FACILITY SUPPORT OF THE WINSAR ARCHIVE FOR CRUSTAL DYNAMICS RESEARCH

Submitted to NSF/NASA/USGS on behalf of the WInSAR Consortium by

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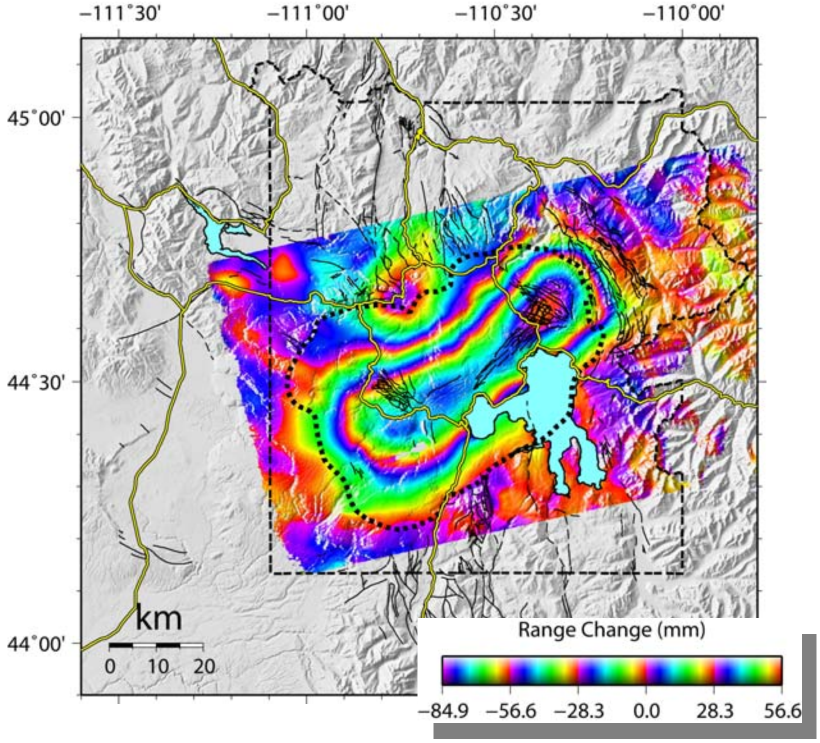

WInSAR
Western North America Interferometric Synthetic Aperture Radar Consortium

PROJECT SUMMARY

Intellectual Merit

The technique of spaceborne Interferometric Synthetic Aperture Radar (InSAR) provides an excellent means of observing deformation over broad areas that is highly complementary to the measurements provided by the global network of GPS receivers. Over the past three years the WInSAR consortium has grown to 45 member institutions pursuing science investigations ranging from the study of deformation associated with earthquakes, volcanoes, and glaciers to land subsidence and InSAR algorithm development. Recent policy changes at the European Space Agency as well as the 2006 launch of the *ALOS* satellite have enabled WInSAR to go global. Accordingly the facility component of WInSAR has moved to UNAVCO from the Southern California Earthquake Center. Here we propose to continue the maintenance and expansion of the WInSAR archive and software. Our proposal will facilitate InSAR research for US scientists. The science themes, as formulated by the WInSAR users, include:

- The earthquake cycle throughout the world including the San Andreas Fault and Basin and Range;
- Volcanic activity throughout the world including South America, Hawaii, Aleutians and Cascade/Yellowstone;
- Groundwater and coastal hazards throughout North America;
- Mountain building in South America and the Himalayas;
- Rifting in Iceland and East Africa; and
- InSAR noise source mitigation and time series analysis.

The objectives of the proposed work are to:

- Develop a robust multi-satellite SAR data ordering, distribution & archiving system;
- Purchase new data both globally and over North America in support of WInSAR science themes; and
- Work toward open-source community InSAR software.

We request a total of $150K/year ($50K each from NASA, NSF and USGS) for 3 years to maintain the data distribution and archive facility at UNAVCO as well as to acquire SAR data and make it available to the WInSAR consortium members. This proposal for $100K/year includes the contributions from NASA and NSF. A separate proposal will be submitted to USGS.

Broader Impacts

These science objectives are highly complementary to the Plate Boundary Observatory objectives of EarthScope. GeoEarthScope provides partial funding for the purchase of InSAR data and the development/maintenance of the archive at UNAVCO. This proposal provides the additional funding needed to support the science activities outside of EarthScope such as the study of volcano deformation in the Aleutians, Hawaii, and South America and surface subsidence due to groundwater withdrawal. A major strength of this proposal is integration or research and education. WInSAR data are used in 21 courses at 14 of the top research universities in the US. WInSAR data have been used in 26 PhD and MS theses since 2000. The students come from all background and ethnic groups. The research results are widely published (at least 34 refereed journal publications in the past three years) and many innovative web pages to capture the interest of young students.

1. INTRODUCTION

The user base and satellite imaging choices are rapidly expanding in the field of Interferometric Synthetic Aperture Radar (InSAR). The makeup and science interests of the Western North America InSAR (WInSAR) consortium reflect these changes. Initially formed by a small group of investigators, WInSAR has grown to 45 member institutions pursuing science investigations ranging from earthquakes, volcanoes, and glaciers to land subsidence and InSAR algorithm development. However, the primary WInSAR goals remain the same: provide open access to SAR data for (mostly) US scientists and promote the use and development of InSAR technology for scientific investigations.

WInSAR serves a unique role within the InSAR community. All current and past InSAR satellites are operated by foreign space agencies: *ERS-1/2* and *Envisat* are operated by the European Space Agency (ESA), *Radarsat* is operated by the Canadian Space Agency (CSA), and *ALOS* is operated by the Japanese Space Agency (JAXA). Unlike most data collected by US satellites, which are freely available to anyone with an internet connection, all scientifically-relevant SAR data have significant costs and copyright restrictions. Such limitations on data exchange impede scientific progress since published results cannot be easily reproduced - the foundation of the scientific method. WInSAR facilitates bulk data purchases and makes its holdings freely available to its members at password-protected websites. Membership involves a simple e-mail application and signing foreign space agency data use and copyright restriction documents. More WInSAR information, including its bylaws, can be found at http://winsar.unavco.org.

Originally, WInSAR data purchases were limited to Western North America and the facility was appropriately hosted by the Southern California Earthquake Center. However, recent policy changes at ESA as well as the 2006 launch of the *ALOS* satellite have enabled WInSAR to go global and, as discussed below, the facility component of WInSAR has moved to UNAVCO. Here we propose to continue the maintenance and expansion of the WInSAR archive and software.

The objectives of the proposed work are to:

- Develop a robust multi-satellite SAR data ordering, distribution & archiving system
- Work toward open-source community InSAR software
- Purchase new data both globally and over North America in support of WInSAR science themes

These science themes include:

- The earthquake cycle throughout the world including the San Andreas Fault and Basin and Range
- Volcanic activity throughout the world including South America, Hawaii, Aleutians and Cascade/Yellowstone
- Groundwater and coastal hazards throughout North America
- Mountain building in South America and the Himalayas
- Rifting in Iceland and East Africa
- InSAR noise source mitigation and time series analysis.

Continued support of the WInSAR facility at UNAVCO will expedite crustal dynamics research providing unique InSAR measurement capabilities to a large community of researchers. Networks of seismometers, GPS antennae, and other geodetic instruments provide exceptional temporal coverage of the co-seismic, post-seismic, and inter-seismic motions, but their spatial coverage is poor. InSAR complements these systems by providing dense (10's of meters) spatial resolution but at a much lower sampling rate (> 24 days). InSAR coverage also is global so, for example, one can investigate multiple continental fault systems and capture all stages of the earthquake cycle. In addition to our past WInSAR activities, we propose to acquire and archive the new L-band SAR data currently being collected by the PALSAR instrument on the *ALOS* satellite. PALSAR is the first L-band synthetic aperture radar having the duration (up to 12 years) and orbital accuracy needed to monitor slow crustal deformation globally. The main advantage of the L-band (23 cm wavelength) PALSAR over C-band (5.8 cm wavelength) is that deeper penetration of vegetated areas results in less temporal decorrelation enabling interferograms to have longer time separation. This will facilitate the study of slow crustal deformations in vegetated areas.

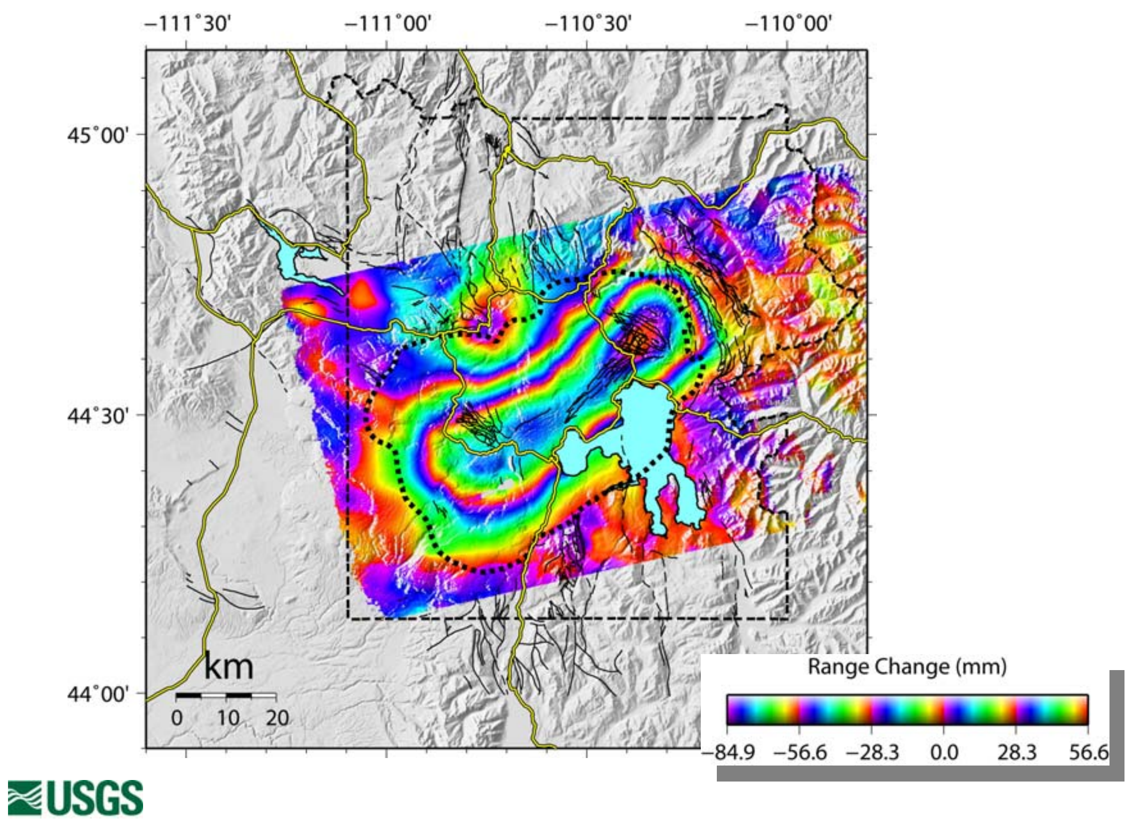

Figure 1. Vertical deformation at Yellowstone Caldera between October 8, 2004 and September 23, 2005, derived from Envisat SAR data (personal communication, Chuck Wicks, USGS, 2006). One fringe represents 28 mm of line-of-sight motion. Total uplift is about 80 mm. The InSAR data capture the spatial extent of the deformation while the continuous GPS data in the area (Figure 2) provide the detailed time history of the deformation.

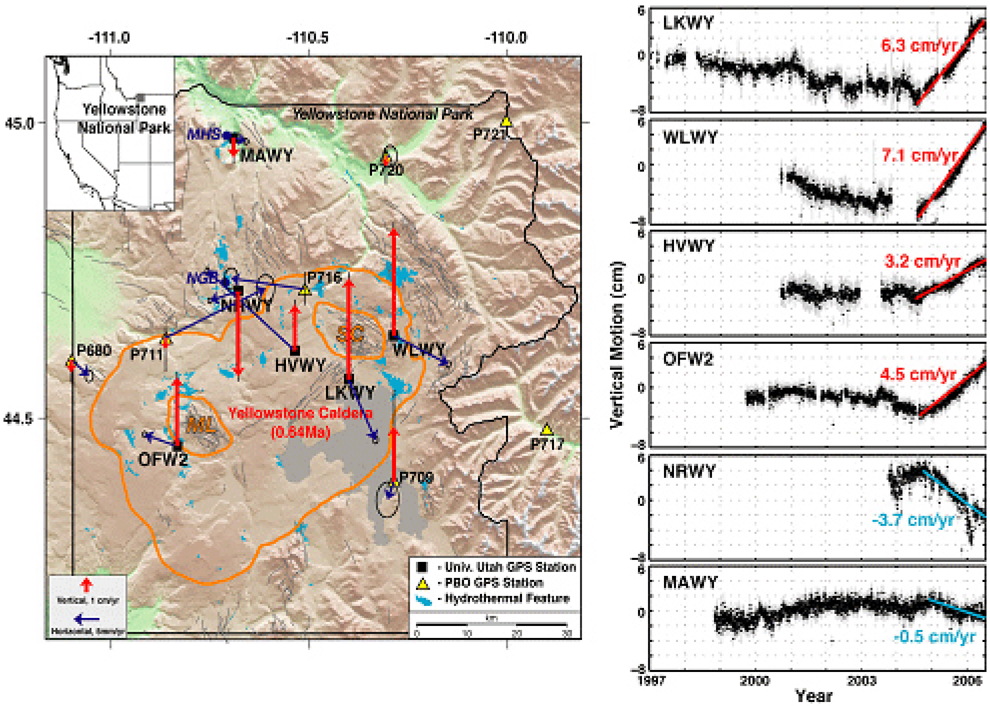

Figure 2. (a) Locations of measured uplift and horizontal motions from GPS stations in the Yellowstone caldera. (b) Time series of vertical motion measured at six sites. The long trend of caldera-wide subsidence shown in InSAR image in Figure 1 reversed dramatically to very rapid uplift in late 2004 reaching rates of up to 7 cm/year. GPS and InSAR observations of the uplift have been inverted for source parameters. These models point to expanding sill-like structures at depth and suggest that a new intrusion of magma into the mid-crust or pressurization of a deep hydrothermal system likely caused the uplift within the Yellowstone caldera. Personal communication W. Chang, R.B. Smith, C. Wicks, C. Puskas, and J. Farrell, 2007 (NSF/USGS funded research).

2. Background

The western part of North America is the focus of intensive scientific research into a variety of plate boundary processes including earthquakes, volcanism, mountain building, and micro-plate tectonics. For example, the characterization and more complete understanding of the plate boundary deformation system, and its relationship to the occurrence of earthquakes, is a rich scientific problem that may ultimately lead to a reduction in seismic risk. Other natural processes that induce surface deformation, such as land subsidence induced by water or oil extraction, are also at work in western North America. The InSAR technique provides an excellent means of observing deformation over broad areas. It is capable of decameter-level spatial resolution at monthly or greater intervals. InSAR has proven to be a powerful tool to characterize large-scale deformation associated with active faults. It also can resolve small-scale deformation features such as shallow creep, postseismic and interseismic deformation. And it is an ideal tool for measuring land subsidence and improving digital terrain models.

WInSAR is a consortium of universities and research laboratories (Table 1) established by a group of practicing scientists and engineers to facilitate collaboration in, and advancement of, Earth science research using radar remote sensing. WInSAR helps coordinate requests for data acquisition and for data purchase, aiding individual investigators by simplifying interactions with data providers and with government agencies funding science.

The long-term goals of WInSAR are to:

- Promote the use and development of InSAR technology for scientific investigations, in particular but not limited to, seismic and magmatic processes, plate boundary deformation, land subsidence, and topographic mapping
- Acquire SAR imagery in western North America, archive and catalog the data, and disseminate it for use by member organizations
- Provide value-added InSAR products & software for use by the scientific community
- Advocate the open exchange of SAR data by seeking to enlarge the number of member organizations
- Solicit funds and promote programs and space missions to meet these objectives

The growing role of WInSAR as a facilitator of InSAR research collaborations worldwide motivated the recent change in WInSAR host organization. Under the stewardship of the Southern California Earthquake Center (SCEC), WInSAR has more than doubled its membership to 45 institutions. With the increased membership came a broadening range of radar interferometry interests which has grown beyond the scope of SCEC. Consequently, WInSAR voted in 2006 to make UNAVCO their new host institution. The overall mission, organizational structure and research activities have not changed. The primary role of UNAVCO is to provide administrative and logistical support for WInSAR activities such as financial and data management.

UNAVCO, a non-profit, membership-governed consortium, supports and promotes Earth science by advancing high-precision techniques for the measurement and understanding of crustal deformation. UNAVCO also supports education to meet the needs of the community and the public.

Table 1. WInSAR United States and Foreign (Adjunct*) Members as of 3/2007

Arizona State U.	Oregon State U.	U. Calif., San Diego	U. Utah
Calif. Inst. of Tech.	Purdue U.	U. Calif., Santa Barbara	U. Wisconsin, Madison
Central Washington U.	San Diego State U.	U. Calif., Santa Cruz	Western Washington U.
Cornell U.	Stanford U.	U. Hawaii	Woods Hole Ocean. Inst.
George Mason U.	USGS	U. Kansas	
Idaho State	U. Alaska	U. Memphis	
Indiana U.	U. Arkansas	U. Miami	Adjunct Members*
Jet Propulsion Lab.	U. Colorado	U. Missouri	Simon Fraser U.
Lawrence Livermore	U. Calif., Berkeley	U. Nevada, Reno	U. College London
Los Alamos Nat. Lab.	U. Calif., Davis	U. Oregon	U. Western Ontario
MIT	U. Calif., Los Angeles	U. Southern Calif.	
Ohio State U.	U. Calif., Riverside	U. Texas, Austin	*access but no ordering

3. IMPACT OF FACILITY ON SCIENCE, RESEARCH, AND EDUCATION

In preparation for this proposal we asked the WInSAR membership about their future research interests, publications, student theses, and courses that use WInSAR data.

3.1 RESEARCH PLANS USING WINSAR DATA AT UNAVCO

In the area of future research, we obtained responses from the following 23 members:

Zhong Lu, *USGS*: USGS scientists will be conducting a Persistent Scatterer InSAR (PSInSAR) study of deformation in the Cape Mendocino area. This will tap the ERS-1/2 archive. We will also conduct a coherence test of ALOS data in the Mendocino area. The Magellan Fault zone in South America will be the focus of a pilot study using ERS/ENVISAT data and ALOS data. In addition, USGS scientists will carry out PSInSAR studies over Park Field area using ERS-1, ERS-2 and Envisat images.

Mark Simons, *Caltech*: We will pursue small amplitude tectonic deformation signals in the Basin & Range using stacks of ERS and Envisat data integrated with continuous GPS data. If WInSAR gets ALOS data for S. America, then we will continue our ongoing studies of the seismic cycle in Peru and Chile with that data. We are also going back and reassessing coseismic models of the Landers earthquake.

Zhenhong Li, *University College London, UK*: We will use WInSAR data to (1) develop and validate atmospheric correction models for reducing water vapour effects on SAR interferograms; (2) develop advance InSAR/GPS integration techniques to detect slow deformation signals (e.g. interseismic and postseismic signals); and (3) investigate tectonic deformation of the Eastern California Shear Zone and Yucca Mountain, Nevada (collaborating with Dr. Geoffrey Blewitt and his colleagues at Univ. of Nevada, Reno).

C.K. Shum, *Ohio State University*: We propose to apply InSAR techniques using WInSAR data including ALOS L-band PALSAR, Envisat ASAR and other SAR interferometry to study: (1) the dynamics of ice mass flux across the grounding zone in the Filchner/Ronne Ice Shelf region in E. Antarctica, and (2) the ocean tidal dynamics in the "thin" ice covered seas in Schirmacheroase Oasis in Dronning Maud Land, Ross Sea, and Filchner/Ronne ice shelves, Antarctica. We also propose a radar sensor calibration/validation and InSAR technique development component with the scientific objectives: (1) to compare PALSAR L-band measurements with those of C-band SAR (e.g., ERS-1, SRTM) and X-band (SRTM) over two types of land covers: an ablation ice sheet (Dronning Maud Land, E. Antarctica) and a well-known land region in North America near Hudson Bay region and the Great Lakes region; and (2) to study the feasibility to improve the ability for determination of accurate baseline length for repeat pass interferometry using ALOS PALSAR by applications of precision orbit determination methodologies to enhance the knowledge of the orbit accuracy of ALOS.

Gilles Peltzer, *UCLA*: California projects, Fault and earthquake processes: Analyze deformation field from InSAR data near surface rupture to observe response of fault zone to co-seismic strain. Use time series data to infer temporal behavior of post-seismic deformation. Develop poro-elastic models to describe observed deformation. Exploit longer time series data acquired by ERS and Envisat to characterize fast slip rate observed along the Blackwater fault using limited ERS data.

Kristy F. Tiampo, *University of Western Ontario*: Studies of volcanic regions around the world. Groundwater deformation studies in both the US and Canada. Bayesian integration of GPS and InSAR signal, in conjunction with other geodetic data (LIDAR, for example) into a 4-D field with error estimates, and associated inversions.

Matt Pritchard, *Cornell*: For research, I hope that WInSAR will acquire data in some areas of the northeast (particularly upstate NY) so that several natural and anthropogenic sources of deformation can be monitored. This area is of course challenging for C-band radar, but a dense collection of ERS and Radarsat data can be used to test advanced post-processing techniques, and hopefully ALOS data will also be acquired.

Mike Taylor, *University of Kansas*: The University of Kansas is interested in using the WInSAR archive to quantify slip rates along faults that comprise the Eastern California Shear Zone (ECSZ). Additionally, faults that comprise the ECSZ are generally not through-going structures. Rather, significant faults typically display an en echelon geometry and feed slip into extensional or contractional fault step-overs, or bends. Characterizing the deformational style and quantifying the strain accumulation at these fault terminations will assist in quantifying bulk strain within the ECSZ of the Mojave.

Andrew V. Newman, *Georgia Institute of Technology*: Over the next 3 years, I plan to use data obtained through the WInSAR consortium to develop robust spatial deformation sequences for ongoing magmatic processes across the globe. Areas of specific focus for WInSAR data include Long Valley Caldera in California, the Valles Caldera and Socorro Magma Body in New Mexico, and Santorini Caldera in Greece. InSAR data will be combined with ongoing GPS studies to describe 4-D deformation kinematics.

David Schmidt, *University of Oregon*: My group is studying fault related deformation, land subsidence from groundwater recharge and extraction, as well other crustal deformation signals in the western US.

Roland Bürgmann, *Univ. of California, Berkeley*: We will continue our efforts to study tectonic and non-tectonic deformation in Central California including investigations of (1) locking distribution and seismic potential of active strike-slip faults, (2) uplift rates and kinematics of active thrust faults, (3) kinematics and dynamics of deep-seated landslides, (4) time-dependent deformation associated with slow slip events and postseismic relaxation processes. We are also eager to continue InSAR based studies of deformation in other regions of the world.

Ricky Becker, *Western Michigan University*: We are working on a couple projects where we will be using WInSAR data in the next 3 years. The first is looking at land subsidence in Amherst, NY, which is apparently due to drying in swelling clays, and possibly due to groundwater extraction. The initial part of this was done outside of WInSAR, but we plan on acquiring more data to use a persistent scatterers approach to the problem. We are also developing work on groundwater drawdown related subsidence in the Boston, MA area.

Rob Mellors, *San Diego State University*: Examine fault movement and properties in the Salton trough and nearby areas; map areas of groundwater withdrawal and estimate aquifer properties in same area.

John Wahr, *Univ. of Colorado*: We have been using WInSAR data to study land surface deformation in eastern Utah related to salt tectonics. Briefly, sedimentary strata in this region lie atop salt layers deposited during the evaporation of ancient seas. The salt is relatively mobile, and as it moves around or gets squeezed out there is accompanying displacement of the overlying sediments. We are continuing to use WInSAR data to look at salt tectonic displacements in other regions of Utah and western Colorado.

Falk Amelung, *University of Miami*: Gravitational spreading and the volcanic systems of the Hawaiian Volcanoes, Contemporaneous deformation of the Basin and Range Province, Contemporaneous deformation of the Eastern California Shear Zone, Land subsidence in New Orleans, Louisiana Everglades sheet flow.

Paul Vincent, *Oregon State University*: I plan on utilizing data from Envisat, ALOS, Radarsat, TerraSAR-X platforms (whatever SAR data WInSAR purchases) over the Pacific Northwest from Cape Mendocino to Vancouver Island along the Cascadia Margin. The applications are two-fold: 1) for long-term vertical deformation measurements and 2) for short-term landslide potential and coastal erosion assessments. I will also use any WInSAR data inland along the CSZ to search for new, and monitor and better characterize existing, seismically active crustal faults (e.g., the Scotts Mills earthquake of 1993). I also plan on continuing work in S. Calif (Southern SAF, Superstition Hills Fault, etc.).

Eric Fielding, *Jet Propulsion Laboratory*: We plan to study the postseismic deformation for the Parkfield and San Simeon earthquakes, and the coseismic and postseismic deformation for any new earthquakes that may happen in the next three years. We are using time series analysis to study interseismic and transient deformation associated with the San Andreas Fault system from the Gulf of California up through the Central San Andreas Fault. We also plan to apply time series analysis to western US volcanic complexes, including Yellowstone, Long Valley and Cascades. In addition, we are working on new techniques to distinguish tectonic deformation from non-tectonic ground deformation (related to hydrology and petroleum operations) and atmospheric variations.

Elizabeth Cochran, *University of California, Riverside*: I am using WInSAR data to study postseismic deformation following the Hector Mine earthquake. Specifically, we are interested in the postseismic displacement within a 200 m wide zone along the fault that appears to undergo poroelastic deformation in the months following the mainshock. This was part of my dissertation work with Gilles Peltzer. In the future, I plan to explore several avenues of research using WInSAR data including interseismic strain accumulation and subsidence in California. One specific area of interest is the San Jacinto Valley that has a signal that contains both tectonic and subsidence signals. The results will be of interest to both the tectonic community and the local water authority.

John Bell, *University of Nevada, Reno*: The InSAR lab has been focusing largely on groundwater-related land subsidence throughout Nevada, but has also been investigating tectonic deformation associated with medium-magnitude earthquakes. The Nevada Geodetic Laboratory also housed here at UNR has utilized WInSAR data covering the Yucca Mountain-Death Valley region to examine secular deformation rates using both InSAR and GPS data, and this research will hopefully continue through the Earthscope Program. Researchers in the Department of Geological Sciences and Engineering have been utilizing WInSAR archives during the last several years to measure aquifer/reservoir response to geothermal withdrawals in Nevada. This research has been supported by the Department of Energy and will play an important role in evaluating renewable resources in the next few years.

Ben Brooks, *University of Hawaii*: Continued monitoring of Big Island, Hawaii volcano-tectonic phenomena including: Mauna Loa inflation and possible eruption; Kilauea ongoing eruption; Kilauea south flank slow earthquakes. We also operate a dense continuous GPS network (with Stanford and HVO), creating an important test-bed for persistent scatterer and atmospheric mitigation techniques (e.g. Foster et al., 2006). Investigating and monitoring of relative sea-level changes along coastal western US (e.g. Brooks et al, 2007).

David Sandwell and Yuri Fialko, *University of California at San Diego*: Investigate shallow fault creep along the San Andreas Fault system. Investigate postseismic deformation mechanisms in the Eastern California Shear Zone and throughout the world. Investigate the widths of fault damage zones in response to changes in crustal stress.

Howard Zebker, *Stanford University*: We will be using WInSAR data to investigate crustal deformation processes in the western US and in Hawaii. Our main areas of emphasis will be on the San Andreas fault system for seismic studies, and on Hawaiian and Cascade volcanoes for research on volcanic processes. Our main emphasis will be to investigate the time dependence of subsurface processes that are exposed as deformations of the crust. Our general approach will be to use various InSAR methods to characterize deformation over time and then infer changes at depth through inverse modeling.

Rowena Lohman, *Jet Propulsion Laboratory*: We plan on applying Kalman-filter and persistent scatterer methods to data within the Salton Trough, an area that is characterized by isolated regions of very high coherence (roads, cities, farmhouses) surrounded by agricultural fields. The goal of this work is both to quantify activity along the Imperial fault and to identify any transient deformation episodes associated with the volcanic and hydrothermal activity within the Salton Trough.

Sean Buckley, *Univ. of Texas at Austin*: We will make use of the data for InSAR time series analysis algorithm development (e.g., PSInSAR). Our intent is to share processing techniques and software with the user community. We are also pursuing investigations of land subsidence and aquifer modeling in several locations including the Gulf of Mexico coast. The vegetation and atmospheric effects in coastal areas require advanced InSAR processing predicated on a regular acquisition campaign.

3.2 Teaching Activities using WInSAR data at UNAVCO

Integration of teaching and research is best measured by the planned teaching activities making use of the WInSAR archive. Teaching plans for courses using WInSAR data are:

Caltech - Mark Simons, GE193 - Applied Tectonic Geodesy, GE166 - Radar Imaging of the Earth for Geoscience Applications

Cornell - Matt Pritchard, EAS 731: Graduate seminar on Ground water, surface deformation and InSAR, 5 graduate students in two departments (Earth & Atmospheric Sciences and Biological & Environmental Engineering) each completed a term project with actual WInSAR data processed data with ROI_PAC.

Georgia Institute of Technology - Andrew V. Newman, Modern Geodetic Methods (Fall 2006): Using WInSAR data from the Hector Mine Earthquake I developed a series of web pages that outline InSAR processing using the ROI_PAC software.

San Diego State University **–** Mellors, Computer applications for geologists, (GEOL 300), undergraduate course that covers all aspects of the geosciences including remote sensing and image analysis. Topics in Geophysics, (GEOL 630), graduate level course on select topics. INSAR and GPS processing is topic of the 2007 semester.

Scripps Institution of Oceanography – Fialko and Sandwell, SIO239 Radar Interferometry and ERTH135/SIO236 Satellite Remote Sensing. In SIO239, each student makes an interferogram using data from the WInSAR archive.

Stanford University – Zebker, EE254 Radar Principles is offered each year.

University of California, Berkeley **–** Burgmann, EPS 116 - Structural Geology and Tectonics, Processing and analysis of WInSAR data is an option for the research projects required of graduate students taking my EPS216 Active Tectonics course. I also incorporated results from our and other WInSAR research projects in a number of lectures in our general undergraduate intro course EPS050 Planet Earth.

Univ. of California at Los Angeles - Gilles Peltzer, ESS 162-262: Adv. Remote Sensing.

University of Miami - Falk Amelung, Satellite Radar Interferometry in the Earth Sciences Geophysical Inverse Theory

University of Nevada Reno - Bell: Department of Geological Sciences and Engineering has added a graduate level course titled "Radar imaging—Geoscience applications" that draws extensively on WInSAR data for instructional purposes.

University of Oregon - David Schmidt, An upper-division undergraduate course in Radar Interferometry where students process WInSAR data as part of their course project.

Univ. of Texas at Austin – Buckley, An annual grad level course in which WInSAR data over several locations are used as part of class projects. These data provide students with hands-on experience processing both earthquake and subsidence InSAR data sets. Attended by geological science and aerospace and electrical engineering students.

Western Michigan University - Ricky Becker, We have started using WInSAR data in the remote sensing course at Western Michigan University (GEOS 5210, Remote Sensing Applications in Geological and Environmental Sciences), in the new section of the course covering radar interferometry.

Western Washington University – Crider, We anticipate WInSAR data being used for student projects within the context of new courses; these courses will focus on (1) active tectonics and (2) geological remote sensing."

3.3 STUDENT THESES USING WINSAR DATA 2000 - 2006

A second measure of the integration of research and teaching is the number of student theses making use of the WInSAR facility. We expect student data usage to increase during the next 3 years to reflect the expanding membership and archive.

Baek, S., DEM generation and ocean tide modeling over Sulzberger Ice Shelf, West Antarctica, using synthetic aperture radar interferometry, Ohio State U., August 2006.

Baessler, M, On the determination of 3-D ice stream velocity fields in Antarctica using interferometry from multiple SAR sensors, The Ohio State University, August 2001.

Baker, S. PhD, 2006, Volcano spreading and the magmatic systems of the Hawaiian volcanoes, University of Miami

Boisvert, Alex, 2001, Synthetic Aperture Radar Coherence Study of San Diego County and Interferometric Study of Deformation along the Coyote Creek fault, California. M.S. Thesis, San Diego State University.

Buckley, S. M., Radar Interferometry Measurement of Land Subsidence, Ph.D. dissertation, The University of Texas at Austin, 2000.

Cochran, E., UCLA, PhD in 2005.

Chen, C., Statistical-cost Network-flow Approaches to Two-dimensional Phase Unwrapping for Radar Interferometry, Ph. D. Thesis, Stanford Univ., June 2001.

Gudipati, K., Long-Term Subsidence Monitoring Using Synthetic Aperture Radar Interferometry, Masters thesis, The University of Texas at Austin, 2003.

Hoffmann, J., The Application of Satellite Radar Interferometry to the Study of Land Subsidence Over Developed Aquifer Systems, PhD Thesis, Stanford, January 2003.

Jackson, J. Integrated Space Geodetic Study of Ground Deformation over the Socorro Magma Body, New Mexico, MS thesis, Georgia Institute of Tech., summer 2007.

Jonsson, S., Modeling Volcano and Earthquake Deformation from Satellite Radar Interferometric Observations, Ph. D. Thesis, Stanford Univ., June 2002.

Johanson, I. (2006) Slip Characteristics of San Andreas Fault Transition Zone Segments, 160 pp. University of California, Berkeley.

Lin Liu, Physics department, University of Colorado.

Leuro, E., Radar Interferometry Measurement of Land Subsidence in El Paso,Texas, Masters thesis, The University of Texas at Austin, 2004.

Lyons, S. N., Investigation of fault creep in southern California using InSAR and GPS, Ph. D. Thesis, 237 pp, Scripps Inst. of Oceanography, La Jolla, CA, 2002.

Marsic, S., Active Deformation at Canyonlands National Park: Distribution of Displacements Across the Grabens Using Spaceborne Geodesy, MS Thesis, USC,‘03.

Pickard, Stacy, Subsidence in Borrego Springs as Observed by InSAR, Undergraduate thesis, San Diego State University, 2005.

Price, E., Coseismic and postseismic deformation associated with the 1992 Landers, CA, earthquake measured by SAR interferometry, PhD Thesis, Scripps Inst of Ocean., ‘99

Pritchard, M. E., Recent crustal deformation in west central South America, Ph.D. thesis, Calif. Inst. Technol., Pasadena, 2003

Samsonov, S., Integration of Differential InSAR and GPS measurements for studying surface deformation, PhD thesis, March 2007, University of Western Ontario.

Schmidt, D.A., The kinematics of faults in the San Francisco Bay area inferred from geodetic and seismic data, Ph.D. thesis, University of California, Berkeley, 2002.

Shacat, C. University of Hawaii, MS thesis 2006.

Davis Thomsen, Monitoring Ground Subsidence due to Groundwater Withdrawal at Buckman Wells, New Mexico using InSAR, MS Thesis, Scripps Inst. of Ocean., 2005

Utley, J.A., 2004, Using InSAR and GPS to detect subsidence in Pahrump Valley, southern Nevada and California: M.S. thesis, University of Nevada, Reno, 91 p.

van Zandt, Afton, Creep measurements and depth of slip along the Superstition Hills faults as observed by InSAR, Undergraduate thesis, San Diego State Univ., 2006.

Watson, K., SIO InSAR Cookbook and investigations of the Newport-Inglewood fault zone, M.S. Thesis, Scripps Institution of Oceanography, 107 pp., 2001.

4. WORK PLAN

4.1 DEVELOP A ROBUST MULTI-SATELLITE SAR DATA ORDERING, DISTRIBUTION AND ARCHIVING SYSTEM

This task is focused on reducing the time and effort spent by individual investigators navigating the software tools and bureaucracy associated with ordering data from each of the satellite SAR data providers. The goal is to develop a single Internet-based interface for members to peruse, order and retrieve SAR data from any one of a number of satellites. It should include (1) a subsystem for data delivery, with a data search and order interface that includes selection by baselines values and an on-line L0 archive in a specified format; and (2) a procedure for near timely acquisition and processing in the event of an earthquake.

The current searching and ordering capability served us well in the era of the ERS spacecraft but needs updating to accommodate new missions and imaging modes. For example, the current WInSAR website provides searching capability for *ERS-1*, *ERS-2* and *Envisat* data. However, only *ERS* requests can be made through the current system. The European Space Agency requires a different ordering process for *Envisat* data. Ordering *Radarsat*, *ALOS* and future *TerraSAR-X* data will each require yet another ordering process. Our intent is to make these issues as transparent as possible to the user.

We are addressing these issues on two fronts. First, investigators with the most experience with a given data provider are working closely with UNAVCO staff to document the data ordering process. Second, we have formed a Standards and Formats subcommittee to make recommendations to UNAVCO staff to streamline the ordering process and establish distribution and archiving strategies that will work for existing and future SAR missions. The UNAVCO Archivist will handle the smooth running of tasks such as request tracking, order submission, receiving and ingesting data and maintaining the database contents. The Archivist will work with the various space agencies to gain expertise in their ordering systems to ensure data are ordered and delivered in a timely way.

Specific tasks under this objective for the UNAVCO programmer are to expand current capabilities in several areas.

- The current archive and requesting system is based on *ERS* and *Envisat* track-frame paradigm. However, *Envisat* data are also provided in a swath or strip format. The programmer will refine the current WInSAR database to fully incorporate *Envisat* track-frame and swath/strip data requests and to enable ingestion of *Envisat* swath and strip data files. The programmer will add order request capability for *Envisat* data.
- The programmer will add the capability for WInSAR users to place *ALOS* and *Radarsat* order requests, and to ingest *ALOS* and *Radarsat* data files. This will involve close collaboration between the UNAVCO programmer and WInSAR investigators experienced with handling *ALOS* and *Radarsat* data to properly expand the database.
- To facilitate data selection and tasking, the programmer will develop a web GUI for users to work with consisting of a unified spatial view of current holdings and future acquisition tasking for all satellite systems and modes. This view will include selection capability.

4.2 PURCHASE NEW DATA BOTH GLOBALLY AND OVER NORTH AMERICA

Western North American science investigations remain a high priority within WInSAR and will continue to constitute a majority of our scientific publications. In fact, the number of western North America scientists and investigations motivated the formation of GeoEarthScope (GeoES) to arrange for the acquisition of aerial and satellite imagery of this region. Over the next 18 months, UNAVCO will use GeoES funds to purchase SAR imagery over western North America in support of EarthScope. WInSAR users have the option at any time to join the GeoES user group for a given study site and gain access to these data. The software infrastructure development envisioned in this proposal will provide a search and download mechanism for either WInSAR or GeoES-purchased data. The UNAVCO programmer will collaborate with GeoEarthScope personnel so that both GeoEarthScope and WInSAR users benefit from completion of software development tasks. As GeoES funds ramp down, the out years of this proposal increase data purchases to continue our western North America acquisitions. These data will constitute a nearly two-decade multi-satellite interferometric time series.

Consistent with the WInSAR transition to global investigations, an emphasis will be placed on using the funds from this proposal to purchase data outside the western North America region. These data purchases will complement the GeoES western North America purchases and will expand the WInSAR collections to facilitate science on the seismic cycle throughout the world, global volcanic activity, groundwater and coastal hazards, mountain building, rifting, and InSAR noise source mitigation and time series analysis.

As in the past, scheduling and purchases of new data for the WInSAR archive is based on requests from individual users. One of the roles of the WInSAR EC is to balance the data requests with the available funding.

4.3 WORK TOWARD OPEN-SOURCE COMMUNITY INSAR SOFTWARE

There are a variety of open source and commercial InSAR processing packages available today, each with their own input/output conventions. Quantitative comparisons of these various packages are needed to enhance the reliability and credibility of InSAR results, especially when advanced methods such as time-series analyses are being developed. However, these comparisons require common formats and standards as well as a supported open-source software package. We propose to work toward open-source community InSAR software. Models in other communities include MB-System which is used to process interferometric sonar data from a variety of instruments mounted on hundreds of different shipboard platforms (www.ldeo.columbia.edu/res/pi/MB-System). MBSystem relies heavily on the open-source GMT software (http://gmt.soest.hawaii.edu). Virtually all science users and most commercial users rely on these two systems for their multibeam sonar processing needs. The GPS community went through a similar transformation by developing the Receiver Independent Exchange Format (RINEX) in 1989. Although a variety of GPS processing packages are available, they all ingest data in the RINEX format. The availability of this common format facilitates cross-comparison of GPS navigation and positioning results. While it may not be feasible or desirable to have the global InSAR community use a single software system, we propose the following:

1. Provide completely open interferometric test data sets for benchmarking codes. This will involve selection of suitable interferometric pairs of *ERS-1/2*, *Radarsat*, *Envisat*, and *ALOS* data. JAXA has already agreed to make a suitable *ALOS* pair openly available on their web site.
2. Process these interferometric pairs using open-source codes and provide sample outputs on the UNAVCO web site.
3. Advocate for a common WINEX input data format and possibly some standards on output data format for direct comparison of results.
4. Hold a workshop to benchmark InSAR codes and discuss ancillary data (orbits and corrections) as well as software developments such as ScanSAR interferometry and polarimetric InSAR.

Tasks 1-3 will be carried out by UNAVCO staff in collaboration with WInSAR scientists. For task 4, we will propose to host a workshop at UNAVCO. This will involve a future proposal to help pay for the travel of the participants and the organizational effort at UNAVCO.

5. FACILITY TECHNICAL CAPABILITIES AND SCIENCE IMPACT

As discussed above the WInSAR distribution and archive facility is now hosted by UNAVCO. UNAVCO has significant experience maintaining and distributing geodetic-quality GPS time series data for the crustal dynamics community. Previously the WInSAR facility was maintained by volunteer efforts of the WInSAR Executive Committee using small amounts of funding provided by the Southern California Earthquake Center. The size and scope of WInSAR has grown so that a software engineer/archivist will be needed to maintain the operation and provide adequate response to user requests. Hosting both the GPS data and the InSAR data at the same location will have important scientific benefits since the data sets are highly complementary. The future placement of GPS antennae can be guided by InSAR analysis of site stability. The errors in the InSAR interferograms can be more thoroughly characterized when the users can visit one site for both data sets. UNAVCO has a history of hosting completely open access to all data. The WInSAR archive has restrictions and the UNAVCO technicians and scientists will work with the various space agencies to provide the most free and open access to SAR data allowed by data providers. Better and more open InSAR data access will enable US scientists to pursue the scientific challenges of the next three years.

6. RESULTS FROM PRIOR NSF, NASA AND USGS SUPPORT (EAR-0425887 $450,000 - OCTOBER 1, 2004 TO JUNE 30, 2006)

The WInSAR Consortium was funded to purchase and archive *ERS* SAR data covering the arid areas of Western North America. Three agencies provided yearly support ($50K-NASA, $50K-NSF and $50K-USGS). Approximately 2200 scenes were obtained and made available by ftp to WInSAR members. These funds also paid for regular scheduling of *ERS-2* and *Envisat* SAR acquisitions over areas of scientific interest including: the Los Angeles Basin, the San Francisco Bay area, much of the southern San Andreas fault zone, Long Valley Caldera, the Mojave Desert and other areas of tectonic/volcanic interest.

Example WInSAR Results. Highlights of WInSAR results were compiled by Howard Zebker (previous WInSAR Chair) for the interagency InSAR meeting at the Fall 2006 AGU meeting in San Francisco. http://winsar.unavco.org/newsletters/winsar2006review.ppt. Papers published using WInSAR data are listed in the reference section of this proposal.

NSF Cooperative Agreement EAR-031760, "Support of UNAVCO Community and Facility Activities", 7/1/2003–9/30/2007, $13,009,777. PI: Charles M. Meertens.

UNAVCO, Inc. is a non-profit membership-governed organization that supports and promotes Earth science by advancing high-precision geodetic and strain techniques such as the Global Positioning System (GPS), InSAR, and borehole strain and tiltmeters. There are currently over 90 UNAVCO Members and Associated Members. Through this core NSF Cooperative Agreement, UNAVCO operates a Facility that provides engineering, an equipment pool, data, archiving, and information technology support to NSF (EAR and OPP) - and NASA-funded peer-reviewed projects. The Facility supports peer-reviewed science projects of research investigators who individually, or in large collaborative projects (such as the *PBO Nucleus* or even larger, multi-disciplinary, multi-agency *EarthScope MREFC*) study Earthquake processes, mantle properties, active magmatic systems, plate boundary zone deformation, intraplate deformation and glacial isostatic adjustment, global geodesy and plate tectonics, global change, and polar processes. Additionally, UNAVCO supports UNAVCO Community activities including bi-annual national Science Workshops, short courses at the Facility, external advisory committee meetings, and support for education and outreach activities. Detailed reports of UNAVCO Facility activities and PI projects supported can be found at: http://www.unavco.org/pubs_reports/reports/reports.html.

7. EDUCATION AND OUTREACH

The NSF-funded RESESS program (Research Experiences for Students in Solid Earth Science) at UNAVCO recruits interns from underrepresented populations and provides a research experience, a learning community, and various mentoring experiences with the intent of identifying talented undergraduates and nurturing their academic careers through the Masters Degree. RESESS can include faculty mentors from the WInSAR research community and select interns who are interested in this area of study.

In developing curricular materials for upper level undergraduates, introductory students in general education in colleges and universities, and in the Earth science classroom, the visual nature of InSAR imagery is a natural complement to GPS time series. UNAVCO is in the process of developing these materials. The integrative nature of using various tools brought to bear on one problem is a high priority for science education.

There is considerable interest in traveling exhibits for a variety of venues to address the science supported by UNAVCO. Through the installation and management of the Plate Boundary Observatory (PBO), the geodetic component of EarthScope, UNAVCO has developed contacts with numerous local, regional, and national parks that are eager for exhibits on the science advanced through UNAVCO support.

The UNAVCO strategic plan includes working with IRIS to include the science of UNAVCO within their portable museum exhibit.

- The UNAVCO Education & Outreach Program can be a liaison between the WInSAR scientific community and schools, parks and other venues in which this exhibit would be appropriate. For example, UNAVCO is working with the Johnson Ridge Visitor Center at the Mt. St. Helens National Monument. They are redesigning their exhibits, and fascinating images of Mt. St. Helens would fit well within their proposed exhibit.
- UNAVCO will act as a broker between this project and scientists at UNAVCO member institutions who can benefit by this project by addressing broader impact for an individual's research.
- We can help sustain this program past the funding period by incorporating this exhibit into UNAVCO's Education and Outreach program as appropriate, and helping to disseminate the availability of this exhibit to individual researchers who can help fund exhibits at their local institutions, funded by their institutions or their own research grants. The minimal cost of a unit is an efficient way to provide research to local audiences.

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Budget Justification

The WInSAR Archive is funded by three agencies: NSF, NASA and the USGS. We are requesting $150K per year for data acquisitions and for new infrastructural development of the WInSAR data ordering, ingestion, and distribution system, to be divided equally among the three agencies. We request that each agency contribute $50K per year, a level consistent with prior funding for WInSAR. If this proposal is funded, NASA will transfer $50K per year to NSF to co-fund this work. This component of the proposed activities (NSF and NASA combined) is therefore for $100K per year. A separate request is being made to the USGS for the remaining $50K.

The WInSAR Archive has functioned as a data selection (for ordering) system and a data distribution system with a web interface for users. The holdings catalog is capable of handling scenes from the European Space Agency (ERS and ENVISAT). The WInSAR Archive needs software and database development work to support the expansion of the cataloging of swath-based data from ENVISAT, and swath or scene based data for Radarsat and ALOS. The WInSAR function that provides data selection for ordering and tasking needs to be broadened to include capability for displaying all SAR platforms. These tasks will be performed by UNAVCO software and database development staff. The software development is phased out in the third year of the proposal. Archivist support is included for all three years. The Archivist will handle placing and tracking orders, incoming data management, data ingestion, metadata management, and user support.

The first and second year budgets are the same. Salaries and fringe are included for a software developer (6 months) and an Archivist (3 months), and make up 46% of the total modified direct costs. The developer will expand the Archive software to provide the enhanced capabilities described above. The Archivist will handle ordering and data management. To foster understanding with the international space agencies providing the data, 1% of the total modified direct costs will go towards travel for a WInSAR scientist to visit one of the Agencies. The remaining 54% of the total modified direct costs in the first and second years will go toward data acquisitions described below.

The third year budget includes continued Archivist support, but no longer includes software development support. Salaries and fringe for the Archivist (3 months) will make up 12% of the total modified direct costs. The remaining 88% of the total modified direct costs in the third year will go toward data acquisitions described below.

Prior support for WInSAR included funds primarily for data acquisitions. For this proposal, significant personnel costs as described above are requested. Each year, remaining funds after personnel and travel costs will be used for data acquisitions. While WInSAR expenditures for data acquisitions are reduced, this reduction is offset by the availability of SAR data through two other avenues. First, during 2007-2008, GeoEarthScope has significant funds intended for purchase of western US SAR data. Second, an interagency consortium including NASA, NSF and USGS has provided significant funds for the purchase of global JAXA (Japanese Space Agency) ALOS data through the Alaska Satellite Facility. WInSAR investigators will have access to data acquired through these avenues.

WInSAR Archiving and Development Budget									
Project Time Period	2008		2009		2010		Total Cost		Total Project Costs
10/1/2007 to 9/30/2010	NSF	NASA	NSF	NASA	NSF	NASA	NSF	NASA	
Salaries									
Software Engineer (4,4,0 mos)	10,000	10,000	10,300	10,300	-	-	20,300	20,300	40,600
Archivist (2,2,2 mos)	3,333	3,333	3,433	3,433	3,536	3,536	10,303	10,303	20,606
Total Salaries	13,333	13,333	13,733	13,733	3,536	3,536	30,603	30,603	61,206
Full Benefits (53.25% for FY 2007)	7,100	7,100	7,313	7,313	1,883	1,883	16,296	16,296	32,591
Total Salaries and Benefits	20,433	20,433	21,046	21,046	5,419	5,419	46,899	46,899	93,797
Purchased Services									
Scenes purchase (outside of GeoEarthScope areas)	24,000	24,000	22,000	22,000	38,000	38,000	84,000	84,000	168,000
Total Purchased Services	24,000	24,000	22,000	22,000	38,000	38,000	84,000	84,000	168,000
Travel									
Domestic (1 trip, 1 traveler, Fairbanks)	500	500	-	-	-	-	500	500	1,000
Foreign (1 trip, 1 traveler)[1]			500	500	-	-	500	500	1,000
Total Travel	500	500	500	500	-	-	1,000	1,000	2,000
Total Direct Costs	44,933	44,933	43,546	43,546	43,419	43,419	131,899	131,899	263,797
Modified Direct Costs									
Total Direct Costs	44,933	44,933	43,546	43,546	43,419	43,419	131,899	131,899	263,797
Modified Total Direct Costs (MTDC)	44,933	44,933	43,546	43,546	43,419	43,419	131,899	131,899	263,797
UNAVCO Indirect Rate[2]	4,943	4,943	6,532	6,532	6,513	6,513	17,988	17,988	35,975
TOTAL	49,876	49,876	50,078	50,078	49,932	49,932	149,887	149,887	299,772

Notes:

[1]One trip, one traveler ESA, Frascatti, Italy, or JAXA, Tsukuba, Japan

[2]The estimated UNAVCO On-Site Indirect rate is 11% for FY 2008, 15% for FY2009, 15% for FY2010

UNAVCO Facilities

UNAVCO, Inc. is a non-profit membership-governed organization that supports and promotes Earth science by advancing high-precision geodetic and strain techniques such as the Global Positioning System (GPS), InSAR, and borehole strain and tiltmeters. There are currently 97 UNAVCO Members and Associate Members. WInSAR voted to make UNAVCO their new host institution in early 2006. WInSAR's overall mission, organizational structure, and research activities did not change with the transfer of administration from its prior host, SCEC/USC, to UNAVCO. UNAVCO's primary role in WInSAR is to provide administrative and logistical support for WInSAR activities such as finance management and data management. The WInSAR Executive Committee and UNAVCO are currently finalizing the process of establishing WInSAR's new administrative framework at UNAVCO.

The proposed WInSAR archive development and data acquisition builds upon extensive UNAVCO Facility expertise in data management for GPS as well as InSAR-specific capabilities being developed as part of GeoEarthScope. UNAVCO’s broader expertise includes managing an extensive GPS equipment pool, onsite factory-certified equipment repair, field engineering, managing and archiving GPS and InSAR data and products, providing software tools, and continuously updating and improving best practices in all these areas.

Through a core NSF Cooperative Agreement UNAVCO operates a Facility that provides engineering, equipment, data management, archiving, and information technology support to NSF (EAR and OPP Antarctic and Arctic programs)- and NASA-funded peer-reviewed projects. The Facility supports peer-reviewed science projects of research investigators who individually, or in large collaborative projects such as the *PBO Nucleus* or even larger, multi-disciplinary, multiagency *EarthScope MREFC*, to study Earthquake processes, mantle properties, active magmatic systems, plate boundary zone deformation, intraplate deformation and glacial isostatic adjustment, global geodesy and plate tectonics, global change, and polar processes. Additionally, UNAVCO supports UNAVCO Community activities including bi-annual national Science Workshops, short courses at the Facility, external advisory committee meetings, and support for education and outreach activities. Detailed reports of UNAVCO Facility activities and PI projects supported can be found at: http://www.unavco.org/pubs_reports/reports/reports.html.

Data Support

The principal task of the UNAVCO Facility Data Group is to provide data management and archiving services to the UNAVCO Community through the UNAVCO Data Center. The Data Center manages, stores, and provides access to high-precision geodetic and other crustal deformation related data and metadata including all data collected with UNAVCO. Current holdings consist of 3 million files and over 5 Tb. The data are held online on enterprise class RAID systems, and on multiple tape copies, both onsite and offsite. The principal component of the data is the GPS data and products from 1200 continuous GPS sites and 650 GPS campaigns. A recent addition is the WInSAR collection. Data Group personnel include seven professionals, with expertise in data management, software engineering, database programming, database administration and system administration. The Data Group has developed a highly scalable system for archiving continuous GPS data and for community access to the data. The group develops data translators, editors and quality control tools used extensively by the research community. In addition, the Data Group develops applications for on-line database access for metadata searches and interactive map tools that support PI research and education and outreach activities. The Data Group also manages all Facility IT databases for equipment management, project management, inventory, purchasing, and the front-end systems for UNAVCO's financial databases.

Engineering Support

The UNAVCO Facility Engineering Group provides the crustal deformation and Polar science communities with state-of-the-art equipment, facilities, and a highly qualified staff to support individual investigations and large collaborative efforts. The Engineering Group overall provides first level support to approximately 50 core projects annually, plus support on a resource available basis to many additional community projects. By maintaining community based capabilities and best practices for making highly precise measurements of Earth deformation and Polar processes, the quantity and quality of scientific data returned for scientific research is enhanced significantly over what could be accomplished by individual institutions operating independently.

The Engineering Group maintains an equipment pool of approximately 350 state-of-the-art GPS receivers and ancillary equipment, which may be used by investigators on qualified research projects. In addition to the equipment pool, the Engineering Group maintains an extensive support structure to assure the highest quality of data return for scientific research. The group maintains staff and facility capabilities to support the deployment and best practice application of equipment for scientific research. Resources and capabilities include: equipment depot and laboratory facilities for maintaining repairing, testing and deploying equipment; systems integration and software development capabilities for development customized systems; formalized facilities and capabilities for property management, import/export, logistics and shipping; business systems for project financial management, tracking and reporting; staff expertise in project management, field engineering, technical support and training; and established processes and procedures for supporting scientific research.