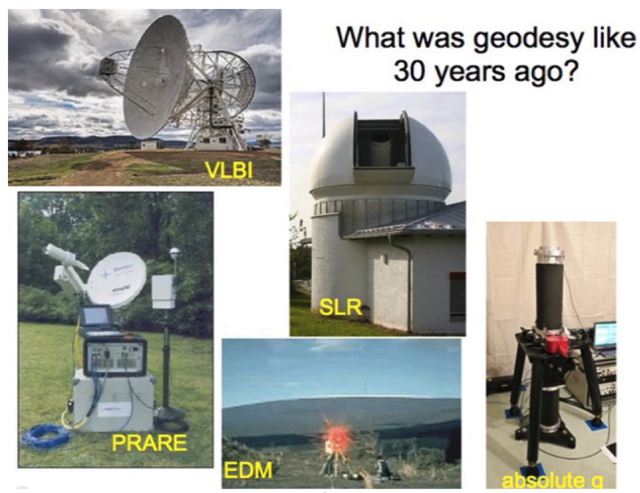


Title slide of Jeff Freymueller's Ignite! talk.

and where are we going?", from the fundamentals of atomic clocks, electronic distance measurements, radar development, optical distance determinations. 1984 saw the transition from results driven by large government labs to academic PIs driving the science. The paradigm shift to plate tectonics with Tuzo Wilson's paper in 1965, and Jason Morgan's 1968 rate determinations invited a new generation of requirements, laid out in the Williamstown Report, including 1 cm/year rate precision at a time that we could only locate within 10m. In 1986 – 16 years after the Williamstown report, VLBI successfully determined the rate of Atlantic spreading. Now the capabilities for high rate, high precision, widespread GPS geodesy, driving to tens of microns of accuracy for transient signal detection

Ken Hudnut looked back 60 years, recognizing USGS pioneers who led "Earthquake and Volcano Geodesy 'Early Days'" from EDM, geodolite, and leveling to 1-second latency GPS. In 1953, on a topographic survey, Jim Savage and his slide rule were the computer. George Plafker, Will Prescott, and Mike Lisowski were also USGS leaders, and the 1980 Mt St Helens eruption was pivotal in engaging this generation. He recognized Roger Bilham, who said GPS is simply not good enough, and then went on to found UNAVCO. Tom Herring, who heard GPS maligned a bit, went on to improve the atmospheric models. Mike Bevis, EOS editor, invited Jim Savage and Will Prescott to lay out the cons and pros of the usefulness of GPS and the the SCIGN array to capture earthquakes. In 1994, GPS observations of the Northridge earthquake allowed disambiguation of the nodal fault plane, and earthquake geodesy had come of age. SCIGN went on to innovate with monuments, adapters and radomes, the San Andreas fault Zipper Array, and now GNSS in real time with less than a second latency for earthquake early detection and warning.

Kristine Larson was "Present at the Creation" – and reflected on being a graduate student in the early days of GPS. Her "plastics moment" (re: The Graduate) occurred when she was told she would work on GPS. She was in on the ground floor with the SCUM collaboration (Scripps, Caltech, UCLA, MIT). She recognized Jim Davis, Will Prescott and Bill Strange as great geodesists. She recognized John Beavan, Gerry Mader, Herb Dragert and Jim Ray, as great geodesists who came down in the trenches with the students and post-docs. While DOD supported the GPS constellation, surveyors drove the cost of receivers down, creating great opportunity. She spoke to the enormous debt we all owe to the IGS for orbits and coordinates; now over 12,000 cGPS in an open data environment. The 1998 adoption of open data for continuous stations was pivotal. And opportunities for innovation have been great: Creating a tide gage, determining snow depth. She has come back to the same data and the same problems as our collective knowledge has evolved.

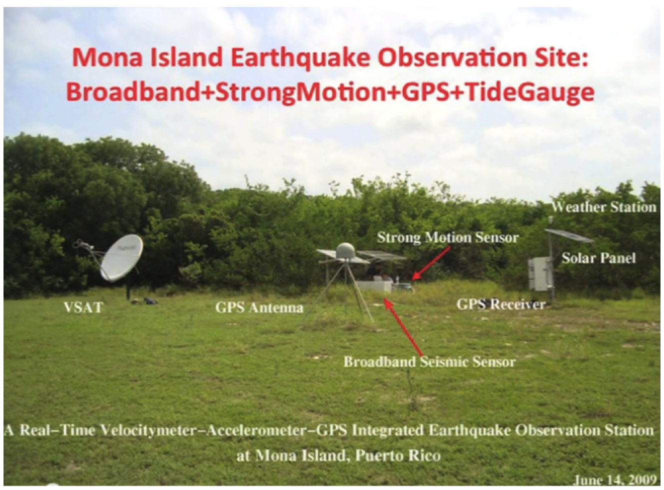


Kristine Larson gives a visual history of advances in geodesy during her Ignite! talk.

David Sandwell's "16 years of WInSAR: Making Lemonade" addressed four topics: How he got started in geodesy (Seasat!). Do we still need WInSAR? (yes!) Where are the US SAR satellites? (dark) And a brief history of WInSAR. Sandwell worked on the 1978 radar altimeter and SAR on SEASAT. Global gravity from SEASAT. In 1989 the first SAR interferogram, from the Salton Sea, was published by Gabriel, Goldstein and Zebker, followed by the Landers and Hector Mine earthquakes that occurred in an optimal environment for InSAR. The technical, data access, and vendor restrictions have challenged this community. The WInSAR consortium, which began as part of SCEC and now operates under the UNAVCO umbrella, promoted open access to data from the early days – where community members share data sets while competing in science. The US has a strong complement of US radar satellites launched by NROL (National Reconnaissance Office - #39), but they are dark, and were revealed by Edward Snowden. Foreign satellite assets have sustained this community. While some commercial data have come with a cost, ESA and JAXA have been the stars of the show.

Bob Wang regaled us with "An eight year history of UNAVCO support in Puerto Rico and the Virgin Islands." While a professor in Puerto Rico from 2006 to 2011, UPR established a network of 23 GPS stations on the islands, collocated with tide gages, for earthquake early warning, and also excellent for the study of landslides. There are now 23 established permanent stations, with a 15-km spacing along the coast. Establishment of a regional PRVI reference frame, stable to 1.8 mm/year, supports a spectrum of more detailed studies such as the integrated GPS, TLS, and weather observations of a landslide at the Ponce and El Yunque Rainforest National Park, where interactions between rainfall and landslide motion are now well established.


Vince Cronin of Baylor University holds court by demonstrating geodetic teaching tools in the enGAGE Interactive Space at the 2014 UNAVCO Science Workshop on Tuesday, March 4, 2014. (Photo/Beth Bartel, UNAVCO)



Bob Wang illustrates the instrument set up for investigating Puerto Rico and The Virgin Islands in his Ignite! talk.

Education

Short courses. Two short courses offered during the Science Workshop trained 70 students and professionals in the theory and methods of strainmeter science and hydrogeodesy. Participants learned how to use strainmeter data provided by the Plate Boundary Observatory and how to use GPS to study the water cycle.

enGAGE interactive space. The enGAGE Interactive Space premiered at this year's workshop to showcase educational tools and technology concurrent with the poster sessions. The space featured demonstrations of classroom activities for teaching strain, an up-close look at a GPS antenna and Terrestrial Laser Scanner (TLS), a display of one of the three TI-4100 Navstar Navigation System GPS receivers that gave UNAVCO its start, and a slideshow of historical photos.

Networking

E-NET. The Expanding Networks through Mentoring (E-NET) program formally connects graduate students and early career professionals with established researchers in the UNAVCO community. Mentors and mentees met at the opening reception Monday evening for introductions and brief discussions of goals for the workshop and then connected again throughout the week. This is the second time UNAVCO has facilitated the E-NET program at the Science Workshop.

Field trip. Wednesday afternoon, participants were invited to tour the mouth of Fourmile Canyon for a demonstration of TLS and to examine impacts from the September 2013 floods. Participants were introduced to TLS technology and survey design, scanner capabilities and operation, field data collection workflow, and preliminary results of topographic changes due to the September flood event.

UNAVCO tour. A tour of the UNAVCO headquarters in Boulder on Wednesday gave participants a window into UNAVCO operations. The tour covered the entire facility including the GeoLogistics Center and took a look at the engineering, equipment, and data archive facilities along with other infrastructure.

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ABSTRACTS

Solid Earth

A refined, interseismic geodetic vertical velocity field
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Analysis of the Inter-Diking Deformation Pattern at the Ongoing Dabbahu-Manda Hararo (Afar), Ethiopia Rift Segment Using GPS and InSAR Technique
Esubalew Adem, Elias Lewi

Cascadia slow slip events and earthquake initiation theories: Hazards research with Plate Boundary Observatory geodetic data
Evelyn Roeloffs (evelynr@usgs.gov) and Nick Beeler (nbeeler@usgs.gov)

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B. Lowry (a), F. Gomez (b), W. Zhou (a), M.A.Mooney (a), B. Held (b), J. Grasmick (a) (a) Colorado School of Mines, Golden, CO, United States (b) University of Missouri at Columbia, Columbia, MO, United States

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Huang-Kai Hung and Ruey-Juin Rau, Department of Earth Sciences, Naional Cheng Kung University, Taiwan

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Dario Solano-Rojas and Shimon Wdowinski School of Marine and Atmospheric Science, University of Miami
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Estelle Chaussard. Seismological Laboratory, University of California, Berkeley, 215 Mccone Hall # 4760, Berkeley, CA 94720

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Yang Zhang (yangzhang@unr.edu), Corne Kreemer, William C. Hammond, Geoffrey Blewitt

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Jiangbo Yu, Guoquan Wang, Timothy Kearns, Linqiang Yang

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Patricia Mothes-1, Paul Jarrin Tamayo-1, Jean-Mathieu Nocquet-2, Mohamed Chlieh-2, Alexandra Alvarado-1 and Hector Mora-3
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Julie Elliott (1), Matt Pritchard (2), Andrew Melkonian (2), and Mike Willis (2)
(1) Purdue University, West Lafayette, IN (2) Cornell University, Ithaca, NY

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Broadening impact through effective communication, and the power of partnerships
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Building sea level rise narratives through interactive visualizations
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Curricular module for introductory geophysics or structural geology courses to quantify crustal strain using EarthScope PBO GPS velocities
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Diedre Lamb and Rick Bennett, University of Arizona

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Engaging teachers, interpreters and emergency management educators in disaster preparedness and EarthScope science through joint professional development workshops
Beth Pratt-Sitaula (CWU & UNAVCO), Robert Lillie (OSU), Robert Butler (Univ of Portland), Nancee Hunter (OSU), Bonnie Magura (Portland Publ Schls), Roger Groom (Portland Publ Schls), Chris Hedeen (Oregon City SD), Jenda Johnson (Lava Video Prod), Charles Ault (Lewis & Clark Coll), Shelley Olds (UNAVCO), Michael Coe (Ceder Lake Res Grp)

Enhancing diversity in the Geosciences by testing the rigidity of the Eurasia plate using GPS
Diedre Lamb and Rick Bennett, University of Arizona

Explore a Shifting Earth through a Hands-on Museum Exhibit
Shelley Olds, UNAVCO; Celia Schiffman, UNAVCO; Bob Butler, University of Portland; Mark Farley, Hatfield Marine Science Center; Seth Frankel, Studio Tectonic; Nancee Hunter, Hatfield Marine Science Center; Bob Lillie, Oregon State University

GETSI Project: GEodesy Tools for Societal Issues An initiative to create teaching modules for undergraduates based on the
application of geodetic data sets
Bruce Douglas (Indiana University), Beth Pratt-Sitaula (UNAVCO), Becca Walker (Mt San Antonio College), Meghan Miller (UNAVCO)

Hands-on physical models that help students learn about crustal deformation and strain
Vincent Cronin (Baylor Univ.), Beth Pratt-Sitaula (UNAVCO), Shelley Olds (UNAVCO) and Nancy West (Quarter Dome Consulting)

Ocean Science

A distributed, coaxial-cable-based strainmeter for onshore and seafloor geodesy
Meng Wei, Tao Wei, Jihua Fu, Yang Shen - University of Rhode Island

Challenges in using GPS data to address sea level rise issues at the global and local scales
G. Wöppelmann

Early Detection of Tsunami Scales using GPS
Song and collaborators

Geodesy for Evaluating the Impact of Sea Level Rise on NASA Centers and Facilities
R. Steven Nerem1, Dallas Masters1, Charles Meertens2, Lynda Bell1, Keith Williams 2
1 University of Colorado/Boulder, Colorado Center for Astrodynamics Research 2 UNAVCO, Boulder, Colorado2

Relative sea level change in Western Alaska as constructed from repeat tide gauge and GPS measurements
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Technology

A network approach to estimation of GPS Velocity uncertanties
Ksenia Dmitrieva, Paul Segall

A Seismogeodetic Early Warning System for the Pacific Northwest
Brendan Crowell, Paul Bodin, David Schmidt, John Vidale

Enhancements and Plans for GMSTAR
David Sandwell, Rob Mellors, Xiaopeng Tong, Matt Wei, and Paul Wessel

The Activities of EPOS WG4 towards the Integration of the Pan-European Infrastructures dedicated to GNSS and other Geodetic Data
R.M.S. Fernandes (1,2); L.C. Bastos (3); C. Bruyninx (4); N. D'Agostino (5); J. Dousa (6); A. Ganas (7); M. Lidberg (8); and WG4 Members

What fraction of common-mode errors which have been mitigated in the NA12 datum are artifacts of GPS data processing?
Jay Goldfarb1, James Broermann2, Geoffrey Blewitt1, William C. Hammond1, Rick Bennett2, and Corne Kreemer1 (jgoldfarb@unr.edu)
1. Nevada Geodetic Laboratory, Nevada Bureau of Mines and Geology University of Nevada, Reno
2. Tectonic Geodesy Laboratory, University of Arizona (James Broermann: james@email.arizona.edu)

PHOTOS

For more photos of the UNAVCO Science Workshop, and the field trip, check out UNAVCO on SmugMug.

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