Workshop Report
Hydrogeodesy Synthesis Workshop:

Scripps Institute of Oceanography (SIO)
October 25 – 27, 2017

Final Report - Prepared by Shimon Wdowinski (FIU), Kristine Larson (UCB), Adrian Borsa (SIO), and Dan Cayan (SIO)

Workshop objectives

One of the major challenges of the 21st century is securing freshwater for an increasing world population, as well as for preserving natural ecosystems. Various water resource components and their spatial and temporal variations are estimated using hydrologic models but the model results are affected by uncertainties. Improved monitoring and understanding of water resource components is being achieved by geodetic techniques, which are fairly new tools that can provide highly accurate measurements of the Earth's surface and its changes over time. For instance, technologies such as Radar Altimetry, LIDAR, GPS Interferometric Reflectometry (GPS-IR), and InSAR provide observations of surface water levels in rivers, lakes, and wetlands, and surface deformation from groundwater flow and storage changes. Gravimetric observations (e.g., GRACE) directly measure changes in terrestrial water storage (TWS), and GPS is now being used to recover Total Water Storage (TWS) changes from earth surface displacements. GPS-IR can also be used to measure soil moisture, snow depth, and vegetation water content changes. Using geodetic observations in the service of hydrology is challenging because (1) the measured geodetic signal reflects contribution from multiple processes, including tectonic and atmospheric loading, and not only hydrological ones, and (2) the geodetic observations are often presented in units and language that are not used or understood by hydrologists. To overcome these issues and to expand the potential of the hydro-geodesy sub-field, the workshop objective included the following:

1) Separating hydrological loading from tectonics and other signals
2) Obtaining measures that can help reduce hydrologic model uncertainties and provide meaningful hydrological interpretations
3) Advancing Interdisciplinary Research between geodesists and hydrologists
4) Supporting current and planned NASA missions

Workshop schedule

25 October 2017 (Wednesday) - Morning Sessions: Introduction/Water Science/Geodetic Observations
Afternoon Sessions: Views by the funding agencies/Water Modeling/Terrestrial Water Storage

26 October 2017 (Thursday) - Morning Sessions: Terrestrial Water Storage/Groundwater
Afternoon Session: Surface Water, Freeze Thaw/Poster session

27 October 2017 (Friday) - Morning Sessions: NASA's future hydrological missions/Workshop summary, Expectations, and Opportunities

Detailed information of the workshop's schedule is provided in Appendix B (Agenda)

Presentations and discussions

The two and a half day workshop included 24 oral and 6 poster presentations distributed across 8 sessions. Each session included time for discussion, and additional discussion sessions were held at the end of each day in order to increase participation and contribution from all workshop participants. A detailed description of the sessions and presentations can be found in Appendix B, and abstracts of all presentations are presented in Appendix C.

The interdisciplinary nature of the hydrogeodesy workshop required the participation of experts in both hydrology and geodesy. In order to reduce jargon, misunderstanding and 'language' barriers among participants, the first two sessions were introductions to each field. The introductory *water sciences* session introduced topics in hydroclimate variability and hydrological modeling. The introductory geodesy session, *Geodetic Observations*, presented four geodetic technologies—GRACE, GPS, GPS-IR, and InSAR—that have been used in hydrogeodetic studies.

The bulk of the workshop was organized around three hydrological fields in which geodetic observations have provided significant contributions: Terrestrial Water Storage (TWS), groundwater, and surface water. The first *TWS* session presented hydrological product derived from GPS-IR observations, their validation, and future use, as well as a study of snow volume changes in the Sierra Nevada. The second *TWS* session focused on quantifying regional and continental TWS variations and their measurements using continuous GPS observations. The *Groundwater* session presented the contribution of GRACE, GPS, and InSAR observations of groundwater changes at various scales and their implications for water management, sustainability plans, and aquifer system deformation. The *Surface Water* session presented observations acquired by InSAR, space-borne GNSS reflectometry, and other remote sensing methods that are used for assessing hydrological conditions in wetlands, floodplains, and other flooded areas, as well as their impact on the ecosystem.

The last half day of the workshop was dedicated to the future of hydrogeodesy. The first session of last day introduced NASA's three upcoming *hydrological missions*, GRACE-FO, NISAR, and SWOT, which will provide exciting new opportunities for hydrogeodetic research. The final sessions were devoted to the summary of the workshop and a discussion of expectations and upcoming opportunities for the field.

Outcomes

The workshop successfully served as a meeting place for exchanging knowledge and ideas among experts in hydrology and geodesy. Participants suggested new ideas for increasing information sharing between the two fields and presented ideas for developing new interdisciplinary publications and research projects. The most relevant ideas were translated into the following list of recommendations:

A. Papers
    a. Vision paper for hydrology journal (i.e. what we are doing in this new field?) - *WRR.*
    b. Review paper of relevant techniques - *Review of Geophysics.*
    c. High-impact, short-format "end of drought" paper that unifies various estimates - *Science; GRL; ERL; Science Advances.*

    d. Hydrogeodesy for water management, sustainability - *WRR; Water Sustainability, Earth's Future.*

B. Outreach
    a. Develop list and conveners for AGU 2018 sessions in Hydrology.
    b. Follow-on workshop, Summer/Fall 2019 (?), expanding to early career scientists in particular (with travel grants for students/postdocs from agencies/missions)

C. Stakeholder Development
    a. Build links between CUAHSI and UNAVCO.
    b. Add NOAA to this conversation (how? Who to bring in?). Climate Office.
    c. Bring in state agencies in the western states and beyond—especially civil engineers in water agencies, transportation departments (e.g. DWR, Caltrans)—and link to Scripps Center for Western Weather and Water Extremes (CW3E).
    d. Involve JPL's Western Water Applications Office.

D. Funding
    a. Develop vision/action statement (a white paper) to be used to drive solicitations, targeted at funding agencies (NASA, NSF, NOAA, Army Corp). Provide forward-looking *roadmap* for how agencies can coordinate efforts and bridging different programs.
    b. NSF research coordination networks program (RCN). $500K/5 years (workshop funding, analysis/experiments, web presence) proposal.

E. Experiments
    a. Joint GRACE+GNSS TWSA validation analysis at location(s) with large known water mass changes.
    b. Community experiment bringing together multiple techniques and observations (satellite/airborne/ground), targeting a region of broad hydrology interest that could include mountains, aquifers, coastal ranges, etc.)
    c. Form workgroups on specific technical topics (e.g. spatial resolution of techniques). Introduce hydrogeodesy concerns into UNAVCO GNSS user working group.

Appendix A: Participants

Organizers:

Shimon Wdowinski, Florida International University
Kristine Larson, University of Colorado, Boulder
Adrian Borsa, Scripps Institute of Oceanography
Dan Cayan, Scripps Institute of Oceanography

Participants (sorted alphabetically according to the author's affiliation)

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Appendix B: Agenda

<u>Day 1: Wednesday, October 25, 2017</u>

10:30 Opening notes

Shimon Wdowinski – Hydrogeodesy as a new subfield

10:40-11:15 Overview I - Water Science

Dan Cayan – Water Sciences

Title: Hydroclimate variability and change in the western U.S.

11:15-1:00 Overview II - Geodetic Observations (Panel Lead: Kristine Larson)

Felix Landerer – Grace

Title: From grace to grace-fo: current and future contributions from space-gravimetry for hydrological applications

Bill Hammond – GPS

Title: Effects of Water on Active Crustal Deformation in California and Nevada from GPS Data

Kristine Larson - GPS–Reflections -

Title: How reflected GPS signals can be used to measure hydrologic signals

Estelle Chaussard - InSAR

Title: From surface and groundwater monitoring to characterization of aquifer systems properties with insar

1:00-2:00 Lunch

2:00-2:40 Overview III – View by the funding agencies

Gerald Bawden – NASA

Title: NASA Earth Surface Interior and Hydrology

Jeff Freymueller – Earthscope

Title: The view from EarthScope

2:40-3:20 Overview IV - Water Modeling

Dennis Lettenmaier –

Title: Hydrologic modeling and the role of storage

3:20-4:20 Focus I - Terrestrial Water Storage (Panel lead: Kristine Larson)

Kristine Larson

Title: PBO H2O: Soil Moisture, Snow Depth, and Vegetation Water Content from Reflected GPS Signals

Eric Small

Title: Validation of GPS reflection products and future use.

Steve Margulis

Title: Interannual variations in Sierra Nevada snow volume storage over the Landsat-era (1985-present)

4:20-5:00 End of day discussion (Lead: Dan Cayan)

Day 2: Thursday, October 26, 2017

9:00 -10:20 Focus I (cont.) - Terrestrial Water Storage (Panel lead: Adrian Borsa)

Ethan Gutmann

Title: Quantifying Uncertainty in Continental Scale Hydrologic States

Adrian Borsa

Title: Short-period terrestrial water storage changes from continuous GPS

Don Argus

Title: Sustained water loss in California's mountain ranges during severe drought from 2012 through 2015 inferred from GPS

Eric Small

TItle: Hydrologist perspective on GPS & loading.

10:20-1040 Coffee BREAK

10:40-12:30 Focus II – Groundwater (Panel leads: Tom Farr)

Jay Famiglietti

Title: Estimating groundwater storage changes using GRACE and other satellite and ground-based observations

Cathleen Jones

Title: Measurement of subsidence in the central valley and its impact on the California aqueduct using airborne L-band sar

Michelle Sneed

Title: Land subsidence monitoring and quantitative assessment tools for groundwater sustainability plans

Manoo Shirzaei

Title: Constraining dynamics of central valley aquifer systems from space

Don Vasco

Title: Estimating fluid-induced stress change from observed deformation

12:30-2:00 Lunch Break

2:00-3:00 Focus Ii - Surface Water, Freeze Thaw (Panel lead: Shimon Wdowinski)

Clara Chew

Title: The potential to use reflected GPS signals to map flooded areas and measure sea level

Hahn Chul Jung

Title: Improved terrestrial surface water and groundwater dynamics from remote sensing and modeling

Fernando Jaramillo

Title: Using insar for understanding wetland connectivity in ungauged wetlands

3:00-4:00 End of Day Discussion (Lead: Adrian Borsa)

4:00-5:00 Poster Session (continued on next page)

Thomas L. Enzminger, Eric E. Small, Adrian A. Borsa - Snow water equivalent estimated from GPS vertical displacements: correcting leakage-induced bias with empirically-derived scaling factors

Tom Farr - InSAR measurements of subsidence in the Central Valley, California from 2007 – present

*Matthew Folsom, Shari Kelley, **Ronni Grapenthin** and Mark Person - Surface rebound and groundwater temperature fluctuations at a municipal wellfield during episode of aquifer recovery*

*Andrew J. Luhmann, Susan L. Bilek, **Ronni Grapenthin** and Jonathan B. Martin - Geophysical characterization of karst aquifers using dynamic recharge events*

***Bryant D. Loomis**, S. B. Luthcke, T. J. Sabaka, K. Rachlin - NASA GSFC mascons: signal covariance design and error assessment*

Meredith L. Kraner, William C. Hammond, Corné Kreemer, and Ilya Zaliapin - Seasonal variation of strain in central California and its correlation with seismicity

<u>Day 3: Friday, October 27, 2017</u>

8:30-9:30 NASA's future hydrological missions: GRACE-FO, NISAR, and SWOT

David Wiese

Title: GRACE-2: Potential Improvements in Recovering Terrestrial Water Storage Variations

Cathleen Jones

Title: The NISAR mission

Hahn Chul Jung

Title: The SWOT mission

9:30-10:00 Coffee Break

10:00-11:00 Discussion I - Summaries of focus areas (Session leads: Adrian Borsa, Kristine Larson, Tom Farr, Shimon Wdowinski)

11:00-12:00 Discussion II - Expectations and opportunities (Lead: Adrian Borsa)

Appendix C: Abstracts (sorted alphabetically according to the author's last name)

SUSTAINED WATER LOSS IN CALIFORNIA'S MOUNTAIN RANGES DURING SEVERE DROUGHT FROM 2012 THROUGH 2015 INFERRED FROM GPS

***Donald F. Argus*[1]**, *Felix W. Landerer*[1], *David N. Wiese*[1], *Hilary R. Martens*[2], *Yuning Fu*[3], *James S. Famiglietti*[1], *Brian F. Thomas*[4], *Thomas G. Farr*[1], *Angelyn W. Moore*[1], *Michael M. Watkins*[1]

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[2]Department of Geosciences, University of Montana, Missoula, USA
[3]School of Earth, Environment, and Society, Bowling Green State University, Ohio, USA
[4]Department of Geology and Environmental Science, University of Pittsburg, Pennsylvania, USA

Drought struck California during 7 of the 9 years from 2007 through 2015, reducing the state's available water resources. Pumping of Central Valley groundwater has produced spectacular land subsidence. Uplift of the adjacent Sierra Nevada mountains has been proposed to be either tectonic uplift or solid Earth's elastic response to unloading of Central Valley groundwater. We find that, of the 24 mm of uplift of the Sierra Nevada from October 2011 to October 2015, just 5 mm is produced by Central Valley groundwater loss, less than 2 mm is tectonic uplift, and 17 mm is solid Earth's elastic response to water loss in the Sierra Nevada. We invert GPS vertical displacements recording solid Earth's elastic response to infer changes in water storage across the western U.S. from January 2006 to August 2017. We find water changes to be sustained over periods of drought or heavy precipitation: the Sierra Nevada lost 15 ±19 km3 of water during drought from October 2006 to October 2009, gained 18 ±14 km3 of water during heavy precipitation from October 2009 to October 2011, and lost 45 ±21 km3 of water during severe drought from October 2011 to October 2015 (95% confidence limits). Such large changes are not in hydrology models: snow accumulation in October is negligible and long-term soil moisture change is small. We infer there must be large loss of either deep soil moisture or groundwater in river alluvium and in crystalline basement in the Sierra Nevada. The results suggest there to be parching of water in the ground during the summer of years of drought and seeping of melting snow into the Sierra Nevada in the spring of years of heavy precipitation.

BIO: Donald Argus is a research scientist at Jet Propulsion Laboratory, California Institute of Technology.

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HYDROCLIMATE VARIABILITY AND CHANGE IN THE WESTERN U.S.

Dan Cayan[1], *Mike Dettinger*[2], *David Pierce*[1]

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[2]U.S. Geological Survey, Carson City, NV, USA

The western United States experiences considerable hydrologic variability in response to regional climate fluctuations that are termed "anomalous" by climate scientists because they depart from long-term average conditions. The spatial and temporal variability of precipitation and associated hydrologic components is especially large. Regional climate fluctuations persist for seasonal to multi-decadal durations, usually in association with larger scale climate patterns. They play a crucial role in determining regional hydrologic variability by affecting trends of important drivers such as precipitation and temperature, sometimes by promoting particular blends of influential weather events. In California and other regions of the West, much of the annual precipitation is delivered on fast time scales by a relatively few very large storms, which are usually atmospheric river events. Besides supplying water, as exhibited in fluctuating snow pack and built-reservoir volumes, these storms also drive year-to-year differences in annual precipitation totals, while also causing most of the region's floods. During years or multi-year periods when these very large storms are absent, the region may fall into drought. Historically, droughts have had a strong presence in the West, but recent droughts have exhibited unusually warm temperatures, likely a harbinger of dry events in future decades when climate change threatens to make overall conditions even warmer. Also, large storms are frequently involved in "busting" drought. Other early signs of climate change that have been observed include declines of mountain snow packs, which supply spring and summer runoff for the region. Along with warmer surface temperatures have come higher elevation freezing levels, more rain and less snow, and earlier snowmelt and earlier snowmelt runoff. Temperature during cool seasons of drought years in recent decades has more often been warmer than climatological average than cooler. Anthropogenic climate changes, which are projected to build as greenhouse gas concentrations rise, will result in further warming and amplified hydrologic changes. For substantial parts of the western U.S. climate change will shift the hydrologic system toward higher extremes, smaller snow packs, and longer more intense dry seasons. Global climate models suggest that precipitation may shift toward fewer overall wet days but somewhat increased extreme storm events. Further shifts in snowpack, runoff and increased moisture loss to the atmosphere would reduce soil moisture and stream flows in summer. Annual discharge in arid western watersheds may decline, which would exacerbate dry spells. Heavier winter precipitation events and higher elevation rain/snow transition zones would yield greater flood volumes in some mountain catchments by the latter half of the 21st Century. Pointwise *in situ* observations are sparse in most mountain catchments, and, along with other issues that are brought out throughout the meeting, leaving us with important uncertainties in water balance of surface and subsurface water components, providing strong impetus for complementary observations from geodetic techniques.

BIO: Dr. Cayan is a Research Meteorologist at the Scripps Institution of Oceanography, University of California San Diego. His work is directed at understanding climate variability and changes over the Pacific Ocean and North America and climate impacts on water, wildfire, health, and agriculture in California and western North America.

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FROM SURFACE AND GROUNDWATER MONITORING TO CHARACTERIZATION OF AQUIFER SYSTEMS PROPERTIES WITH INSAR

***Estelle Chaussard*[1]**, *Roland Bürgmann[2], Pietro Milillo[3], Brett Baker[4], and Eric J. Fielding[3]*

[1]State University of New York at Buffalo, NY, USA
[2]University of California, Berkeley, CA USA
[3]Jet Propulsion Laboratory, CA, USA
[4]Santa Clara Valley Water District, CA USA

Water management typically relies on water level data and spatially limited deformation measurements. Geodetic surveys with InSAR (Interferometric Synthetic Aperture Radar) have demonstrated the capabilities to provide remote, large-scale monitoring of surface water and groundwater resources. These techniques have also recently been shown to enable characterization of the physical properties of aquifer systems and assess the efficiency of management efforts.

Here we present an introduction of the InSAR technique and of the time series analysis methods applied to surface water and groundwater monitoring. We illustrate applications of InSAR to surface water monitoring with examples of the Everglades in Florida. We use the Santa Clara Valley (Silicon Valley), in the south the of San Francisco Bay Area, to illustrate applications to groundwater monitoring.

Beyond monitoring we present examples of how InSAR can be used to characterize aquifer systems properties and their temporal changes, which is useful to monitor the health of aquifer systems. We show that after calibration we can accurately predict hydraulic head levels from the observed deformation, which could provide a low-cost alternative to traditional monitoring. Finally, we show that high temporal resolution InSAR allows us to investigate changes in an aquifer system during a period of unprecedented drought in California, and assess the success of the water management practices.

BIO: Dr. Estelle Chaussard is a Professor of Geophysics with 10 years of experience in the development and usage of geodetic techniques to measure crustal deformation associated with a variety of processes. She has used InSAR to characterize aquifer properties, assess management efforts, and understand the processes controlling the dynamics of groundwater.

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SPACEBORNE GNSS-REFLECTOMETRY CAN SENSE EARTH'S WATER CYCLE, TOO

Clara Chew[1]
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The ability for ground-reflected Global Navigation Satellite System (GNSS) signals to sense changes in Earth's water cycle has been shown by many tower and aircraft experiments. The ability for these signals to sense the water cycle from a satellite platform, however, is still a topic of current research. With the December 2016 launch of the Cyclone GNSS (CyGNSS) mission, a constellation of eight small satellites carrying GNSS reflectometry receivers, there are enough data to finally answer whether or not spaceborne GNSS reflectometry "works" for surface hydrology studies. Here, I will show observations from the CyGNSS mission and how changes in the ground-reflected signal is associated with changes in surface water, even when the water is obscured by dense vegetation.

BIO: Dr. Chew is a postdoc at the University Corporation for Atmospheric Research. Her research interests focus on the development of GNSS-Reflectometry for applications related to surface hydrology.

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SNOW WATER EQUIVALENT ESTIMATED FROM GPS VERTICAL DISPLACEMENTS: CORRECTING LEAKAGE-INDUCED BIAS WITH EMPIRICALLY-DERIVED SCALING FACTORS

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Abstract

GPS vertical displacements have shown promise as a means of monitoring changes in terrestrial water storage (TWS) and its individual components. Recent modeling work used realistic distributions of water mass to calculate synthetic displacements at real GPS station locations. These displacement fields were inverted for changes in hydrologic load, which were compared to the input in order to quantify error. The results demonstrated that the operational GPS network in the western United States (WUSA) can accurately reproduce the timing and relative magnitude of annual peak snow water equivalent (SWE) at the mountain range scale. However, GPS-derived estimates of hydrologic load suffer from a low bias due to mass leakage induced by both a smoothing parameter and by insufficient station density. At the mountain range scale, high correlation between the known input load and the synthetic GPS-inverted load enables bias removal via time-varying linear scaling. Here, we outline the procedure for deriving these scaling factors at the mountain range and finer spatial scales via a modeling approach. Time-varying scaling is necessary to account for differences in leakage due to seasonal variations in load gradients between mountains and adjacent lowlands. Mountain-range-scale scaling factors are specific to a given station distribution, area of interest, inversion spatial resolution, and smoothing constraint. Inverted estimates may also be scaled on a grid-cell-by-grid-cell basis; however, leakage between adjacent grid cells introduces noise into the input-inverted load relationship such that sub-basin-scale spatial loading patterns cannot be reproduced via scaling of inverted loads.

BIO (50-word maximum): Tom Enzminger is a Ph.D. student in the Department of Geological Sciences at the University of Colorado Boulder. He uses vertical displacement records from continuous GPS stations to estimate changes in mountain snow loading, with the aim to develop an independent dataset for use in water resource management.

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InSAR measurements of subsidence in the Central Valley, California from 2007 – present

Tom G Farr
Jet Propulsion Laboratory

Subsidence caused by groundwater pumping in the rich agricultural area of California's Central Valley has been a problem for decades. Over the last few years, interferometric synthetic aperture radar (InSAR) observations from satellite and aircraft platforms have been used to produce maps of subsidence with cm accuracy. At JPL, with funding from the CA Dept. of Water Resources we have processed InSAR data from multiple satellites spanning the period 2007 – present (Farr et al., 2017). As multiple scenes were acquired during these periods, we can also produce histories of subsidence at selected locations and transects showing how subsidence varies both spatially and temporally. Maps and Geographic Information System (GIS) files have been furnished to decision-makers at the California Department of Water Resources to enable better management of groundwater resources and for further analysis of the 4 dimensional subsidence time-series maps. At the direction of the DWR, we have recently expanded to alluvial basins throughout the state.

The maps show two main areas of subsidence in the San Joaquin Valley which subsided at a maximum rate of about 30 cm/yr until about 2014 when the rate nearly doubled due to the drought. Recent rains in California caused a pause, and even a reversal of subsidence in some areas. Because of a lack of data on pumping rates, it's difficult to determine the cause of the rebound, but the rapidity of the rebound after the start of the rains implies it was cessation of pumping and perhaps some recharge in the upper parts of the aquifer system. The short repeat interval of Sentinel-1 over the San Joaquin Valley (6-12 days) makes it possible to track the rebound as it propagated across the Valley from NE-NW-SW and back north.

Work is continuing on using subsidence and ancillary data from wells to produce a better understanding of how the San Joaquin Valley responds to water inputs and outputs both spatially and temporally. This should allow a predictive capability, potentially defining sustainable pumping rates related to water inputs.

Two tools being developed and tested at JPL for this work are ARIA (Advanced Rapid Imaging and Analysis) and WaterTrek. The first promises the ability to 'keep up' with the deluge of InSAR data being sent down now from Sentinel-1 and soon from NISAR. The DWR project is a test case for the ability to produce interferograms and soon time series for users with little or no InSAR expertise for further analysis. WaterTrek is essentially a GIS that assimilates not only InSAR time series, but also ancillary data such as water height in wells, GPS time series, GRACE time series, snow-water equivalent, rainfall, runoff, evapo-transpiration, and model outputs derived from these inputs. The ability to do things as simple as cross-correlations between hydraulic head and subsidence should improve our understanding quickly.

Farr, T.G., C. Jones, Z. Liu, 2017, Progress Report: Subsidence in the Central Valley, California, March 2015 – September 2016, Available at:
http://www.water.ca.gov/waterconditions/docs/2017/JPL%20subsidence%20report%20final%20for%20public%20dec%202016.pdf, 37 pp.

* work performed under contract to NASA and the CA Dept. of Water Resources

SURFACE REBOUND AND GROUNDWATER TEMPERATURE FLUCTUATIONS AT A MUNICIPAL WELLFIELD DURING EPISODE OF AQUIFER RECOVERY

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The Buckman wellfield near Santa Fe in New Mexico, USA, has provided municipal water to communities in the Española Basin for 35 years, and has a history of substantial (> 100 m) drawdowns and inelastic subsidence. Recent changes to the design and operation of the wellfield have resulted in significant water level recovery. Here we examine both elastic rebound caused by changes in hydraulic head, and fluctuations in groundwater temperatures during a period of rapid water level recovery. The surface deformation is not uniform, and patterns of uplift and subsidence reveal buried structure and compartmentalization of the aquifer system. A discontinuous feature in InSAR observations is found to be associated with lateral changes in vertical thermal gradients and water chemistry. Repeat measurements of vertical thermal gradients in monitoring wells show increased groundwater temperatures (~0.5 ^{o}C) during the recovery. These increased temperatures are observed at shallower depths, and are co-located with areas of surface uplift. High correlation is also observed between surface deformation and water levels in production wells when not in use, allowing for first-order approximation of elastic storage parameters (0.0004 – 0.0021). These values suggest that elastic deformation is being sustained in the field. A pressure point source model applied to the surface deformation signal shows that about 1/36 of the volume lost from 1997 – 2003 was recovered between 2007 – 2010. Simple, one-dimensional hydrothermal models of pumping, downward flow and convective cooling followed by conductive recovery are qualitatively consistent with observed increases in groundwater temperatures.

BIO (50-word maximum): Dr. Grapenthin is an Assistant Professor of Geophysics at New Mexico Tech conducting research in geodesy, active tectonics and volcanology. He has used space geodetic techniques and hydrological observations for studying crustal deformation in response to tectonic hydrological load changes.

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SYNTHESIS WORKSHOPS

Jeffrey T. Freymueller[1]

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Organizing Synthesis Workshops are one of the key activities of the current EarthScope National Office (ESNO). This talk describes the goals and expected outcomes of the Synthesis Workshops and how the ESNO will use the outcomes. We hope that each workshop will result in the genesis of one or more effective working groups that will continue activities after the workshop. The ESNO can offer resources to working groups to help them with continued meetings (e-collaboration) and opportunities for outreach and publicizing their work.

BIO (50-word maximum): Dr. Freymueller is a Professor of Geophysics with more than 30 years of experience in geodesy and the application of space geodesy to geophysical problems. He has worked on problems ranging from plate tectonics and earthquakes to active volcanism, changes in the cryosphere and hydrological load changes.

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QUANTIFYING UNCERTAINTY IN CONTINENTAL SCALE HYDROLOGIC STATES

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Text of abstract may not exceed one page, including speaker bio (50-words max) and contact information.

Comparing models and measurements requires an accurate quantification of the uncertainty in both. We discuss three major sources of uncertainty in model based estimates of continental domain hydrologic states such as soil moisture and snow water equivalent. These three components are uncertainty due to meteorological forcing data, due to hydrologic model construction, and due to parameter selection within the hydrologic model. Meteorological uncertainty comes in part from errors in measurements of key variables, particularly precipitation, but mostly from the sparsity of the measurement network, e.g. there are very few precipitation measurements in the mountains where snowpack is most important. We have developed an ensemble meteorological forcing dataset that quantifies this uncertainty and is shown to be a statistically reliable representation of this uncertainty. Uncertainty in hydrologic model construction stems from our lack of knowledge of how the hydrologic system operates and the simplifications required to develop a model of that system. These range from processes related to the change in snowpack albedo over time to the representation of key limits to evapotranspiration, i.e. how should a model parameterize light, temperature, or soil moisture limitations. We have developed a modeling framework (SUMMA) to systematically explore the range of possible modeling process and spatial complexity options. Although this provides a representation of multiple modeling alternatives, it is not known to reliably represent all errors in modeling of hydrologic states. Finally, once one has determined the model structure, there remains a large uncertainty due to the unknown model parameters, e.g. the soil hydraulic conductivity. This may be the largest source of uncertainty and improvement in these parameters represents one of the greatest needs in applied hydrologic modeling today. We now have the capabilities to more reliably quantify the uncertainty in key hydrologic states in a way that could be used to improve constraints on the interpretation of geodetic measurements for hydrology to understand when geodetic measurement changes are not due to hydrology but should instead be interpreted as changes due tectonic, or related processes.

BIO (50-word maximum): Dr. Gutmann is a researcher at the National Center for Atmospheric Research with a background in remote sensing, hydrologic and atmospheric modeling. His recent work has focused on climate applications for water resource management, GPS interferometry based snow and soil moisture measurement, and satellite remote sensing.

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EFFECTS OF WATER ON ACTIVE CRUSTAL DEFORMATION IN NEVADA AND CALIFORNIA FROM GPS DATA

William C. Hammond

Nevada Geodetic Laboratory, Nevada Bureau of Mines and Geology, University of Nevada, Reno

In this presentation I explore the rates, patterns and overlap in space and time of geodetic signals related to water in California and Nevada. While hydrological signals are present in both horizontal and vertical time series, I here focus on vertical signals because they are often easier to separate from other background processes such as tectonic deformation. These signals are accessible though high-precision GPS networks such as the NSF EarthScope Plate Boundary Observatory, and other networks in these states. The GPS data are processed using a uniform methodology at the Nevada Geodetic Laboratory, using the JPL GIPSY/OASIS software and data products, and placed into a single global frame of reference (IGS08). We apply robust methods to the time series data to extract trends and interpolated maps of seasonal motions. The MIDAS and GPS Imaging algorithms together derive fields that are insensitive to signals present at single epochs or stations and help reveal the patterns of vertical motion that are consistent among neighboring stations and hence are well supported by the data (Blewitt et al., 2016 JGR; Hammond et al., 2016, JGR).

The signals are diverse, and are attributable to multiple physical processes that are revealed in the GPS time series in different ways. Signals that I explore include, 1) continental scale hydrological loading that appears in the amplitude and phase (time of year of highest vertical position) of seasonal oscillations in vertical positions that vary geographically but are present over the entire area, 2) aquifer compaction and poroelastic deformation that can have larger seasonal amplitudes and phase that is opposite to that of hydrological loading, 3) earthquake cycle signals present in the vertical component that result from strain accumulation and postseismic viscoelastic relaxation from past earthquakes, 4) active uplift of Sierra Nevada mountains that has a small amplitude (likely <0.5 mm/yr) but is potentially separable from hydrological unloading by its spatial pattern, 5) unloading at the Long Valley, CA magmatic center that evolves in concert with seasonal loading of the Sierra Nevada and drought-related changes in rate of Sierra Nevada uplift, 6) related changes in tectonic interseismic strain rate patterns in the central Walker Lane east of the Sierra Nevada. Together these observations reveal interactions between vertical land motion, geologic and aquifer structure, climate, tectonic and magmatic systems, whose exact mechanisms are not fully understood. Thus, exploring hydrology with GPS data will require acknowledging, and improving our understanding of, non-hydrological signals.

BIO (50-word maximum): William C. Hammond is a professor of geoscience with ~23 years of experience in studying the properties and dynamics of the solid Earth. He uses GPS and other geodetic techniques to study deformation of the Earth including tectonic deformation, earthquake cycle, and mountain uplift in the western United States.

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USING INSAR FOR UNDERSTANDING WETLAND CONNECTIVITY IN UNGAUGED WETLANDS

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The Ciénaga Grande de Santa Marta (CGSM) is one of the world's most productive tropical wetlands and one that has seen some of the largest dieback of mangroves on record. Despite the CGSM's importance, and the fact that the human-driven loss of hydrological connectivity appears to be one of the main reasons for this mangrove mortality, the wetland continues to be ungauged, hampering restoration efforts. Here we use a remote sensing technique, termed Interferometric Synthetic Aperture Radar (InSAR), to determine the CGSM's current state of hydrological connectivity after persistent modification by roads, man-made channels and flow regulation. We processed 29 ALOS-PALSAR acquisitions taken during 2007-2011 and generated 66 interferograms, which provide information on relative surface water level changes in the CGSM. We found that spatiotemporal changes in water level along two transects in the wetland were partly explained by water discharge changes at a station located 30 km upstream on the largest tributary of the wetland, the Magdalena River. In general, freshwater inputs into the wetland only occurred when mean daily discharge at this station exceeded 700 m3/s. The interferogram analysis also revealed discontinuous patterns of water level changes along man-made channels. These discontinuities indicate that old channels are acting as barriers to the wetland's hydrologic connectivity, and might even be the primary contributor to the overall hydrologic conductivity loss within the wetland. We recommend that increasing freshwater inputs from the Magdalena River and restored connectivity of wetlands on both sides of the man-made channels are needed to rehabilitate the CGSM's mangrove ecosystems. This study emphasizes the potential of using InSAR helps determine hydrological connectivity in wetlands that are completely or poorly ungauged.

BIO: Fernando Jaramillo is a Civil Engineer with a Ph.D. in Physical Geography and focus in hydroclimatology. His area of expertise extends from human water consumption at the global scale to attribution of human and climatic changes in the freshwater system.

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MEASUREMENT OF SUBSIDENCE IN THE CENTRAL VALLEY AND ITS IMPACT ON THE CALIFORNIA AQUEDUCT USING AIRBORNE L-BAND SAR

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In 2014, as drought conditions in California dramatically worsened, water resource managers at the State of California Dept. of Water Resources (DWR) engaged researchers at the Jet Propulsion Laboratory to measure subsidence in the Central Valley using satellite and airborne SAR in order to assess the effects of increased groundwater withdrawal. Here we report on the results of the airborne SAR component of that study, which was undertaken specifically to identify subsidence-related impact to the California Aqueduct, but which show a number of interesting features related to both groundwater and oil extraction.

The study, which is ongoing, uses the InSAR time-series Small Baseline Subset (SBAS) method applied to data acquired with the L-band UAVSAR instrument between 2013 and 2017. Two scenes have been acquired since 2013-2014, and a new scene was recently added to cover the gap between them around the Lost Hills oil field. We describe the processing method, which uses adaptive spatial smoothing based upon interferometric coherence to reduce noise in low coherence areas. The InSAR results show 'hot spots' of subsidence associated with individual wells or clusters of wells; more generalized broad-area subsidence; and smaller scale subsidence very near the aqueduct that appears to be caused by hydro-compaction of soil, most likely the result of seepage from the aqueduct. Patterns of vertical land movement are discussed in the context of the groundwater basin characteristics local to features. Results are also shown for subsidence due to oil extraction along the western edge of the valley, where the instrument is able to resolve adjacent areas of uplift and subsidence at high resolution.

The airborne study for DWR was initially undertaken as a test of whether the higher resolution subsidence map could provide useful information to inform operation and maintenance of the California Aqueduct, and within that context has been used to identify new and rapidly developing subsiding sections of the structure. In addition, and beyond that application, the subsidence hot spot identification enabled with high resolution instruments is now recognized as a valuable capability for identifying impact to other infrastructure, for detailed situational awareness of developing conditions, particularly at early stages when root cause can be determined, and as a potential tool for monitoring compliance with groundwater regulation in the future.

BIO: Dr. Jones is a radar scientist at NASA's Jet Propulsion Laboratory, California Institute of Technology, where her research is focused on using radar remote sensing for studying natural and man-made hazards. Her research includes identification of hazards affecting flood control and water conveyance infrastructure and measurement of subsidence in InSAR-challenging areas.

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IMPROVED TERRESTRIAL SURFACE WATER AND GROUNDWATER DYNAMICS FROM REMOTE SENSING AND MODELING

***Hahn Chul Jung*[1,2]**, *Michael Jasinski*[1], *Augusto Getirana*[1,3], *Batuhan Osmanoglu*[1], *Sujay Kumar*[1] *and, Matthew Rodell*[1]

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The capability of remote sensing and modeling to understand and monitor the integrated surface water and groundwater dynamics, including global rivers and floodplains has greatly expanded over the past decade. Several important advances have been made in incorporating satellite measurements into hydraulic and land surface models, including gravity measurements from GRACE, and altimetry from Synthetic Aperture Radar (SAR) data, and satellite passive microwave observations of soil moisture and snow, in addition to more traditional land cover data from multispectral observations from MODIS and Landsat.

For example, interferometric processing of Synthetic Aperture Radar (SAR) data from the central portions of both Amazon and Congo Wetlands provides centimeter-scale measurements of water level change. The Amazon is marked by a myriad of floodplain channels, but the Congo has comparatively few. Amazon floodplain channels, lakes and pans are well interconnected, whereas the Congo wetlands are expanses with few boundaries or flow routes. The hydraulic processes that build the Amazon floodplain are not similarly apparent in the Congo. Also, radar data over the recent flooding in the Departments of Salto, Paysandú and Artigas of Uruguay has been analyzed. The analyses included a polarimetric composition of pre- and post-flood imagery from Sentinel-1 to map out the flood extent. This polarimetric composition can distinguish new water from old allowing for mapping out the areas with standing water, especially in rural areas. Over the urban areas the results are not as clear due to double bounce effects.

In addition, the contribution of rivers and floodplains to terrestrial water storage (TWS) variability has been quantified state-of-the-art models to simulate land surface processes and river dynamics, and to separate TWS into its main components. Changes in surface water storage (SWS) are a principal component of TWS variability in the tropics, where major rivers flow over arid regions, and at high latitudes. We conclude that SWS contributes 8% of TWS variability globally, but that contribution differs widely among climate zones.

Remotely sensed data has also been incorporated into land surface data assimilation models. The development of land data assimilation systems (LDAS) has provided improved estimates of land surface fluxes and states over regional to global domains. LDAS systems generate gridded time series data products at consistent temporal and spatial scales. Built within NASA's Land Information System (LIS) http://lis.gsfc.nasa.gov/), examples include the North American Land Data Assimilation System-2 (NLDAS-2) and the Global Land Data Assimilation System (GLDAS), among many others.

BIO (50-word maximum): Dr. Jung, a research scientist at SSAI/NASA GSFC, has used synthetic aperture radar, GRACE, altimeter, and optical images for wetland hydrology, flood mapping, and hydrodynamic modeling. His current research focuses on water balance from a multi-land surface model perspective.

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SEASONAL VARIATION OF STRAIN IN CENTRAL CALIFORNIA AND ITS CORRELATION WITH SEISMICITY

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Our recently completed analysis of seasonal strain in Central California using horizontal GPS data shows positive extensional dilatational strain peaking in the dry season (August/September) and negative contractional strain peaking in the wet season (February/March) across the creeping section of the San Andreas Fault. The timing of this observed seasonal strain is seemingly out of phase with the expected pattern associated with elastic loading of the Great Valley of California. In addition, no seasonality in dilatation is observed across the locked section of the San Andreas Fault south of Cholame, CA. By examining time series of baseline changes in length for pairs of GPS stations crossing the San Andreas Fault, we are able to verify this seasonal strain result.

We use the GPS Imaging technique to place our seasonal strain and baseline time series in the context of seasonal deformation in the southwestern United States. This processing technique can generate an image of vertical displacement based on weighted medians while remaining insensitive to outliers. It confirms that the location of the horizontal seasonal strain effect across the creeping section is well correlated with the location of the highest vertical seasonal amplitude.

Furthermore, we investigate possible reasons for the abrupt change in seasonality between the creeping and non-creeping sections of the San Andreas Fault and look for potential correlations with seismicity. Several tests are performed to relate seismicity data to our estimates of seasonal strain. After declustering the seismicity catalog, we bin the earthquakes by month and latitude to spatially match the peak regions of seasonal strain in our study region. We explore several methods to assess the statistical significance of our result.

BIO: Ms. Kraner recently completed her MS degree in Geophysics from the University of Nevada, Reno. She is a NASA Earth and Space Science Fellow and is interested in the relationship between seasonal geodetic signals and seasonal variations in seismicity along active fault structures.

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FROM GRACE TO GRACE-FO: CURRENT AND FUTURE CONTRIBUTIONS FROM SPACE-GRAVIMETRY FOR HYDROLOGICAL APPLICATIONS

Felix W Landerer[1], ***David N Wiese***[1]

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The Gravity Recovery and Climate Experiment (GRACE) satellites have provided an unprecedented, unique view into Earth's water cycle over the last 15 years. The time-variable gravity observations from space have provided the first holistic and complete picture of near surface mass changes in the various storage compartments of Earth's water cycle: from sea level change to variations in river basins and deep aquifers, which would otherwise go unmonitored in many regions of the world. This legacy of discoveries – from global, to continental, to regional, basin and sub-basin scales – will be continued with the launch of the GRACE Follow-On satellite pair in early 2018.

GRACE observations of water storage changes have been very successful and are now widely used for research and applications. Continued improvements in the data processing have increased spatial resolution and sensitivity (i.e., in the so-called mascon data products), reduced noise and uncertainty, and opened the door for novel processing and data combination techniques (e.g., via model assimilation or joint-inversion with GPS). As more observations from various techniques become available with different spatial and temporal sampling characteristics, it is crucial to advance capabilities and methods that can optimally combine and utilize these data sets (e.g., by joint inversions for terrestrial water storage).

As we move towards GRACE Follow-On (scheduled for launch in spring 2018), the science data system will also deliver so-called QuickLook products to enable a near-real-time, low-latency data flow, e.g., to further advance integration of GRACE-like observations into hydrology-related monitoring (floods, droughts) and assessment applications.

BIO (50-word maximum): Dr. Landerer is the Deputy Project Scientist for GRACE Follow-On, and has over 15 years of experience using space geodetic techniques and satellite as well as in-situ observations for studying Earth's water cycle and surface mass redistributions.

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HOW REFLECTED GPS SIGNALS CAN BE USED TO MEASURE HYDROLOGIC SIGNALS

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Geophysicists have been strong proponents of using GPS satellites to measure crustal n particularly those associated with plate tectonics, volcano deformation, and earthquakes. Becaus motions are quite small, continuously-operating, dual-frequency GPS instruments have been depl large networks around the world, particularly in seismically active regions of the world. At th time, government agencies have found GPS to be useful for a variety of infrastructure activities, a sponsor networks of continuously-operating, dual-frequency GPS receivers. What was not apprec the time these GPS networks were installed was that reflected GPS signals could be measur sufficient precision to turn a geodetic-quality GPS receiver into a bi-static radar. In this metho the power of the direct GPS signal interferes with the reflected GPS signal, producing a moc whose frequency, amplitude, and phase depends on land-cover characteristics, e.g. dry snow, we wet soil, dry soil, and vegetation water content. Geometrically, it depends on the height of tl antenna above the ground and the elevation angle of the satellite with respect to the horizon. Co to most satellites, the footprint of this bi-static radar is small, ~1000 m^2, but this is still larg other *in situ* measurement techniques. These new GPS data can be used to help validate hyc products from remote sensing satellites. While initially tested for hydrologic applications, tl reflection method can also be used to measure water levels and tides.

BIO (50-word maximum): Dr. Larson is a GPS geodesist and faculty member at the University of Colorado. She develops new applications for GPS, incl. seismology, snow, soil moisture, tides, and volcanic plume sensing.

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Hydrologic modeling and the role of storage

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I review the general structure of a class of land surface hydrology models (LSHMs) that represent hydrologic processes at large scales (typically fractions of degrees latitude by longitude). My comments apply generally for instance to the North American Land Data Assimilation System (NLDAS) suite of LSHMs. Most of these models represent the land surface as a set of rectangular grids, although some may use hydrologic response units (HRUs) as an alternative, which could, for instance, be subcatchments as represented by a river drainage network. For each fundamental unit (I'll refer to these as grid cells, recognizing that they could be HRUs) an LSHM solves the water balance equation, $P - E = Q + dS/dt$, where P = precipitation, E = evapotranspiration, Q = runoff, and S = storage, which for most models consists of soil moisture plus snow water equivalent (SWE), but can (in some models) include groundwater, and perhaps glaciers and ice sheets, and in a few models may include surface water (e.g., lakes, rivers, reservoirs, etc.). The runoff produced by each grid cell is typically routed through a representation of the channel network (usually this is a post-processor) to produce an estimate of streamflow at the basin outlet (which may be coincident with a stream gauge, in which case modeled and observed streamflow can be compared). In off-line simulations, precipitation is the primary forcing, and evapotranspiration and runoff, as well as storage, are predicted. Some LSHMs coincidentally solve the land surface energy balance, $Rn – G = S + \lambda E$, where Rn = net radiation, G = ground heat flux, S = sensible heat, and λE = latent heat. Note that E is a common term in the water and energy balance equations; in models which solve both the water and energy balance equations, an iteration is performed for an effective land surface temperature, which is a term in the emitted longwave radiation (in Rn), as well as S and E (note that some models represent effective temperatures for the land surface and vegetation separately). E also depends on surface wind, as well as vapor pressure deficit, and Rn is the sum of net longwave and net shortwave radiation. Hence, in full energy balance models, the forcings (in addition to P) include downward longwave and shortwave radiation, surface wind, and vapor pressure deficit, as well as surface air pressure. Some models short-circuit the solution of the surface energy balance equation by assuming that the surface temperature is equal to the surface air temperature, thus avoiding the need to iterate for effective surface temperature (however, in the NLDAS models the forcings effectively are the same whether or not the full energy balance is computed). Other (mostly older) models prescribe a potential evapotranspiration (PET) which may be computed externally, and in some cases is even "tuned" rather than being computed using the NLDAS forcings. Most of the NLDAS models explicitly represent vegetation in some manner, and the vegetation representation is inherent in the evapotranspiration computation – actual evapotranspiration (AET) is computed given the energy forcings (which may be converted to PET as an intermediate step) and then storage S, as well as vegetation characteristics (e.g., leaf area index, or LAI) modulate the interaction between the energy forcings and AET. All LSHMs represent in some fashion the movement of moisture through the soil column, which typically is represented by multiple layers. Although the specifics differ, most models have some representation of a fast runoff response (what hydrologists term either saturation or infiltration excess, hence is dependent on moisture near the surface) as well as a slow (base flow) response which is dependent on deeper storage (most models represent the soil column as multiple layers). The sum of fast and slow runoff is routed through the channel network as indicated above. All of the NLDAS LSHMs incorporate a snow model as well. Essentially the snow model sits on top of the soil (and vegetation) layer, and while differences exist, in most models snowmelt is treated the same way as rainfall on bare vegetation or soil. Hence, the snow model accounts for the accumulation of falling precipitation as SWE (including, in some models, the role of vegetation), as well as its ablation (sublimation or melt). Many variations exist in the general structure I've outlined, such as greater or lesser complexity in the representation of vegetation, layering of the soil column (and in some models, prediction of soil temperatures and thermal fluxes, as well as soil freezing), interaction of snow with vegetation, lateral transport of moisture in both the soil column and as snow, among other differences. However, all LSHMs are forced with P (and perhaps other surface meteorological variables) and produce Q and E, as well as S in various forms. Finally, while hydrologists generally view the land surface as being forced by the atmosphere, most of the NLDAS models are structured for incorporation in coupled land-atmosphere (weather and climate) models, in which case P and the other off-line forcings are produced by the atmospheric model.

Bio: Dennis P. Lettenmaier has interests in hydrologic modeling and prediction, hydrology-climate interactions, and hydrologic change. He is an author or co-author of over 300 journal articles. He was the first Chief Editor of the American Meteorological Society Journal of Hydrometeorology, and is a past President of the Hydrology Section of the American Geophysical Union.

NASA GSFC MASCONS: SIGNAL COVARIANCE DESIGN AND ERROR ASSESSMENT

***Bryant D. Loomis*[1]**, *S. B. Luthcke*[1], *T. J. Sabaka*[1], *K. Rachlin*[2]
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The key design parameter for producing time-variable gravity mascons with GRACE data, is the set of signal covariance matrices applied in the regularized least squares estimation. We present the improved iterative solution approach from the NASA Goddard Space Flight Center (GSFC), which now applies inter-satellite range-acceleration residuals in the construction of the monthly mascon signal covariance matrices. We also present and validate new estimates of the mascon noise uncertainties and signal leakage errors. The accurate assessment of signal leakage is difficult, and as a result this significant error source is often ignored. We have computed rigorous estimates of the leakage by constructing the full monthly resolution operators and applying them to our monthly solutions. Our new mascon product provides users with the information needed to assign total uncertainties to mass change time series of individual mascons or any user-defined collection of mascons that defines a region of interest, where the total uncertainty is the appropriate combination of the noise and leakage errors. Realistic solution uncertainties facilitate the proper scientific interpretation and assimilation of the NASA GSFC mascon product.

BIO: Dr. Loomis is a research geophysicist with the Geodesy and Geophysics Laboratory at NASA GSFC, and is a current member of the GRACE/GRACE-Follow On Science Team, the NASA Sea Level Change Team, and the NASA High Mountain Asia Team. His primary focus is the estimation and analysis of time-variable gravity.

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CONSTRAINING DYNAMICS OF CENTRAL VALLEY AQUIFER SYSTEMS FROM SPACE

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The accelerated rate of decline in groundwater levels and land subsidence across California's Central Valley results from over-drafting and low rates of natural recharge, which is exacerbated by recent drought periods. However, the lack of high resolution observations to constrain the properties and evolution of the aquifer system pose a serious challenge to water management efforts and put the water security at high risk. Here, we report on joint analysis of the measurements of land vertical motion and groundwater head levels across the Central Valley California. The land vertical motion data are obtained by integrating 1600 high quality L-Band interferograms and 300 continuous GPS stations. While the groundwater head levels are measured at 1604 wells. The combination of these data sets allows investigating the dynamics of aquifer systems at an unprecedented resolution.

Filling the spatial gaps between measurements from individual wells and gravimetric satellites, our data uncovers underground processes at the scales of 100s of m to 100s of km. Investigating the depletion and degradation of aquifer systems during 2007 – 2010, when the entire valley experienced a severe drought, we find that ~2% of aquifer storage is permanently lost across the valley. Additionally, the peak seasonal groundwater oscillation is 10.11 ± 2.5 km^3, and is modulated on a long term groundwater loss with total volume of 21.32 ± 7.2 km^3 over this period. The sub-basin estimates, however, indicate a heterogeneous response, controlled by hydrogeology and driven by recharge and demand. Thus, knowledge of large scale distribution of aquifer properties and the impact of droughts on storage capacity of a stressed aquifer system is of great importance for water management and forecasting the availability of water resources during future drought periods

BIO: Dr. Shirzaei is a geodesist/geophysicist and for the past 10 years has been involved in various research efforts dealing with advanced SAR data processing and crustal deformation modeling. He has developed several algorithms for InSAR time series analysis as well as inverse and forward elastic, viscoelastic and poroelastic modeling codes and software.

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MONITORING BASIN-SCALE SNOW WATER EQUIVALENT (SWE) USING GPS VERTICAL POSITION DATA

Eric E. Small[1]*, Thomas Enzminger*[1]*, and Adrian Borsa*[2] ***[BOLD the presenter's name]***
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GPS monitoring of solid Earth deformation due to surface loading is an independent approach for estimating seasonal changes in terrestrial water storage (TWS). In western U.S. (WUSA) mountain ranges, snow water equivalent (SWE) is the dominant component of TWS. There are many approaches for monitoring SWE, all with unique strengths and weaknesses. While several studies have generated SWE estimates from GPS-measured vertical displacements, the error associated with this method remains poorly constrained. We examine the accuracy of SWE estimated from synthetic displacements at 1395 continuous GPS station locations in the WUSA. Displacement at each station is calculated from the predicted elastic response to variations in SWE from SNODAS (Snow Data Assimilation System) and soil moisture from the NLDAS-2 (North America Land Data Assimilation System) Noah model. We invert synthetic displacements for TWS, showing that both seasonal SWE as well as interannual variability can be estimated from data recorded by the existing GPS network. Because we impose a smoothness constraint in the inversion, recovered TWS exhibits mass leakage from mountain ranges to surrounding areas. This leakage bias can be removed with a linear rescaling that is insensitive to the TWS load pattern. These gain factors vary seasonally, with highest values at the times of peak SWE. GPS data can be used to estimate mountain-range-scale SWE, but effects of soil moisture and other TWS components must be subtracted from the GPS-derived load estimates.

BIO: Dr. Small has 20 years of experience studying the terrestrial water cycle using remote sensing, models, and in situ observations. He has used ground-based GPS reflection data and GPS vertical position data to study soil moisture, snow water equivalent, and vegetation.

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LAND SUBSIDENCE MONITORING AND QUANTITATIVE ASSESSMENT TOOLS FOR GROUNDWATER SUSTAINABILITY PLANS

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Groundwater is relied on for part of California's water supply. Despite its essential role, the state's groundwater system is under considerable strain and until recently has been largely unregulated. California's Sustainable Groundwater Management Act of 2014 (SGMA) provides a framework to comprehensively measure and manage groundwater and empowers local agencies to assess hydrologic conditions that can cause "undesirable results." Land subsidence, resulting from compaction of unconsolidated aquifer systems caused by groundwater extraction, is listed as one of SGMA's "undesirable results" and adversely affects many groundwater basins in California. Subsidence generally is gradual and widespread, such that the occurrence often goes undetected for decades until revealed by repeated elevation surveys or infrastructure damage. As a result, consideration of subsidence, and if necessary, subsidence monitoring and management, is required for inclusion in Groundwater Sustainability Plans (GSPs). Subsidence monitoring can result in early detection, provides a measure of water-resources sustainability within relevant planning horizons, and produces data and information needed for subsidence management. A variety of monitoring and quantitative assessment tools are available for measuring and understanding the processes and consequences of subsidence.

Measurements of change in land-surface elevation or aquifer-system thickness can be obtained by repeated leveling or Global Positioning System (GPS) surveys, continuous GPS stations, extensometry, Interferometric Synthetic Aperture Radar (InSAR), radar altimetry, and(or) Light Detection and Ranging (LiDAR) techniques. One or more of these methods are used in subsidence studies throughout the world. The integration of various measurement techniques leverages the diverse spatial and temporal scales of the datasets. For example, continuous GPS data provides hourly or daily subsidence histories at fixed locations, whereas InSAR data shows the areal extent of subsidence over several weeks or months. Depth-specific extensometer data, groundwater levels, lithologic data, and laboratory consolidation test results can be used to understand and estimate properties that govern the local stress/strain response of the aquifer system. Vertical land-surface changes and groundwater levels used together enable estimates of the critical head at which inelastic subsidence initiates, and the skeletal elastic and inelastic aquifer system storage properties that control subsidence magnitude. One or more co-located extensometers, or an extensometer co-located with measurements of land-surface elevation change, are useful for delineating the depth intervals at which compaction occurs. Integrating local lithology into the analysis, particularly the depth intervals of fine-grained deposits, may help identify specific deposits susceptible to compaction. Results of consolidation tests provide estimates of potential magnitudes and rates of compaction. This information helps improve hydrologic and aquifer-system compaction models, which in turn can be used effectively to incorporate land subsidence constraints in water-resource management strategies to refine best management practices for GSP implementation.

Michelle Sneed is a hydrologist with the U.S. Geological Survey. Her research focuses on land subsidence related to fluid-pressure changes. She is a member of the UNESCO Working Group on Land Subsidence, the recognized leader in promoting global land subsidence studies. Michelle received BS and MS degrees in geology from CSU, Sacramento.

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ESTIMATING FLUID-INDUCED STRESS CHANGE FROM OBSERVED DEFORMATION

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Observed deformation is sensitive to a changing stress field within the Earth. However, there are several impediments to a direct inversion of geodetic measurements for changes in stress. Estimating six independent components of stress change from a smaller number of displacement or strain components is inherently non-unique. The reliance upon surface measurements leads to a loss of resolution, due to the attenuation of higher spatial frequencies in the displacement field with distance from a source. We adopt a technique suited to the estimation of stress changes due to the injection and/or withdrawal of fluids at depth. In this approach the surface displacement data provides an estimate of the volume change responsible for the deformation, rather then stress changes themselves. The inversion for volume change is constrained by the fluid fluxes into and out of the reservoir. The distribution of volume change is used to calculate the displacements in the region above the reservoir. Estimates of stress change follow from differentiating the displacement field in conjunction with a geomechanical model of the overburden. We apply the technique to Interferometric Synthetic Aperture Radar (InSAR) observations gathered over a reservoir in the San Joaquin Valley of California. An analysis of the InSAR range change reveals that the stress field within the overburden, varies rapidly both in space and in time.

BIO: Dr. Vasco is a senior scientist with over 30 years of experience in seismic imaging, seismic source analysis, geophysical inversion, flow modeling, and the analysis of deformation due to fluid flow. He has numerous publications on the use of surface deformation data to image fluid flow in geothermal fields, oil and gas reservoirs, carbon sequestration sites, and in shallow pumping tests, including a recent book entitled, 'Subsurface fluid flow and imaging' published by Cambridge University Press.

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HYDROGEODESY AS A NEW SUB-FIELD

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One of the major challenges of the 21st century is securing freshwater supply for the increasing world population as well as for preserving natural ecosystems. Direct hydrological observations, such as surface- and ground-water level measurements, provide important but partial information of water storage and fluxes characterizing the hydrological cycle. Typically, hydrological monitoring provides high temporal resolution measurements at a limited number of observation points, which are useful for characterizing temporal changes. However, the spatial resolution of these measurements is rather limited. Some gaps in hydrological monitoring can be filled by geodetic observations, which can be indicative of hydrological processes. Small but measureable surface changes, as measured by GPS and InSAR, often reflect crustal and surface deformation in response to changes in terrestrial water storage (TWS) or due to aquifer system deformation. In addition, precise gravity measurements acquired from space (e.g., GRACE) or on the ground, are also indicative of changes in TWS or groundwater level. Another useful geodetic technique is GPS Interferometric Reflectometry (GPS-IR), which measure spatially integrated hydrological properties, including soil moisture, snow depth and vegetation index.

In this workshop we promote the use of geodetic observations for hydrological monitoring and studies. Furthermore, we advocate for using the term "hydrogeodesy" as an applied scientific sub-field that uses accurate geodetic observations to measure, or infer, hydrological quantities and their changes over time (processes, fluxes). The workshop brings together experts from hydrology and geology, in order to increase integration and communications among scientists from both fields.

BIO: Dr. Shimon Wdowinski is an Associate Professor for Geophysics at the Department of Earth and Environment, Florida International University. He has used space geodetic and remote sensing technologies for studying wetland hydrology and vegetation structure from space.

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GRACE-2: POTENTIAL IMPROVEMENTS IN RECOVERING TERRESTRIAL WATER STORAGE VARIATIONS

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The Gravity Recovery and Climate Experiment (GRACE) has provided an unparalleled perspective on observing the global water cycle, providing monthly estimates of total water storage globally at approximately 300 km spatial resolution. Scientists from a variety of disciplines have called for increasing the spatio-temporal resolution and accuracy of GRACE-type measurements, citing potential benefits for a wide variety of scientific applications. In this talk, we discuss the limiting sources of error for GRACE, and ways in which these can be potentially mitigated in future missions. We focus on a hypothetical mission architecture consisting of two pairs of satellites, one pair in a polar orbit and the other pair in a lower inclined orbit (~70^{o}), which provides an effective means to increase the spatio-temporal resolution of GRACE-type measurements. High fidelity closed-loop end-to-end numerical simulations are used to demonstrate potential improvements in data quality that such a mission could provide.

BIO: Dr. Wiese has 12 years of experience working with satellite gravimetry data. His research focus areas include the design of future satellite gravimetry missions, data processing of current satellite gravimetry missions (lead developer of the JPL GRACE Mascon solution), and science applications of time-variable gravity data.

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