2013 – 2018 UNAVCO Community Proposal
Geodesy Advancing Geosciences and
EarthScope:
GAGE Annual Project Report

Year 4: 01 July 2016 - 30 June 2017

EAR – 1261833

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Geodesy Advancing Geosciences and EarthScope: GAGE Annual Project Report

Year 4 reporting period: 01 July 2016 - 30 June 2017

0. Introduction (Miller)

Herein we report the activities of the 4th year (GAGE Y3Q4-Y4Q3) of the 5-year UNAVCO Cooperative Agreement 2013 – 2018 UNAVCO Community Proposal Geodesy Advancing Geosciences and EarthScope (EAR – 1261833). This reporting period is offset one quarter from the award year in order to meet reporting deadlines established in fastlane. The Facility, through this Cooperative Agreement (CA), provides engineering, equipment and data services that support research projects for investigators using a spectrum of geodetic techniques to conduct scientific investigations that include the study of earthquake processes, mantle properties, active magmatic systems, plate boundary zone deformation, intraplate deformation and glacial isostatic adjustment, global geodesy and plate tectonics, atmospheric science, global change, polar science, and hydrogeodesy. These projects are NSF-EAR Earth Sciences, NSF-PLR Arctic and Antarctic, and NASA-funded and include individual Principal Investigator (PI) projects, as well as large interdisciplinary collaborative community projects for shared infrastructure and open data sets, such as AfricaArray, GNET, COCONet, and POLENET, and the larger multi-disciplinary, multi-agency EarthScope project PBO network and associated imaging and campaign GPS components.

For more than three decades, UNAVCO has supported geodesy research and education, under a number of administrative structures, and has played an important role in advancing geodesy innovation for science. Since 1984, university partners have shared geodetic instrumentation and data, and have collectively operated facilities to support geodesy research under the auspices of UNAVCO, with lead sponsorship and core funding from NSF and NASA. UNAVCO’s organizational home and management structure evolve to meet the needs of scientists and sponsors. Over the years, additional support from NASA, NOAA, USGS, and others have expanded UNAVCO’s reach and leveraged the core investments.

Geodesy is a global science and UNAVCO plays an important role in international collaborations that realize the modern terrestrial reference frame. Recent international cyberinfrastructure projects such as COOPEUS have built a framework for a sustainable, transatlantic, environmental-research infrastructure and EarthCube. UNAVCO participate in International GNSS System governance and working groups, as well as the European Geophysical Union, American Geophysical Union, WEGENER, and the Scientific Committee on Antarctic Research (SCAR). Several new technologies also drive growth at UNAVCO, both for direct measurement of deformation and for geodetic imaging. UNAVCO’s TLS field engineering and instrument support has matured and operates as a vibrant core activity, although full integration into core funding continues to pose challenges. High-rate, low latency (“real-time”) GPS continues to drive a broad, expanding, and demanding set of applications. Further innovations are seeded by ground-based interferometric radar, autonomous observing platforms for optical observations, formal integration of GPS and InSAR as the new generation of satellites is launched, and many others.

This annual report presents the highlights, activities, and performance metrics for Year 4 of the GAGE award. To assure timely submission, and because the report must be approved prior to the actual year end, the narrative describes work from Y3Q4 through Y4Q3, and metrics include a complete summary of years 1, 2, 3 and a roll up Y4Q1-3. The narrative may also report on some events from Y4Q4. The following appendices are also provided:
1. The UNAVCO Community and Consortium

1.1 THE UNAVCO CONSORTIUM

UNAVCO, a non-profit, university-governed consortium, facilitates geoscience research and education using geodesy. The consortium includes 114 US academic Members, primarily degree-granting institutions, that participate in its governance and science community (Figure 1-1). Another 108 Associate Members include organizations that share UNAVCO’s purpose at home and abroad, giving UNAVCO global reach in advancing geodesy (Figure 1-2). Three new Members (M) and five new Associate Members (AM) joined UNAVCO during the reporting period.

- Full members: Smith College, University of Colorado, Colorado Springs, and California State University, Sacramento
- Associate members: C4G/UBI - The Collaboratory for Geosciences (C4G) hosted at University of Beira Interior (UBI) Portugal, Korea Institute of Geoscience and Mineral Resources, University de La Rochelle, University of Bologna, and University of Waterloo

Figure 1-1: UNAVCO Membership profile. Universities and affiliated research organizations make up UNAVCO’s governing membership, and include major research universities, comprehensive Master’s granting universities, as well as a growing base of selective liberal arts colleges and minority serving institutions.

Figure 1-2. UNAVCO Associate Member profile since incorporation. Associate Members come from around the world. Associate Members share UNAVCO’s purpose and form a global community for scientists who may otherwise be professionally or geographically isolated. This community engages in international partnerships essential to the advancement of global geodesy and UNAVCO’s mission.
Facility Highlights:

UNAVCO publishes summaries of community support and facility projects as Highlights, available on the homepage of the website. Broadly, these summaries provide a sampling of various projects and activities supported by the facility; specifically they showcase outreach activities, education and community focused events, installation of new instrumentation, operations and maintenance summaries, new software and technologies available to the community, and geophysical event responses. During this reporting period 26 Highlights were published with almost a third featuring Data Event Responses.

A full listing of Highlights is available online.

1.2 UNAVCO SCIENCE COMMUNITY

While the UNAVCO consortium comprises 222 institutional Members and Associate Members, its community includes the scientists, educators, and other professionals who are committed to its mission and use its resources. Thousands of individuals from around the world formally interact with UNAVCO on an ongoing basis through its scientific collaborations, governance, science planning coordination, engineering services, data services, and its Education and Community Engagement activities.

1.2.1 Community Publications

The geodesy community publication database is a compendium of science and education publications that have referenced UNAVCO, used UNAVCO equipment or services, or used the UNAVCO-supported NASA Global Navigation Satellite System (GNSS) Network (GN), including data from EarthScope and the Plate Boundary Observatory. The impact of UNAVCO-supported publications are reported with three key metrics (Figure 1-3): (1) number of journals tracks the subdiscipline diversity of UNAVCO-supported projects within the geosciences, (2) the number of individual contributions that reference UNAVCO, its major projects, or other distinctive search terms, and (3) tens of geodesy articles that directly or indirectly rely on UNAVCO’s fundamental contributions that are foundational to any modern study of positioning or imaging geodesy. For instance, every global GPS survey relies on fundamental tools like teqc (developed and supported at UNAVCO) or the ITRF (supported by UNAVCO enhancement and maintenance of the GGN and other key GPS/GNSS stations, and UNAVCO support for coordination of the IGS, etc.). It also includes projects modeled on UNAVCO-developed technologies, such as those deployed in the Plate Boundary Observatory (PBO), such as the national Chinese deformation network BEIDOU whose design was informed by numerous visits and technical exchanges between CEA and UNAVCO. Publications in this last group only rarely references UNAVCO directly. The search uses a larger set of tested criteria in an attempt to capture every high-precision global geodesy paper that relies on UNAVCO fundamentals. The criteria have been refined to minimize spurious results, for instance by only searching a restricted set of subjects and carefully constructed word associations. We expect that in the nearly 1,000 publications found, some outlier papers are included, and some worthy papers are missed. Nonetheless, this metric provides us with a stable and objective proxy of the growth trend in the reach of UNAVCO work. Because the numbers are so large, they are plotted as 10s of publications each year. The complex nature and wide scope of UNAVCO work precludes differentiation of the publications supported specifically by the GAGE award.
Figure 1-3. UNAVCO Geodesy Community Publications, January 2003 through August 2017. Note that 2017 includes only eight months of the year.

1.2.2 Publications, Abstracts, and Other Products Created by UNAVCO Staff
Publications and conference abstracts by UNAVCO staff are available in research.gov. In addition, UNAVCO staff produced other materials in service to the community including data DOIs, technical documents accessible to the community via the Knowledge Base, and web Highlights and Science Snapshots (Table 1-1).

Table 1-1. GAGE Facility products; award to date.

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<thead>
<tr>
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<tbody>
<tr>
<td>Datasets Published by DOI</td>
<td>1820</td>
<td>1051</td>
<td>246</td>
<td>368</td>
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<td>Knowledge Base Documents Create</td>
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<td>108</td>
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<td>Science Snapshots Published</td>
<td>9</td>
<td>14</td>
<td>15</td>
<td>15</td>
<td>53</td>
</tr>
</tbody>
</table>

1.2.3 Broader Impacts for Community, Governance and Management

UNAVCO Websites
UNAVCO staff manage multiple websites in service to the community. Websites are accessed by the UNAVCO community, broader science community, educators, students and the general public (Table 1-2). UNAVCO websites are managed by the Web Team (Web Editor in Chief and Web Administrators), Section Editors, and staff subject matter experts who contribute web content. Content for the seven main sections of the primary UNAVCO website (Community, Projects, Instrumentation, Data, Software, Science, and Education) are the responsibility of seven Section Editors.

Table 1-2. GAGE to date activity for the primary UNAVCO websites. The number of users metric quantifies the number of different site visitors. Total number of sessions quantifies the number of visits to the website separated by > 0.5 hr. Number of “page views” quantifies the number of
**UNAVCO Outreach and Impact**

UNAVCO outreach activities are conducted by UNAVCO staff across all programs. Staff regularly interact with the public, stakeholders, National Park Service staff, schools, and other similar groups. Table 1-3 summarizes the numbers of events conducted and Table 1-4 summarizes individuals reached. Large event visitors include visitors to the PBO/GPS museum display at the Hatfield Marine Science Center and interactions at the USA Science and Engineering Festival. Other interactions are of higher duration and impact, but smaller overall in number.

UNAVCO makes a substantial investment in participation in the annual meetings of GSA and AGU both in the form of presentations and an exhibit booth. The exact number of interactions is difficult to document. Attendance at the GSA annual meeting is typically over 5,500 and the AGU Fall Meeting is on the order of 24,000. Interactions include community members, other scientists, researchers and students. UNAVCO also had an exhibit presence at the 2017 Seismological Society in Denver, where staff connected with geosists, and with students who could benefit from UNAVCO resources and services, and the integration of geodetic and seismic data.

**Table 1-3. Activities and products for all UNAVCO Programs (GI, GDS, ECE).**

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<tbody>
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<td>Short Courses</td>
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<td>28</td>
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<tr>
<td>Workshops and Outreach Events</td>
<td>56</td>
<td>43</td>
<td>54</td>
<td>33</td>
<td>186</td>
</tr>
<tr>
<td>Internship Programs</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>11</td>
</tr>
</tbody>
</table>

**Table 1-4. Number of people reached through the activities identified in Table 1-3, organized by audience.** Researchers and research faculty includes most faculty who do not teach; university and college faculty includes tenure and non-tenure track faculty whose work typically includes teaching, research, and service. Other Professionals include those who do not identify as faculty or in the pipeline categories. Examples of Other Professionals include Emergency Managers, Park Interpreters, Federal Agency staff, and Sponsors. Large event visitors are individuals visiting museum displays and conference exhibit booths.

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<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Researchers + Research Faculty</td>
<td>146</td>
<td>81</td>
<td>146</td>
<td>52</td>
<td>425</td>
</tr>
<tr>
<td>University + College Faculty</td>
<td>288</td>
<td>125</td>
<td>213</td>
<td>98</td>
<td>724</td>
</tr>
<tr>
<td>Post-docs</td>
<td>42</td>
<td>19</td>
<td>160</td>
<td>4</td>
<td>225</td>
</tr>
<tr>
<td>Graduate Students</td>
<td>166</td>
<td>209</td>
<td>459</td>
<td>27</td>
<td>861</td>
</tr>
<tr>
<td>Undergraduate Students</td>
<td>234</td>
<td>163</td>
<td>239</td>
<td>127</td>
<td>763</td>
</tr>
<tr>
<td>Public / K-12 Students</td>
<td>178</td>
<td>144</td>
<td>729</td>
<td>418</td>
<td>1469</td>
</tr>
<tr>
<td>K-12 Faculty</td>
<td>207</td>
<td>149</td>
<td>442</td>
<td>207</td>
<td>1005</td>
</tr>
<tr>
<td>Other Professionals</td>
<td>389</td>
<td>158</td>
<td>242</td>
<td>137</td>
<td>926</td>
</tr>
<tr>
<td>Large Event visitors</td>
<td>113,137</td>
<td>69,550</td>
<td>78,882</td>
<td>40,936</td>
<td>302,505</td>
</tr>
</tbody>
</table>
2. Geodetic Infrastructure Program

2.0 GI Program Highlights for GAGE Y4

PBO Staff Rebuild Station Destroyed by Chimney Wildfire in 2016
In August of 2016, P278 was destroyed by the Chimney wildfire in coastal Central California. The station had been constructed during the San Simeon M6.5 December 22, 2003 earthquake response and had been running continuously since January 2004. Logistics for rebuilding the site were challenging because site access required a helicopter and the extent of the damage to the station was unknown. The extremely long fire season prevented UNAVCO from chartering a helicopter and access the site until November 2016.

The site was in rough shape, with all non-steel parts destroyed (Figure 2-1a). The composite radome on the GNSS antenna was melted into a pile of sludge, cables melted inside conduits, and the solar panels were shattered into tiny pieces. The aluminum equipment enclosure was mostly vaporized and the solar batteries melted. The short-drilled braced monument, the enclosure post, and the solar panel brackets survived and thus could all be reused. We used the opportunity to upgrade this remote, helicopter-only accessible site with a new GNSS antenna and Septentrio PolaRx5 receiver. Once the repairs were completed, the station was again back online (Figure 2-1b).

Figure 2-1a. The GNSS antenna at PBO station P278 after the Chimney Fire in August, 2016; clearly a bit worse for wear (Photo: C. Walls/UNAVCO).
Figure 2-1b. P278 after all repairs were completed (Photo: C. Walls/UNAVCO).

**Alaska 2017 Summer Helicopter Operations**

Alaska summer field season was in full swing during GAGE Y4Q3. Following the EarthScope National Meeting in Anchorage that involved tours and field trips led by UNAVCO staff, the annual helicopter operations push started in early June 2017. The two largest field events included joint operations with USGS-AVO on both Augustine and Unimak Islands. These joint operations continue to be a cost effective way to conduct operations in Alaska.

Most of the Augustine work consisted of battery replacements, including one at Ursus Head, where 56 batteries were replaced. The camp and staging area on Augustine Island was cleaned up, which will make the area more usable for the coming years. Bears were busy and grumpy on Unimak this year as well. UNAVCO engineers replaced 7 solar panels, 1 SCIGN dome, and conducted 1 major hut repair on the island; some of the station repairs were required by damage from bears. All major goals for this field season were met, for example the installation of a new BGAN terminal and antenna at Petrof Lake (Figure 2-2), and all unexpected repairs were also completed.

Figure 2-2. Hut with new BGAN terminal/antenna at PBO GNSS site AC35, Petrof Lake, Alaska. (Photo by K. Austin/UNAVCO).
2.1 GI OVERVIEW

The UNAVCO GI program integrates all geodetic infrastructure and data acquisition capabilities for continuously operating observational networks and shorter-term deployments. Supported activities include development and testing, advanced systems engineering, the construction, operation, and maintenance of permanent geodetic instrument networks around the globe, and engineering services tailored to PI project requirements. The GI program coordinates closely with Geodetic Data Services program (Section 3) to assure the highest standards of data quality control, integrity of metadata, ease and transparency of data access for the UNAVCO user community, and to provide appropriate and timely metrics on data usage for sponsors. Major projects currently supported by the GI program include the 1,112 station Plate Boundary Observatory (PBO), Polar networks in Greenland and Antarctica (GNET and ANET, together known as POLENET), COCONet spanning the Caribbean basin, TLALOCNet in Mexico, the multi-disciplinary AfricaArray, and several other smaller continuously observing geodetic networks. At the close of Y4, the GI group headcount is now 38 with 36.40 FTE, including staff supported by NSF EAR and OPP and NASA. The overall headcount as well as FTE are down 2.0 relative to the close of GAGE Y3. There are no plans to add additional staff to the GI group at this time.

2.2 COMMUNITY AND CONTINUOUSLY OBSERVING NETWORKS

2.2.1 Plate Boundary Observatory and Related Projects

![Map of the NSF Plate Boundary Observatory](image)

Figure 2-3. Map of the NSF Plate Boundary Observatory, the geodetic facility of EarthScope, which includes ~1100 cGPS, 76 BSM, 6 LSM, 79 seismometer, 26 tiltmeter, and 145 surface met stations.

UNAVCO operated and maintained the following instruments in Y4 as part of the PBO network:

- 1132 permanent GPS stations (1100 PBO core, 32 other)
- 76 borehole strainmeters (74 PBO core, 1 NSF Continental Dynamics, 1 DOE CO2 Storage)
- 79 borehole seismometers (78 PBO core, 1 NSF Continental Dynamics)
- 23 borehole pore pressure sensors
- 26 shallow borehole tiltmeters
- 6 long baseline laser strainmeters
- 145 meteorological stations (118 core, 27 NOAA)
- 777 real-time streaming GPS stations (approximate total including ~704 PBO Core/Cascadia, 15 TLALOCNet, 52 COCONet, 5 in Tanzania, 1 in Nepal)

### 2.2.1.1 cGPS Network

The PBO cGPS Operations and Maintenance group (PBO GPS Ops) focused on a number of exciting new initiatives in the past year. Two key areas of focus were: 1) the deployment of Septentrio PolaRx5 receivers, capable of full GNSS tracking, and 2) the upgrade of data communications at a subset of PBO stations to enhance the real-time GPS capabilities of the network. In addition, PBO field engineers continued to maintain the network at a very high level of performance, while also continuing to improve their technical and safety skills.

The PBO GNSS Ops group continued its rigorous field schedule in GAGE Y4, in order to keep the PBO network operating at the high level and while taking on these new initiatives discussed above. In GAGE Y4, the PBO-AK office hosted for a second year a summer intern, Ellen Knappe, a PhD student in geodesy at the University of Montana. Ms. Knappe assisted PBO field crews with PBO maintenance activities in Alaska. PBO engineers conducted 509 PBO GPS site visits, resolving 1155 GPS issues during 862 engineer-days in the field. An additional 88 days of engineer travel involved required meetings and training. Other PBO GPS Ops staff travel included activities related to Rio Grande Rift project support (4 days), and TLALOCNet (101 days) and COCONet (36 days) network support.

### Continued Septentrio and Data Communications Upgrades

In addition to the 100 Septentrio PolaRx5 purchased in FY2016, 15 receivers were purchased in FY2017. These receivers were used as the spare receiver pool for PBO, so that non-operational receivers would not be replaced by the older generation Trimble NetRS or NetR9 receivers. To date, 104 Trimble NetRS receivers have been replaced with the new generation Septentrio PolaRx5 receivers, including 21 from ODOT (see below). With the previously activated GLONASS on 140 Trimble NetR9 receivers (6 deployed to the San Francisco Bay Area with RTX enabled to augment the USGS EEW system), brings the total to 244 GNSS stations network-wide.

Data communications systems were also upgraded throughout the PBO network in order to increase data transfer rates allowing the higher data volumes required to stream the high-rate, multi-constellation data. These upgrades focused on the installation of new hardware to improved various radio networks including Augustine Volcano, Mt. St. Helens, Yellowstone, Mt. Susitna, and Steens Mountain. Data communications were also improved at the PBO station (VDNP) on the Vandenberg Air Force Base and at PBO stations in and around Parkfield, CA. In many locations, cellular communications were replaced by faster radio networks, which are expected to be more reliable during a large earthquake. In other locations, radio antennas were hardened and equipment was treated with icephobic paint to help reduce rime ice build-up in the winter.

### PBO Collaborations (ODOT, IRIS, USGS, and NOAA)

UNAVCO continued to work closely with a number of agencies to take advantage of existing and potential synergies. In Alaska, for example, UNAVCO entered an MOU and partnered with the Alaska Ocean Observing System (AOOS) to establish GNSS stations for ocean tide measurement, with the first station slated for installation in September 2017. UNAVCO is also partnering with NOAA to place meteorological instruments at 20-30 PBO stations in Alaska, likely in the 2018 field season. Also, as part of an MOU with the Oregon Department of Transportation (ODOT), UNAVCO deployed Septentrio PolaRx5 receivers (purchased by ODOT) at three PBO stations in FY2017.

In FY2017, UNAVCO was funded by USGS to support the integration of PBO RT-GNSS observations into the ANSS ShakeAlert, a production Earthquake Early Warning system for the high-risk metropolitan regions of Washington, Oregon, and California. The proposal was designed to ensure successful integration of GNSS observations into ShakeAlert by providing robust and reliable high-rate GNSS data transmission before, during, and immediately after a large (>M7) seismic event.
PBO-AK staff also continued to work closely with the USGS-Alaska Volcano Observatory (USGS-AVO), IRIS Transportable Array (TA), the Alaska Earthquake Center (AEC), the University of Alaska-Fairbanks, and the NOAA National Tsunami Warning Center to support joint operations, share resources, and to streamline work in Alaska making it more cost effective for all the institutions. In preparation for the summer joint operations in Alaska, PBO staff participated in an end of season review of joint operations (Fall 2016) as well as a joint operations planning meeting (Spring 2017) with the IRIS Transportable Array, AEC and USGS-AVO. These meetings allowed PBO management to identify areas of success as well as areas for improvement which resulted in the completion of all maintenance targets in Alaska on-schedule and under-budget.

**Other Network Support**
UNAVCO staff continued to support the TLAOCNet, COCONet, and Rio Grande Rift projects. Engineers completed the installation of station CN26, in the Parque Nacional de Arrecife Alacranes, Mexico for COCONet. This station represents the final (54th new station installed to date) eGPS-Met station completed as part of the construction phase of the COCONet project, a significant milestone for UNAVCO. The installation of 54 new eGPS station exceeds the project original project goal of 50 new stations.

2.2.1.2 Borehole Geophysics
The Borehole Geophysics program, which includes PBO BSM Operation and Maintenance (PBO BSM Ops), has continued to thrive over the course of GAGE Y4 with continued operations and maintenance of PBO and borehole stations in Oklahoma (DOE), Turkey (GeoGONAF), and Montserrat (CALIPSO, now part of COCONet).

Other activities in GAGE Y4 include upgrades to power and communications. In GAGE Y3 the PBO BSM Ops team evaluated each site for its data integrity and usability as the PBO BSM network approaches nearly 15 years in age. In GAGE Y4Q1, Mick Gladwin of GTSM Technologies visited UNAVCO to finalize the transition from UNAVCO’s dependence on GTSM to repair some key components of the uphole electronics, including the ability to make adjustments to extend the life of gradually degrading downhole strain gauges. At the close of GAGE Y4, UNAVCO now operates independently of GTSM, although Mick remains available for consulting as time permits.

UNAVCO was funded by a subaward from a DOE proposal with Prof. Larry Murdoch at Clemson, which includes UNAVCO engineering effort to install a new borehole instrument package (from the PBO MREFC cache of remaining instruments) in Oklahoma and to develop new ways to remove anthropogenic and natural hydrologic signals with a focus towards improved monitoring of CO2 sequestration reservoirs. Both a GTSM borehole strainmeter and the new instrument package were successfully installed in GAGE Y4 yielding promising results both in the ability to monitor sequestration reservoirs and events as well as demonstrating new borehole strain technology that could be an order of magnitude less expensive than current techniques.

2.2.1.3 Long Baseline Laser Strainmeter Subaward: UC San Diego
UCSD operates and maintains six long baseline laser strainmeter (LSM) instruments for the PBO network through a subaward administered by UNAVCO. UCSD also analyzes the data from these instruments and delivers LSM data products to UNAVCO as part of this subaward. Network operation was mostly stable and cumulative data return was good. This level of performance was made possible by extensive efforts by UCSD personnel, including numerous field site visits and equipment repairs made in the lab. Such issues included ongoing equipment (e.g., reference laser) issues as well as weather (e.g. heavy rains and flash floods) related issues that resulted in periods of instrument downtime and data loss. Interesting geophysical signals were recorded at each of the laser strainmeter sites over the past year. Data processing, products and interpretation are discussed in section 3.3.2.

The LSM network will no longer be supported as part of PBO following the close of GAGE Facility on
September 30, 2018. UNAVCO and UCSD personnel worked to develop a closeout plan throughout Y4. The closeout plan will be finalized prior to and implemented in Y5. Also in Y4, UCSD personnel began developing a manuscript describing the PBO LSM network instrumentation and operation, data analysis strategies, procedures and data products implemented, and key findings resulting from PBO/GAGE subaward support, for submission to a peer reviewed journal in Y5.

2.2.1.4 PBO Network Data Return and Data Quality
The PBO network data return target is 85% for all data types except for tiltmeter observations; tiltmeter data return is not held to the same performance standard as the other sensors, as data are obtained only on a best effort basis. The summary for all PBO sensor types is shown in Table 2-1. The time series for data return percentage since the beginning of GAGE is shown in Figure 2-4. To date, PBO cumulative data return from all instrument types has exceeded the data return target.

<table>
<thead>
<tr>
<th>Period</th>
<th>Target</th>
<th>GPS</th>
<th>Seismic</th>
<th>Borehole Strainmeter</th>
<th>Laser Strainmeter</th>
<th>Tiltmeter</th>
<th>Pore Pressure</th>
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<tbody>
<tr>
<td>Cumulative since 2013-10</td>
<td>85%</td>
<td>96%</td>
<td>98%</td>
<td>98%</td>
<td>99%</td>
<td>86%</td>
<td>95%</td>
</tr>
</tbody>
</table>

Table 2-1. PBO network cumulative data return percentage during GAGE (01 October 2013 through 30 June 2017). Cumulative data return from all instrument types exceeded the minimum target value.

![PBO Network Data Return Percentage (01 October 2013 - 30 June 2017)](image)

Figure 2-4. PBO network data return during GAGE (01 October 2013 through 30 June 2017).

2.2.1.5 Real-Time GPS Network Operations
The total number of sites in the UNAVCO RT-GNSS network at the close of GAGE Y4Q3 is 777. The average completeness across the UNAVCO RT-GNSS network was 82% for each month of the GAGE Y4. This value represents an increase of 3% over GAGE Y3. The average median latency across the network throughout Y4 was 190 milliseconds with 25% of the network typically having latency less than 150 ms and 75% of the network having latencies greater than 320 milliseconds. This significant improvement, 100 milliseconds in median latencies over GAGE Y3, is a reflection of the growth of the RT-GNSS network in California, particularly southern California, where communications are good and tend to have low latencies, and where PBO GNSS Ops staff have invested considerable effort to improve telemetry from remote stations (see above).
2.2.1.6 PBO Permitting Report

GAGE Y4 is the busiest and most costly year under the GAGE Facility for re-permitting PBO stations. From GAGE Y3Q4 through Y4Q3, UNAVCO renewed 191 permits, including 41 annual renewals for federal agencies and some native corporations. All permit renewals included an assignability clause. UNAVCO anticipated roughly $290K for permitting renewals during GAGE Y4. As of Y4Q3, UNAVCO has spent just under $57K, and is projected to spend less than $180K by the end of GAGE Y4 as the overwhelming majority of permit fees will get paid in early September 2017. These savings of over $100K are primarily due to no-cost extension agreements with landowners holding permits for several GPS stations originally costing ~$7-10K per station per ten-year agreement. UNAVCO’s permitting staff levels have remained constant at 1.35 FTE.

The permitting forecast for the first five years of NGEO (proposal submitted by UNAVCO and in review at NSF) remains relatively low compared to GAGE Y4 and Y5, at approximately $120K in renewal fees each year. The permitting budget has been smoothed from year to year and increased slightly in order to avoid another drastic increase in renewal payments during the final years of NGEO. By staggering permit periods, the timelines for renewals are projected to be level over the next decade through 2028. GAGE Y5 is projected to have a slightly lower annual permitting renewal cost than GAGE Y4, with 233 permit renewals at an estimated cost of $243K, but will still require significant effort from PBO permitting staff through the end of the GAGE Facility award.

2.2.2 Field Support for the NASA GGN

UNAVCO, in collaboration with the Jet Propulsion Laboratory (JPL), is responsible for the operations and maintenance of the 59 permanent GNSS stations that comprise the NASA Global GNSS Network (GGN). Eighty-eight receivers are operated in the GGN, as 19 stations have multiple receivers connected to a single antenna, including new mult constellation-capable instruments. The new instruments operate side by side with legacy hardware, and receivers that are part of the NASA Space Geodetic Program (SGP). UNAVCO staff, comprising two full-time Engineers and 20% FTE Project Manager, monitor station network connections, ship replacement equipment to site operators as necessary, and construct new permanent sites as directed by JPL. UNAVCO staff work closely with local collaborators at each station for routine maintenance and troubleshooting data flow interruptions, and perform field maintenance and upgrades. Details regarding UNAVCO GGN project support activities during GAGE Y4 are provided in Appendix C: NASA Project Support.

2.2.3 Polar Projects: POLENET

POLENET support is a year-round effort for the UNAVCO Polar team. With telemetered cGPS networks in Greenland and Antarctica, the cycle of monitoring, planning, preparation and field work is continuous and ongoing. GAGE Y4 POLENET GPS network activities for the UNAVCO Polar Support team focused on the preparation and execution of a challenging 2016-17 ANET field maintenance season, and more recently, similar support of the GNET network, including field maintenance, data flow and network monitoring. GPS network engineering efforts in Boulder were directed towards preparation of O&M field kits to enable rapid repair and upgrade of Antarctic and Greenland sites. Because the NSF to support GNET award has closed, GNET has operated in a minimal support mode since field maintenance during GAGE Y2Q4, supporting only data telemetry and monitoring, while plans for the future of the network are explored. A solid maintenance history and a mature technical design have enabled the GNET network to perform well without significant physical intervention by UNAVCO or other technical staff through the end of GAGE Y3 and much of Y4. Funding was provided in Y4 for GNET site maintenance in the northwest and southeast regions of coastal Greenland. Overall GNET data recovery for the 42 sites, measured by data that reaches the UNAVCO archive, is 90.6%. The GNET network is currently 93% operational.
UNAVCO also completed a successful field maintenance season in the Antarctic. By and large the ANET network was in good condition and maintenance requirements were moderate. In addition to critical preventive maintenance and repair, battery state of health analysis was performed at all sites on the maintenance plan. This testing on GNET and ANET batteries provides us with key data on long-term battery capacity trends throughout the networks, indicating that battery capacity deteriorates an average of 1-2% per year. If the networks remain in place, wholesale battery replacements can be deferred for a number of years. Beyond the field season, ANET support focused on routine monitoring and data flow management of Antarctic sites. Forty-two core ANET sites are operational, with 3 sites decommissioned during Y4. Of the sites remaining, 90% were telemetering data as of August 2017. Cumulative ANET data recovery, measured by data that reaches the UNAVCO archive, is currently at 89.3%. Planning and preparation is underway for the upcoming ANET field season beginning in November. Most sites will be visited, on a maintenance or upgrade priority basis.

LARISSA (LARson Ice Shelf System), a sister network operating on the Antarctic Peninsula, maintains a total of 9 continuous telemetered stations. The NSF award for this project ended last year, leaving this important network in limbo. A collaborative effort with the British Antarctic Survey is currently underway to help support the network in the long-term. The exact funding mechanism and roles are currently being worked out.

The Polar Support team provides networked GPS sites for other PI projects, as well as maintaining reference stations at multiple remote research facilities in the Arctic and the Antarctic. This is reflected in Figure 2-5. Additional information regarding polar network support is provided in Appendix A: Tables listing continuous GPS networks for which UNAVCO is providing support.

![Permanent GPS Stations O&M Supported: NSF Polar](image)

**Figure 2-5.** Continuous GPS sites supported by UNAVCO for NSF-PLR investigators. Actual values are shown from 01 January 2004 through 30 June 2017 along with projected values originally forecast in the GAGE proposal through the end of FY 2017. Fewer stations were supported in GAGE Y4 than in Y1 through Y3, primarily due to decommissioning some of the stations at the end of project award periods.
2.2.4 Support for Other Community Networks

PI cGPS Network Engineering
From July 2016 to June 2017, UNAVCO provided operations and management (O&M) support at various levels to 880 continuously operating GPS stations in 66 different networks, which were installed in support of various NSF-supported PI projects. Although some stations were retired during this reporting period, reducing the overall count from last year’s peak of 910 stations, many stations continue to operate beyond the initial funding period of the original project. The O&M support includes data downloading, state of health monitoring and reporting, resolving communications and equipment issues, shipping replacement equipment, and working with PIs and local contacts to resolve problems. Additional information regarding PI network support is provided in Appendix A: Tables listing continuous GPS networks for which UNAVCO is providing support.

![Permanent GPS Stations O&M Supported: NSF EAR, PBO and Community](image)

Figure 2-6. Continuous GPS sites supported by UNAVCO for NSF-ear PIs, PBO and other Community investigators. Actual values are shown from 01 January 2004 through 30 June 2017 along with projected values originally forecast in the GAGE proposal through the end of Y4. The number of stations supported grew continuously through Y4 as expected, though total number and rate of growth was less rapid than projected. For example, a maximum of 910 stations were supported in Y3 compared to 880 stations in Y4 to date. Part of the reason for the difference between actual and projected station count is that some legacy stations have been decommissioned, reducing the total station count even as new stations were added.

2.3 PI PROJECT SUPPORT

2.3.1 EAR PI GPS Project Engineering and Equipment Support

PI GPS Project Engineering & Equipment Support: NSF-EAR & Community
UNAVCO provides state-of-the-art GNSS equipment and engineering services to PI projects. This includes project management, planning, installation, operations and maintenance of continuous,
permanent GPS/GNSS station networks around the globe. Engineers and technicians also undertake technology development, testing, and systems integration to support new project demands.

**PI GPS Project Support**

In this reporting period (7/1/16 - 6/30/17) UNAVCO supported 49 individual PI projects (10 NSF-EAR, 6 NSF-Other, and 33 Community). UNAVCO staff was involved in proposal development, project planning, network design, monument design, equipment preparation and installation, and establishing real-time data flow. Additionally, UNAVCO supported 34 new PI proposals (15 NSF-EAR, 6 NSF-Other, and 13 Community).

![Field Projects Supported: NSF EAR and Community](image)

*Figure 2-7. NSF-EAR and community field projects supported by UNAVCO. Actual values are shown from 01 January 2004 through 30 June 2017 along with projected values originally forecast in the GAGE proposal through the end of GAGE Y4. The actual number of projects supported, in all categories, is fewer in Y4 to date compared to previous years and original projects. In particular, far fewer GPS NSF-EAR and NSF-Other funded projects were supported.*

**GPS Instrument Pool**

The UNAVCO GAGE receiver pool now consists of 692 GPS and GNSS-capable (Figures 2-8 and 2-9). No new GNSS receivers were purchased to augment the UNAVCO receiver pool for campaign or long term loans, however, several Trimble NetRS receivers from PBO upgraded stations have been used to augment the UNAVCO this receiver pool. This integration enables UNAVCO to better support PI projects. The receiver pool consists of Topcon GB1000, and Trimble NetR9, NetRS, R7 and Septentrio PolaRx5 receivers purchased by UNAVCO for use as campaign receivers or to support for specific NSF-EAR projects and thus are deployed in semi-permanent installations.
Figure 2-8. UNAVCO NSF-EAR receiver pool inventory broken out by receiver type from 01 October 2003 through 30 June 2016. Note: the drop in 2006 is due the NSF-PLR pool no longer being included in the metric.

Figure 2-9. UNAVCO NSF-EAR receiver pool inventory. Actual values are shown from 01 January 2004 through 30 June 2017 along with projected values originally forecast in the GAGE proposal through the end of Y4. The drop between 2006 and 2007 is because the NSF-PLR pool is no longer being included in this metric. In October 2013, the EAR and EarthScope pools were consolidated into a single “GAGE” pool. The number of receivers has surpassed the projected number due to a greater number of receivers being purchased than originally planned. In GAGE Y4, the number of receivers in the equipment pool remained relatively flat due to budget cuts for PI project support.

GPS Instrument Repairs
The GAGE Facility is an authorized Trimble repair facility. Since the introduction of the Trimble NetRS and now up to the recent release of their latest GNSS product, the NetR9, the UNAVCO community has purchased thousands of GPS/GNSS receivers through the UNAVCO-community
purchase program. With this program new receivers come with a five-year warranty with the stipulation that repairs are handled by UNAVCO. UNAVCO continues to repair PBO, COCONet, TLALOCNet, and community receivers and related instruments using a technician working under contract for UNAVCO. UNAVCO also facilitates repairs on the Septentrio PolaRx5 receiver too. During this reporting period, the UNAVCO repair depot handled 144 receiver repairs.

2.3.2 Polar Services

UNAVCO supports diverse science in the polar regions, including geology, glaciology, volcanology, climatology and work at the ocean-ice interface. PI support commonly requires extensive fieldwork, and in Antarctica, travel and logistics are particularly challenging. Five engineers and one project manager support Polar Services. All current team members provide direct support to fielded projects and participate in polar project planning and preparation. Planning and support activities for the Arctic and Antarctic are ongoing year round, currently with significant overlap of the two seasonal efforts. The UNAVCO Polar engineering team supports field seasons in the Antarctic and the Arctic during the year. Antarctic support was provided to 26 different PI and infrastructure projects including six TLS projects. Other support included GPS campaign and permanent station work. To manage the Antarctic field season, UNAVCO deployed six staff to McMurdo Station, from which served as a base to launch work over much of the continent. At the other end of the globe, GAGE Y4 Arctic support was provided to 18 PI projects during the reporting period, which included three TLS projects. Some of these projects were funded by sources other than the NSF and were provided support on a partial or full cost recovery basis.

![Field Projects Supported: NSF Polar](image)

Figure 2-10. NSF-PLR field projects supported by UNAVCO. Actual values are shown from 01 January 2004 through 30 June 2017 along with projected values originally forecast in the GAGE proposal through the end of GAGE Y4. The total number of fielded projects were slightly below average levels seen in GAGE years 1-3. Project support has been provided to non-NSF funded projects, often on a cost recovery basis. UNAVCO has also provided services to the NSF support contractor in Antarctica, a trend seen continuing into the coming field season.
Regular Terrestrial Laser Scanning (TLS) support is provided to PI teams in the Arctic and Antarctic. UNAVCO engineers deploy both a longer-range Riegl VZ-2000 and a shorter-range VZ-400 scanner for polar field applications. This suite of scanners enables a broad range of uses, including small scale volumetric estimates and surface change detection. UNAVCO worked with the NSF to guide the procurement of a new Riegl VZ-6000 laser scanner for polar applications. This TLS instrument provides impressive distance performance and is particularly well suited to ice and snow. The instrument was successfully fielded for a PI sea ice project in Barrow, Alaska. While procured through a CH2M-Hill purchasing agent, the goal is to fold this instrument into the community TLS instrument pool managed by UNAVCO.

UNAVCO has recently introduced Structure from Motion (SFM) as a geodetic imaging tool, using a small aerial UAV platform. The data products from such missions include high resolution geo-referenced imagery, high resolution 3-D point clouds, and surface terrain models. This technology was successfully demonstrated on two Y4 OPP PI projects in the Antarctic. The platform was also in the high arctic to see how the image products performed on flatter, snow covered features in newly forming sea ice. The results were quite promising and are comparable to those achieved with laser scanners. The goal is to use SFM techniques to create cost effective digital elevation maps products for OPP PIs. These products mesh well with those provided by the laser scanners, and should prove to be complementary to each other.

![GPS Receiver Pool: NSF Polar](image_url)

**Figure 2-11.** UNAVCO NSF-OPP GPS receiver pool inventory. Actual values are shown from 01 January 2004 through 30 June 2017 along with projected values originally forecast in the GAGE proposal through the end of GAGE Y4. The total number of receivers in the pool has remained close to projections, with a current total of 339 instruments. The allocation of receivers to each subcategory within the pool has deviated somewhat from projections due to the inherent unpredictability of project loads. A number of these receivers reside in polar networks: 52 in the Arctic and 73 in the Antarctic.

Proposal support letters and budgets were written for 24 Antarctic PI’s. This number includes two projects which include TLS support. During the same period, seven letters and budgets were prepared for the open Arctic solicitation - two of which include TLS support. Currently there are 125 GPS receivers in the Arctic pool and 214 receivers in the Antarctic pool. Of these, 52 are currently in Arctic
networks and 73 are in Antarctic networks.

2.3.3 Geodetic Imaging (TLS)

Geodetic Imaging activities included engineering support for PI projects, planning support for PI proposals, education and outreach, and resource development. In this reporting period (7/1/16 - 6/30/17) UNAVCO supported 32 TLS PI projects (10 NSF-EAR, 1 NSF-Other, 8 Community, 5 OPP Arctic and 8 PLR Antarctic). See Figure 2-12 below.

To meet the needs of a diversifying TLS user community, UNAVCO is actively developing training resources and documentation to support Earth Science TLS users. The TLS Knowledgebase provides resources with a focus on software tutorials and training:
http://kb.unavco.org/kb/category/geodeticimaging/165/

![TLS Projects & Proposals Supported January 1, 2008 - June 30, 2017](image)

Figure 2-12. Number of TLS projects and proposals supported by UNAVCO. Actual values are shown from 01 January 2008 through 30 June 2017. More OPP Arctic and Antarctic projects and proposals have been supported in GAGE Y4 to date than in Y3. The number of NSF EAR projects and proposals is also greater in Y4 to date than in Y3. However, far fewer NSF Other and Community projects and proposals have been supported in Y4 to date compared to Y3. Except for NSF Other, the number of TLS projects and proposals supported in Y4 to date is close to the original projections.

Also during GAGE Y4, the Geodetic Imaging group coordinated with the Polar Services group to support PI C. Polashenski with operations using a newly acquired Riegl VZ-6000 laser scanner. The instrument was fielded in support of the PI’s project in Barrow, AK. This instrument was acquired by NSF in support of the PI project, and once his research is complete, the scanner will be transferred to the UNAVCO instrument pool for broader community use. The Riegl VZ-6000 is a long range, near IR scanner designed for snow and ice applications. UNAVCO provided assistance to the PI for instrument troubleshooting and coordination with the manufacturer. Problems with the VZ-6000 related to miscalibration were identified in the field and were confirmed by UNAVCO staff review of the acquired data sets. UNAVCO also was on call to provide a backup instrument in the event the
manufacturer was unable to provide an interim solution.

Other activities included maintenance and upkeep of the TLS instrument pool. Specifically, UNAVCO’s Riegl VZ-1000 was returned to Riegl in Horn, Austria due to the system failing to boot. Other updates to the TLS support infrastructure included renewal of RiScan Pro and Blue Marble Geographic Calculator annual software maintenance, and a considerable reorganization of the TLS equipment storage space in the UNAVCO Lidar and UAS Lab.

A publication this year in AGU’s Eos journal highlighted the ongoing collaboration between the GI Geodetic Imaging group and ECE in support of geodesy field education. Over recent years we have continued efforts to integrate imaging technologies in geoscience field education and to develop supporting curriculum. The Eos publication highlights these resources; a dissemination workshop held in Y3Q4 at the Indiana University Geologic Field Station in Montana (Pratt-Sitaula et al., 2017).

2.3.4 GI Project Support User Feedback Summary

UNAVCO solicits feedback from supported PIs on the UNAVCO project support experience and provide usability metrics. PI are asked to comment on quality and effectiveness of technical support, equipment and training, administrative support, and cost effectiveness. During this reporting period, 26 PIs responded to the request for feedback on UNAVCO services.

The feedback form asks PIs to rate the specific services from 1-5, with 5 being the best. The question and average responses are shown in the table below (Table 2-2).

Overall the PI responses were very positive. PIs report that engineers who supported their projects were well-prepared and trained, communicated well, and were professional in providing training in field techniques and instrumentation and providing other field operational support such as permanent station maintenance and installation and TLS surveys. PIs are consistently pleased with the value of UNAVCO project support, indicating that it enables them to make most effective use of their limited time and resources. The availability of state-of-the-art instrumentation, training, and software is extremely important to PIs. It was also noted that UNAVCO support enabled research that they could not have otherwise completed.

<table>
<thead>
<tr>
<th>Question</th>
<th>Average Rating (1-5)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>What was your overall impression of the quality and effectiveness of support provided to your project?</td>
<td>4.6</td>
<td>0.24</td>
</tr>
<tr>
<td>Please rate the training provided by UNAVCO.</td>
<td>4.5</td>
<td>0.25</td>
</tr>
<tr>
<td>Please rate technical and/or field support provided by UNAVCO.</td>
<td>5.0</td>
<td>0.00</td>
</tr>
<tr>
<td>Please rate effectiveness of administrative support provided by UNAVCO.</td>
<td>5.0</td>
<td>0.00</td>
</tr>
<tr>
<td>Please rate the cost effectiveness of support provided by UNAVCO.</td>
<td>5.0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Some highlights from the PI responses:
- “This pilot project was minimally funded - the GPS equipment was a critical component of the science and could not have been afforded.”
- “The quality of the support was very good.”
- “The online tutorials were very helpful and easily sufficient to get the equipment up and
“Borrowing the equipment was far cheaper than buying new equipment would have been.”
“Equipment was provided in a timely fashion, was in good condition and easy to use.”
“The equipment worked well. We also had excellent and timely support for capturing 1 Hz data in our survey area.”
“Having the receiver at Poker Flat greatly enhanced our experimental observations for the ISINGLASS rocket campaign.”
“The technical support offered by UNAVCO is of the highest quality.”
“The gear worked great, as usual. The team training prior to field work was very helpful, even though we work with UNAVCO gear regularly.”
“Always appreciate UNAVCO’s ability and willingness to supply excellent support, with with great flexibility.”
“Worked with UNAVCO gear at multiple Antarctic field locations. Really appreciate the self contained nature of the static style GPS kits. Everything necessary for autonomous operation is right there, and is quick to setup and use. Great general-purpose design.”
“Overall GPS setup was much more functional for our field use this year. Realize the challenge of snow machine integration of power and all the vibration on the snow machine GPS units makes this project challenging. Thanks for the attention given to fixing last year’s problems.”

Some constructive criticism, much of which we have already addressed, where possible:

“Maybe provide the compasses with each equipment case.”
“If there is one complaint I have about the NetR9s, it is that I found them difficult to configure on the fly in the field since they required being hooked up to a laptop. This is inconvenient for short occupation campaign measurements taken at different sites over the course of a single day.”
“We should have followed the rules and warned UNAVCO that we needed the 1 Hz data more than a few days before the experiment. They were able to fully accommodate our request.”
“Overall this is a tough question to answer. Perhaps a quicker response on proposal - but I really have no reason to complain.”
“Support was great, as always. Tough conditions led to some failures with cables and the like. While quick response with sending out spares was appreciated, perhaps doubling up on spares of components likelier to fail would be warranted for particularly deep field kits.”

Other comments:
“I just wanted to let you know my new paper using the WISSARD/SALSA GPS array went online yesterday. This is the first peer-reviewed use of Kristine Larson’s GPS reflectometry method in Antarctica, so now, in addition to using these GPS to measure changes in subglacial lakes and changes in ice velocity, we are using GPS to validate global atmospheric reanalysis products and laying the groundwork to use GPS to ground truth ice-sheet surface process models (like wind redistribution of snow and firn compaction). What can’t GPS do these days?”

2.4 DEVELOPMENT AND TESTING

Following the resignation of Engineer III H. Berglund in February, 2017, the GAGE Facility Development and Testing effort is now staffed by 1.75 FTE at the Project Manager III and Engineer III levels, and now also incorporates the PBO strainmeter and GPS testing. Ad hoc contributions to individual D&T projects from other UNAVCO groups were critical to various D&T projects given the reduced, dedicated staffing level, with other UNAVCO staff participating in projects of direct interest to their operational efforts. The establishment of a Development and Testing Product Council has supported tuning efforts across the organization with a focus on four areas: GNSS Systems (receivers and antennas), Data Communications (radios, cellular and satellite), Power Systems (including
batteries, solar charging systems, and fuel cells), and Other Sensors (including borehole strainmeters, meteorological sensors, and tide gauges). The ongoing development of teq software and the implementation of server-based real-time GPS positioning capabilities in close collaboration with GDS are important ongoing projects undertaken by the D&T staff.

The D&T group continues to work closely with Septentrio technical staff to finalize the release of production firmware, optimize receiver configuration for UNAVCO networks, and coordinate the deployment of receivers by UNAVCO field staff. Over 120 PolaRx5 receivers have been deployed in UNAVCO-operated networks, with more planned in the coming year. A major firmware upgrade was released early in 2017, with three critical features that were developed jointly with UNAVCO: BINEX logging and streaming capability, archival quality streaming using “rsync”, and onboard Precise Point Positioning, as well as other smaller additions. Two follow-up sub-decimal version releases followed later in 2017, which addressed minor network security and data format issues as well as an improvement in the RF-interference mitigation capabilities of the hardware.

Other D&T highlights include the characterization of the RF environment of every PBO station that has had a PolaRx5 receiver installed. Using the built-in spectrum analyzer we archived the ambient spectrum at each station, and were able to identify a previously unknown interference sources at ATW2 in Palmer, Alaska, and an antenna failure at P513 in southern California. Work on validating firmware releases for Trimble NetR9 receivers, including a critical fix of a UNAVCO-identified failure mode, evaluation and deployment of communications hardware with multiple VPN capability. We also conducted further testing of real-time positioning algorithms using our in-house designed shake table, including the new PPP capabilities of the Septentrio PolaRx5 receiver as described in detail in the Y4Q1 quarterly report.

2.5 GI PROGRAM SUMMARY

During GAGE Y4, the Geodetic Infrastructure Program focused on completing the challenging borehole strainmeter installations in Turkey with the final installation of uphole electronics, including power and telecommunications systems (5 of 6 stations are delivering data to the UNAVCO archive), the closing out the cGPS/Met station installations in Mexico for TLALOCNet, which now is finished in accordance with the original MRI plan, and continued efforts keep COCONet funded and operational through the close of the GAGE Facility. Continuing O&M for the PBO GNSS and BSM networks remain a high priority and these tasks account for much of the effort and resources available to the GI Program under the GAGE Facility. The PBO GNSS Operations team continues to implement the recommendations from the “PBO Futures” workshop report during GAGE Y4, including installing 104 out of 120 new Septentrio PolaRx5 multi-constellation GNSS instruments at PBO stations. At the time of the writing of this report, 244 multi-constellation GNSS receivers (140 Trimble NetR9 GPS+GLONASS and 104 Septentrio PolaRx5) along with broad-band GNSS choke ring antenna have been deployed across PBO, resulting in a modernization of ~22% of the network.

The GI Director continued efforts on the writing committee for the NASA Challenges and Opportunities for Research in ESI (CORE) workshop held in Arlington, VA 2-3 November 2015; this report was published by NASA and made available to the scientific community in early December 2016 (Davis et al., 2016). In GAGE Y3, GI Director Mattioli acted as PI with GDS Director Meertens as Co-PI on a solicited proposal to the USGS Earthquake Hazards Program ShakeAlert FY2016 Program Announcement GA16AS0042 entitled “Incorporating Real-time GNSS into ShakeAlert: Collaborative Proposal between Central Washington University and UNAVCO, Inc.,” with a requested budget of $2.46M for 2 years. The UNAVCO component of this Collaborative Proposal unfortunately was declined. In GAGE Y4, Mattioli and Meertens used the feedback from the USGS panel along with additional guidance from existing ShakeAlert Centers and USGS staff to develop and submit a substantially revised proposal to the FY2017 USGS Program Announcement G17AS00042 entitled “Incorporating Real-time GNSS into ShakeAlert: Improving telemetry, reducing latency, and

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enhancing robust GNSS data flow at existing PBO stations in CA, OR, and WA,” with a requested budget of $698K for 2 years. This proposal was selected for funding and a new Cooperative Agreement between the USGS and UNAVCO, Inc. was executed in early August 2017. The USGS effort leverages the significant NSF investment in PBO RT-GNSS assets in CA, OR, and WA.

At the close of Y4, the GI group headcount is 38 with 36.40 FTE, including staff supported by NSF EAR and OPP and NASA. The overall headcount as well as FTE are down 2.0 relative to the close of GAGE Y3 as a result of the resignation of Mr. J. Sandru, an Engineer II in the EAR PI Support group in late October 2016, and resignation of Mr. H. Berglund, an Engineer III in the D&T group in February 2017. There are no plans to add additional staff to the GI group at this time.

3. Geodetic Data Services Program

3.0 Geodetic Data Services Highlight

Everything You Need to Know About GPS Data Analysis and Geodetic Products from the Plate Boundary Observatory and Related Networks

The GPS data analysis and data products manuscript that was in preparation for much of GAGE Y3 was published in Y4, in the prestigious peer-reviewed journal *Reviews of Geophysics*. This publication describes the methods used by the GAGE GPS data analysis centers and coordinator to generate data products including station position time series, velocities and other parameters from the 2000+ stations processed for GAGE. The other parameters include coseismic and postseismic signals, seasonal signals related to the hydrosphere and atmosphere, and other transients. Detailed analyses describe the differences and uncertainties in different solutions and how analysis assumptions impact the determination of the reference frame of the Earth.

The GAGE GPS Analysis Center Coordinator is the Massachusetts Institute of Technology (MIT) and the other analysis centers are housed at the New Mexico Institute for Mining and Technology (NMT) and Central Washington University (CWU). NMT uses GAMIT/GLOBK software and CWU uses GIPSY/OASIS software to provide level 2a products. MIT provides level 2b products utilizing the results from NMT and CWU. Two types of discontinuities are noted in the GAGE position time series, equipment changes or damage and earthquakes. The differences between the two methods are small except for changes in the height over time, which may be due to the GAMIT analysis only covering one hemisphere.

The main products are the position time series that show motions relative to a North America reference frame and secular motions of the stations in the velocity field (Figure 3-1). Measurements of vertical velocity for decade-long time series are precise enough to be used to interpret glacial isostatic adjustment and vertical motions related to water load, opening up important new avenues of research and societal applications. In the future, the analysis and data will be updated when the new Earth reference frame is published, upgrades will be considered to process multi-constellation GNSS data, and web services will be enhanced to allow greater access, effective discovery and better integration of different datasets.

3.1 OVERVIEW

The Geodetic Data Services (GDS) program manages a complex set of metadata and data flow operations providing a wide range of geodetic/geophysical observations to scientific and educational communities. Figure 3-2 provides a schematic view of GDS data flow. Sensors currently include GPS/GNSS (downloaded files and streaming real-time (RT-GPS)), borehole geophysics instrumentation (strainmeters, tiltmeters, seismometers, pore pressure sensors and meteorological sensors), long baseline laser strainmeters, and terrestrial laser scanners. Field data are acquired either from continuously operating sites or episodic “campaign” surveys conducted the community. UNAVCO also acquires and distributes satellite synthetic aperture radar (SAR) data from foreign space agencies. GDS services include data operations (managing metadata; data downloading, ingesting and preprocessing); data products and services (generating processed results and QA/QC and state-of-health monitoring); data management and archiving (distribution and curation); cyberinfrastructure; and information technology (systems and web administration). In order to perform this mission, GDS maintains a technical staff, onsite and offsite computer facilities with networking, servers and disc storage, and manages a number of subawards to university groups who provide additional products, software and training. In addition to GAGE core support, UNAVCO receives funding from the NSF EarthCube program, NSF SAVI COOPEUS, and NASA ROSES ACCESS awards.
Figure 3-2. Geodetic Data Services work flow. The workflow for data systems, managed under GAGE by GDS and its subaward partners, continues to evolve to further internal consistency and integration of data workflow, improve robustness, accommodate growth and diversity of data and data products, and facilitate better discovery, access and visualization. These developments are funded with core GAGE and additional NSF and NASA project funding for Cyberinfrastructure enhancements including NSF EarthCube, NSF SAVI/COOPEUS, and NASA ROSES ACCESS and other activities.

The GDS program collects and monitors 90 detailed and six key summary metrics. These metrics include numbers of stations, data and derived data product volumes archived and delivered, user metrics, and software downloads for data from all of the data different sensor types managed by UNAVCO. These metrics are compiled and reported quarterly. The primary key summary metric is the total archived data volume (Figure 3-3). The cumulative volume of data archived since 2004 and through GAGE Y4Q3 is more than 265 TB. This volume has already exceeded projections of 174 TB made for the end of the fourth full year in the GAGE proposal, although the sensor data volume ratios are different from that anticipated. One measure of data usage is the number of users (Figure 3-4a, b). All but SAR data (which has user registration imposed due to constraints from contributing foreign space agencies who provide the data) and RT-GPS data streams have anonymous access so a variety of means are used to compile statistics that are representative of user numbers. The background level of users is currently ~3,000/quarter.
Figure 3-3. Cumulative total UNAVCO data volume archived from 01 January 2004 through 30 June 2017 along with projected values originally forecast in the GAGE proposal through the end of FY 2017. The actual total data volume through June 2017 already exceeds the projected total data volume through September 2017. The distribution of growth among constituent data products differed from projections in the areas of imaging data. Specifically, TLS data volume has grown over the last year but not as rapidly as originally projected while SAR data volume has grown much more rapidly than originally projected in the GAGE proposal. The TLS difference is primarily due to fewer community field projects being supported than anticipated as well as more efficient data product management/storage resulting in smaller file sizes. The SAR volume growth is primarily due to the acquisition of data from new satellite missions such as ALOS-2, TSX, SENTINEL-1 and COSMO-Skymed, and the larger file sizes of new SAR mission products compared to earlier mission products, as well as surges in the volumes of data ordered by PIs. Seismic data volume exceeded projections partly due to greater higher level products generated in response to earthquakes. GPS data volume exceeded projections due to increased numbers of stations being archived, the generation of new higher level products from reprocessing efforts, high rate (1-Hz and 5-Hz) data collected in response to earthquakes, and the addition of new multi-GNSS observables from upgraded stations.
Figure 3-4a. Number of UNAVCO data users by quarter from 01 January 2009 through 30 June 2017. The method of counting users varies by data product, for example by unique IP address, second level domain or unique authentication. Note 1: spikes in the quarters ending 2014-03 and 2016-12 were due to extremely high numbers of unique, unresolved IPs each accessing just a handful of files, with the total volume accessed by these distinct IPs being small. Note 2: starting in 2016-06 the number of RT-GPS users has been artificially low due to problems with the collection of RT-GNSS metrics.

Figure 3-4b. Number of data users excluding GPS (by second level domain or unique authentication) from 01 October 2013 through 30 June 2017. This is a subset of the total data users shown in Figure 3-4a. Note 1: spikes in the quarters ending 2014-03 and 2016-12 were due to extremely high numbers of unique, unresolved IPs each accessing just a handful of files, with the total volume accessed by these distinct IPs being small.
3.2 DATA OPERATIONS AND MANAGEMENT

3.2.1 Network Data Flow

Network data flow covers data and metadata management from thousands of GPS and borehole geophysics instruments operating in the field to the Boulder operations center, a critical activity in support of data archiving and distribution. This task includes instrument configuration management, data downloading and streaming, metadata management, maintenance and other steps related to data flow from the sensors. Staff with responsibilities for data and metadata flow focus on timely handling of operational flow and addressing any issues as they arise. Operational capabilities are supported on a best-effort basis. The heart of the data flow system is the PBO Operational Database (POD). High rate (1 Hz and 5 Hz) GPS data downloads continue to be requested and require additional resources for data handling, processing and storage. To efficiently meet demand, these processes are being streamlined and criteria for data-related aspects of event response continue to be evaluated and improved.

Modifications were required and implemented to accept strainmeter data from the borehole sites in Turkey. The sites in Turkey are the first strainmeters outside of PBO network that UNAVCO collects strain data from. Many assumptions were made in the initial software developed and used to collect and archive data from these instruments within the PBO network. Modifications were made to this software so that data from the Turkey sites could automatically be collected, as well as any future stations.

Updates were made to the GPS/GNSS data flow systems in Y4 to improve efficiency and performance and to add new functionality. A key activity was improved support for the new Septentrio receivers, as the original data flow system was only designed to support Trimble receivers. As an example of improved efficiency, a new way of managing hourly data files from Septentrio receivers was introduced in Y4Q3. Previously, UNAVCO downloaded data from Septentrio receivers via two parallel pathways: by downloading hourly data files generated within the receiver, and by streaming data from the receiver in real-time. This approach was robust in that any epochs missing from the RT stream were recovered when the hourly files were downloaded, but this approach also required additional
bandwidth and communications costs. As of Y4Q3, hourly files are now generated by binning data from the real-time streams; these binned hourly files are then compared to the hourly files created within the receiver, and only the missing epochs (if any) are subsequently downloaded, thus reducing communication costs.

A new software utility for adding new stations to the data flow system was also introduced in Y4Q3. The previously used utility had become unstable due to modernization of the POD database and associated UNAVCO computing environment and was requiring manual updates that were prone to human errors. The newly implemented utility resolved these issues, improving performance and reliability. Also in Y4, significant improvements were made to the Iridium-based polar data download software and systems to ensure a more reliable process and to provide for backups and a failover system in case of hardware problems.

### 3.2.2 Campaign Data Flow

Forty-one GPS campaigns were archived in Y3Q4-Y4Q3, numbering three to four campaigns per month on average. Archiving is in progress for eight campaigns at the close of Y4Q3; completion of these campaigns is awaiting submission of missing data or information by the contributors. For TLS campaigns, the rate averages more than six campaigns archived per month as the new data management system is populated with current as well as historic TLS datasets. A total of 79 TLS campaign datasets were archived between July 2016 and June 2017. This includes not only archiving of TLS raw data, point clouds and metadata but also related GPS data collected for the reference frame application.

### 3.3 DATA PRODUCTS

#### 3.3.1 GPS/GNSS Data Processing and Products

The GAGE GPS Analysis Centers (ACs) and Analysis Center Coordinator (ACC) provided a suite of post-processed data products throughout Y4, including daily geodetic station position solutions, time series, velocity estimates, coseismic offsets, time series properties, and tropospheric (zenith delay) parameters from 2,000+ GPS stations in the PBO, COCONet, TLALOCNet, GAMA, SCIGN, NGS CORS and PI networks. The two ACs, at Central Washington University and New Mexico Tech, used different GPS analysis software packages (GIPSY and GAMIT, respectively) to independently process RINEX (Level 1) data to generate unconstrained geodetic daily position solutions (Level 2a products). From the AC products, the ACC at MIT then generated a unified set of high-quality combined solutions (Level 2b products) in two standard reference frames (NAMo8 and IGS08). As of Y4Q3, the velocity field data products include 2,224 stations (compared to 2,183 in Y3Q3) for all networks and time periods (back to 1996). An updated "Final" (annually generated) PBO Velocity Field solution was released on 2016-12-30. Forty-one new GPS stations were added to the analysis stream from Y3Q4 to Y4Q3, including stations from TLALOCNet, COCONet and PBO as well as PI networks in Oklahoma, Costa Rica and Tanzania.

A new data product was released in Y4Q3: time series offset estimates from a Kalman Filter analysis. This new product includes estimated offsets (NEU) at the times of antenna changes, equipment failures and earthquakes. Current processing ancillary files identify and quantify known offsets but do not provide 3-component (NEU) offset estimates. This new product is intended to help users more easily and directly assimilate known station offsets, and will also facilitate new and enhanced web services at UNAVCO.

At the end of January 2017, the IGS switched its operational products to the newly released IGS14 system, replacing IGS08. Both the CWU and NMT ACs implemented reference frame updates starting January 29, 2017. We plan to transition fully to IGS14 over the coming year. This transition will
include a major effort to reprocess all existing GPS data and then release the full set of time series in IGS14 and NAM14 (IGS14 rotated to the North American Plate). Reprocessing was initially planned to be completed by the end of 2017, however all the IGS and JPL orbit products necessary for this reprocessing are still not available. Reprocessing will therefore begin when these products become available, which may not be until Y5.

Online GAGE GPS data analysis documentation resources were greatly expanded this year. A new document describing the IGS14 transition plan was published on the UNAVCO webpage immediately after release of the IGS operational products, and this document was updated several times as new information became available. The master GAGE GPS data analysis plan was significantly updated and expanded in Y4. New and updated resources were added to the GPS data products web page, the GAGE GPS AC Products Log, and the Google+ web page focusing on GAGE GPS data products throughout the year. A significant accomplishment in GAGE Y4 was the Reviews of Geophysics publication by Herring et al. (2016) described in the GDS Highlight above. The manuscript was in preparation for much of Y3, and was published in Y4.

3.3.1.1 GPS Analysis Center Subaward: Central Washington University
Routine data processing and product operations were stable this period. Enhancements to CWU’s processing hardware, software and workflow were made throughout the year to maintain and improve performance and product delivery. CWU subaward personnel co-authored the Herring et al. (2016) publication highlighted above. CWU has been experimenting with the newly released GipsyX software test suite. While there are no plans to upgrade production PBO/GAGE processing to GipsyX within the next few months, testing and development activities are underway to allow comparison with current software and to prepare for future implementation.

3.3.1.2 GPS Analysis Center Subaward: New Mexico Tech
Routine data processing and product operations were stable during this period. Software updates and system improvements were made throughout the year to maintain and improve performance and product delivery. There were also two major events that occurred in Y4: the development and implementation of generating routing NMT data products using a Virtual Machine (VM) at UNAVCO as well as the physical relocation of the NMT computing cluster from the NMT campus in Socorro, NM to the the UNAVCO Facility in Boulder, CO. The NMT PI began using the VM to provide all routine products to the ACC on June 15, 2017. The NMT computing cluster hardware was then physically relocated from Socorro to Boulder. Routine processing will continue via the VM while the cluster will be used for the large scale IGS14 reprocessing effort anticipated to begin in Y5. The NMT subaward PI co-authored the Herring et al. (2016) publication highlighted above.

3.3.1.3 GPS Analysis Center Coordinator Subaward: Massachusetts Institute of Technology
Routine combination of final and rapid level 2b products was stable, including and 12- and 26-week supplemental solutions. MIT released updated “final” velocity field products in December 2016, and “Snapshot” velocity field products were released on a monthly basis. The new new Kalman filter based time series position offset data product described above were developed and released by the ACC in Y4. Additional information is provided in the GAGE quarterly reports, and full details are provided in the MIT GAGE GPS ACC quarterly technical report available from the UNAVCO web page. ACC subaward PI Tom Herring was lead author on the Reviews of Geophysics article highlighted above.

3.3.1.4 GAMIT/GLOBK Community Support Subaward: Massachusetts Institute of Technology
GAMIT/GLOBK software development efforts continued throughout GAGE Y4. MIT’s primary effort was to operationally test and prepare for distribution a version of GAMIT/GLOBK that offers users code to handle multi-GNSS observables including Beidou, Galileo, and IRNSS observations. By Y4Q3, MIT completed the coding and testing of most of the models necessary to process two-frequency
observations of Galileo and Beidou satellites in GAMIT and to combine the results in GLOBK. A series of data analysis tests were also performed, including a comparison of position solutions between GPS and Galileo.

MIT staff spent 5-10 hours per week in email support of GAMIT/GLOBK software users. From Y4Q3 through Y3Q4 MIT issued 77 royalty-free licenses to educational and research institutions. The total number of institutions who have requested licenses is more than 100 in the US, and more than 1,000 internationally.

3.3.1.5 Custom Data Product Requests
UNAVCO supported a total of 26 custom data requests for high rate (1-Hz and 5-Hz) GPS data downloads from July 2016 through June 2017 including six geophysical event responses (5 earthquakes and one volcanic event) and 20 community PI requests. Figure 3-5 shows the number of geophysical event responses by UNAVCO from 01 October 2013 through 30 June 2017. Many of the non-event custom requests were to support regional airborne LiDAR missions (including NSF projects from NCALM and NEON projects) and various USGS,USACE-CRREL, CALTRANS and commercial survey projects. Geophysical event responses included the following earthquakes:

- 2016-12-08 M6.5 - 160 km W of Ferndale, California
- 2016-12-14 M5.0 - 8 km NW of The Geysers, California
- 2016-12-28 M5.7 - 29 km WSW of Hawthorne, Nevada
- 2017-05-01 M 6.3 - 88 km WNW of Skagway, Alaska
- 2017-05-12 M 6.2 - 79 km SSW of Acajutla, El Salvador

A total of 121 custom GPS data requests have been handled since the beginning of GAGE. UNAVCO continues to develop and implement significant improvements to custom data response operations in terms of staff and procedures, with further improvements planned in the future.

3.3.2 Strain, Seismic and Tiltmeter Data Processing and Products

UNAVCO provided raw and processed data products from 76 borehole strainmeters, 79 borehole seismometers, 26 shallow borehole tiltmeters and 6 long baseline laser strainmeters in the PBO network. UNAVCO also oversees strain and seismic data flow from borehole stations in the ARRA (2 sites), CALIPSO (4 sites) and Turkey (5 sites) networks. Routine data processing and product operations were stable this period. Fully processed high rate (1-sps) borehole strainmeter data were generated in response to 11 earthquakes from Y3Q4 through Y4Q3 as listed below, with these data being made available within 72 hours of the event and posted on the Geophysical Event page. Figure 3-5 shows the number of geophysical event responses by UNAVCO from 01 October 2013 through 30 June 2017.

- 2016-08-09 M7.4 - South Georgia Island region
- 2016-08-12 M7.2 - 109 km E of Ile Hunter, New Caledonia
- 2016-09-03 M5.6 - 15 km NW of Pawnee, Oklahoma
- 2016-11-07 M5.0 - 2 km W of Cushing, Oklahoma
- 2016-11-13 M7.8 - 53 km NNE of Amberley, New Zealand
- 2016-11-21 M6.9 - 37 km ESE of Namie, Japan
- 2016-12-08 M6.5 - 160 km W of Ferndale, California
- 2016-12-14 M5.0 - 8 km NW of The Geysers, California
- 2016-12-28 M5.7 - 29 km WSW of Hawthorne, Nevada
- 2017-01-22 M 7.9 - 41 km WNW of Panguna, Papua New Guinea
- 2017-05-01 M 6.3 - 88 km WNW of Skagway, Alaska

The 2017 Cascadia Episodic Tremor and slip event began in mid February and progressed through the first week of April. The event was recorded by several PBO strainmeters as shown in the Y4Q2 report. The data for this event are available as Level 2 products.
UCSD, through a subaward managed by UNAVCO, processes data and provides products from the long baseline laser strainmeter network. Routine operations, including data editing and cleaning, and product generation were good this period thanks to the efforts of UCSD personnel in the face of the equipment and weather related challenges as described section 2.2.1.3. Interesting transient aseismic signals were being recorded at each of the PBO LSM strainmeter sites this period as described in the quarterly reports.

3.3.3 Meteorological and Hydrologic Data Products

Meteorological sensors are collocated with GPS and other geophysical techniques in order to enhance the datasets, improve network monitoring, and strengthen interpretation of deformation signals. Temperature, humidity and barometric pressure are available directly from the GPS RINEX files, where colocation exists. Routine met product operations were stable throughout the year. Hydrologic loading models based on the Global Land Data Assimilation Models (GLDAS) are now available from UNAVCO FTP site. New and expanded documentation was developed and made available from the UNAVCO website throughout GAGE Y4. New hydrologic data product web services were developed and implemented Y4. As of Y4Q3, GLDAS data products have been updated to GLDAS v2 and NLDAS (National Land Data Assimilation Model).

3.3.4 Lidar – Terrestrial and Airborne Laser Scanning

UNAVCO provides TLS data services and products including basic data processing, data management and data archiving. The standard UNAVCO TLS deliverable is a merged, aligned, georeferenced point cloud, which is accompanied by pertinent metadata products such as site photos, meteorological information, field notes and other ancillary project information. TLS data support is further described in section 3.4.4, lidar data management and archiving. EarthScope ALS data products are supported by OpenTopography; metrics are reported to UNAVCO. No new ALS data product activities have been performed to date under the GAGE Cooperative Agreement.

3.4 DATA MANAGEMENT AND ARCHIVING

3.4.1 GPS/GNSS

The Data Center provides a secure long-term archive for data, data products, and metadata from GNSS instrumentation, and makes data available to the scientific community and the public. User interfaces, APIs, (application program interfaces) and software tools that facilitate data search and access, data handling, and visualization are provided to support full utilization of the data assets. Data sources include UNAVCO-managed instrumentation such as the PBO Network, as well as PI-managed networks and campaigns. Data publication with digital object identifiers (DOIs) is routine for most data sets.

Data archiving and distribution is an operational activity that continues to grow, with a total of 139 stations added for archiving for the year. The new stations were from the following 30 networks: AfricaArray, Antarctica Infrastructure, Antarctica Erebus, Antarctica PI Continuous, Azerbaijan, Bangladesh, British Antarctic Survey, COCONet, Ecuador, Ecuador IGEPN, Ethiopia Tectonics, GGN, HoustonNet, IGS, MacKenzie Mountains, MAGNET, Mid-America, Mississippi Delta, Oak Ridge Earthflow Lab, Oklahoma Deformation, Nepal, Pacaya Volcano, Pakistan, PBO, Puerto Rico, Salmon Falls Creek, Tanzania Volcano Observatory, Telica Volcano, TLALOCNet, and USGS Volcano Semi-continuous (these USGS stations are archived with cost recovery through a purchase order). We continue to add to the suite of GNSS products being archived with additions of a new offsets product from the GAGE analysis team, and revamped hydrologic loading product from the UNAVCO data products team. With the publication of the Herring et al. (2016) paper on GAGE processing, multiple sets of GAGE products were assigned Digital Object Identifiers. This was the first case where
UNAVCO has minted DOIs for GPS/GNSS products. In concert with this continual growth in the number of stations and data products being archived, the volume of data holdings increased throughout Y4. Oracle Storage Area Network hardware with a capacity of 80 TB, to be used for the long-term storage of archived GPS/GNSS data, was put in service.

An integral piece of the infrastructure is the TEQC software, which is used within UNAVCO, the US research community, the IGS, and the global geodetic research community. TEQC software development over the past year has incorporated additional raw format reading functionality; reading the receiver supplied position solution from several receivers with capability for output in the proposed BINEX 0x05 record type; dynamic memory management in parts of the code; refactoring of the GLONASS orbit interpolation functionality; a complete refactoring of the data structures and logic for proper output of GNSS satellite ephemerides in RINEX NAV files; improved GNSS point positioning during QC; fixing of the delta times for compact QC plot files when data gaps are present; and the output of placeholder value for no data epochs within RINEX met files.

This year the RINEX3 pilot project was expanded to incorporate routine RINEX3 generation for all UNAVCO-managed stations with Septentrio PolaRx5 receivers; the process uses Septentrio SBF2RNX executable for translation to RINEX3. To ensure the most up-to-date metadata in the header, UNAVCO developed RINEX3 header editing code, which is used to populate metadata from the Archive database into the RINEX3 header.

This year a major project was initiated and is still underway to migrate the Archive database from the Oracle engine to a Postgres engine. Because of license costs with Oracle, we have made limited use of multiple database instances in ways that maximize performance (such as load balanced clusters and read-only instances for web services and web user interfaces). These limitations are removed with Postgres and will open up capabilities for improved functioning of archiving and data access processes. Completion of the migration is anticipated early in Y5.

3.4.2 Real-Time GPS Data Flow and Management

UNAVCO provides high-rate (1 Hz), low-latency (<1 s) GNSS raw and PPP-AR processed data streams (RT-GNSS) from 777 real-time streaming GNSS stations from the PBO Core/Cascadia, TLALOCNet and COCONet networks. In addition several global sites (<10) are processed.

RT-GNSS data users are classified into three groups: academic, commercial and government. Commercial users were the largest group to access raw RT-GNSS data but government agencies and nonprofit consortia collectively downloaded the largest volume of data. Commercial users formed the largest group of users both in terms of being registered and active, but the government agency and nonprofit consortia downloaded more data in the year.

RT-GNSS PPP-AR processed data is operational for all raw data streams collected with the UNAVCO real-time. UNAVCO monitors the real-time conditions of network including latency, completeness, stability to support ongoing research in Natural Hazard Early Warning Systems (Figure 3-6). Significant effort is continues in the evaluation of solution uncertainties and covariances against alternate processing strategies and baseline best-case post-processed solutions.
Figure 3-6. Data latency by station for UNAVCO’s real-time GPS network on 22 August 2017. The cluster of high latency sites (red) in Northern California use a local network with antiquated radio modems that are backhauled via a VSAT terminal. Budgets, topography, and land permits have made upgrading this part of the network difficult.

3.4.3 Borehole Geophysics Data: Strain, Seismic, Tiltmeter, Pore Pressure

Most strain, seismic, tiltmeter, and pore pressure data metrics remain steady over the course of the year. Surges in data product volumes were observed at various times throughout Y4 as detailed in the quarterly reports. For example, a much higher volume of PBO BSM data products were archived in Y4Q3 than normal due to a major reprocessing effort that included tidal signals being re-estimated and borehole trends being updated for approximately 70% of the network. There was a trend throughout Y4 for increased volumes of BSM data and product deliveries. And there was a surge in seismic data deliveries in Y4Q3. While the data volume metrics are tracked with great precision, the underlying reasons for most delivery surges, and the primary downloader identities, are not tracked.

3.4.4 Lidar – Terrestrial and Airborne Laser Scanning Data

The UNAVCO archive holds more than 6 TB of TLS data as of Y4Q3. Data from TLS PI projects are added to the archive as projects are completed. New archive software was developed during GAGE Y3, and announced at the UNAVCO Science Workshop. Continued efforts in GAGE Y4 have involved populating the new archive and further software development. All datasets in the archive have now been assigned a DOI and an offsite backup of the TLS archive is maintained in Amazon’s Glacier cloud storage service.

TLS data support also focused on improved access to software required by community members to process and analyze TLS data. Data Engineer M. Okal, with support from UNAVCO System Administrators, maintains a software license server and is working to improve documentation on accessing and using these software packages. Available software includes four seats of Leica Cyclone, 20 seats of Riegl’s RiScan Pro and 10 seats of RiSolve, ten seats of Blue Marble’s Geographic Calculator, 10 seats of ArcGIS, three seats of Quick Terrain Modeler, 10 seats of Polyworks, and five seats of Trimble Business Center.
OpenTopography is the official archive and access point for EarthScope ALS data.

### 3.4.5 SAR Data

UNAVCO manages two tasks in support of SAR Data: the archive and GEO Supersites.

#### SAR Archive

UNAVCO has managed the SAR data archive since 2005. Under GAGE, UNAVCO orders scenes from ESA (European Space Agency) and DLR (Deutschland für Luft und Raumfahrt, the national aeronautics and space research centre of the Federal Republic of Germany) in response to WinSAR user requests. In addition, the WinSAR Executive Committee and UNAVCO arranged for a tasking quota with DLR for use by WinSAR. WinSAR user requested tasking orders for the TerraSARX (TSX) mission have been placed on a regular basis. UNAVCO archives WinSAR community TSX and ALOS2 data in the UNAVCO SAR Archive. UNAVCO also manages access to the ISCE SAR data processing software package for all members of the WinSAR Consortium. Additional information regarding ISCE software support and other SAR activities is provided in Appendix C: NASA Project Support.

The volume of SAR data archived has grown substantially from ~2 TB in Y1 to ~115 TB in Y4 due to data from ALOS2/JAXA (Japan Aerospace Exploration Agency) and to a lesser extent TSX data collection. JAXA provides 50 scenes per year for PI proposals and during Y3 & Y4 there was a large surge in data ordered by PIs. Some ALOS2 data files are 50-60GB each, which accounts for the large volume of data. WinSAR scenes from ESA are available without cost under their open data policy.

UNAVCO continues to maintain the core SAR archive infrastructure, including hardware, database, software, and web presence. Data ingest capabilities have been developed to allow UNAVCO to host data from newer satellite platforms such as COSMO-SkyMed, ALOS2, RADARSAT2, and Sentinel which WinSAR community users are beginning to utilize. Search and discovery for these hosted data is possible through the UNAVCO SAR Archive GUI and API interfaces. Access to data from COSMO-SkyMed, RADARSAT2, ALOS1/ALOS2, and TSX are restricted to collaborators on proposals, and the WinSAR Portal interface permits role-based access to groups of users.

ESA is the primary archive for ERS1, ERS2, and Envisat, while the Alaska Satellite Facility (ASF) is primary archive for RADAR-SAT1. For all data not archived in ESA’s Archive4 system or at ASF, UNAVCO is now backing up data up to Amazon Glacier, a commercial cloud storage system. This ensures a complete offline backup of the full UNAVCO SAR archive while minimizing redundancy, beyond duplication.

#### GEO Supersites Support

For the GEO Supersites and Natural Laboratories (GSNL) initiative, UNAVCO orders data from the European Space Agency, together with data management (download and repackaging) of the data received, and upload of the packages to the ESA supported cloud storage (Level 4 archive). UNAVCO continues to support GSNL as needed and Meertens serves on the GSNL Supersites Advisory Committee.

As noted above, UNAVCO now supports TSX, COSMO-SkyMed, RADAR-SAT2, and ALOS2 data collected under the Supersites initiative. For these datasets, the list of PIs with access to the data include international collaborators as well as WinSAR community members. To address this expanded community of users and associated access constraints, we’ve made several modifications to the WinSAR Portal system to allow registration by international partners.

Through recently completed NASA ROSES ACCESS-funded work to develop a Seamless SAR Archive (SSARA), UNAVCO staff members have engaged in joint planning with the European SAR community
(DLR, ESA, CEOS, etc.) regarding federated access to data, data processing environments, and metadata and product formats. The goal is to leverage the SSARA work to build federated access to data hosted by the space agencies that participate in Supersites. Additional information is provided in Appendix C: NASA Project Support.

3.4.6 Support of the IGS Central Bureau

As part of its NASA component tasks, UNAVCO provided support for the International GNSS Service Central Bureau (IGSCB) throughout GAGE Y4. Activities included the provision of participant and logistical support for the GGOS Consortium Meeting and the IGS governing board meeting in December 2016; IGS network coordination support; IGS Site Log Manager support; RINEX3 support; and software and cyberinfrastructure support. Numerous UNAVCO staff members also served on IGS committees including the IGS Governing Board, the IGS Governing Board Executive Committee, the IGS Infrastructure Committee, and the IGS Antenna Working Group. Details regarding UNAVCO support activities for the IGSCB in GAGE Y4 are provided in Appendix C: NASA Project Support.

3.5 CYBERINFRASTRUCTURE

UNAVCO develops cyberinfrastructure with core GAGE funding, supplementary funding to GAGE, the SAVI/COOPEUS and EarthCube awards, and NASA ROSES ACCESS awards. UNAVCO continues to work on REST web services to support the community with alternative methods to retrieve data, in alignment with efforts to move towards REST web services with standards for services and formats coordinated internationally and nationally and within and across scientific domains. These efforts expand the cyberinfrastructure capabilities of UNAVCO geodetic data systems. An educational video on how to use the GPS position web service has been added to the UNAVCO web site.

In an effort to standardize web services and user presentation, the software team refactored the existing time series web services for GPS station positions, pore pressure, tilt and velocity. A new hydrological loading service was also developed and deployed. The earlier middleware server used to support web services is no longer being supported by the vendor and these services were moved to a new lightweight open source web server. At the same time these services were refactored to use a common set of parameter and output names. The updated GPS station position service was tested and deployed to production in Y4.

Current web services only support GeoCSV and GeoJSON output formats. Different response formats for GPS web service requests, including Timeseries XM are being investigated. UNAVCO is participating in a NASA Earth Science Data System Working Group that is proposing changes to the Open Geospatial Consortium TimeseriesML specification. UNAVCO contributed to an Open Geospatial Consortium engineering report that proposes changes for creating a less verbose means of providing GPS position data in XML. This would provide another output format, to be made available through the existing GPS position web service. UNAVCO is also investigating the use of the current specification as a means to combine station event and metadata modification information within the same time series response. This would eliminate the need to make multiple web service calls for different types of information that might have impact on the time series data.

This year a new EarthCube Building Blocks project, “Deploying MultiFacility Cyberinfrastructure in Commercial and Private Cloud-based Systems (GeoSciCloud)”, was initiated by UNAVCO in collaboration with IRIS and the GAGE GPS data analysis centers at Central Washington University and New Mexico Tech. GeoSciCloud has numerous independent tasks that are being implemented in the Amazon cloud environment for the first year of the project. An Amazon AWS virtual machine running PostgreSQL was provisioned and a copy of the archive database schema and contents was loaded, and initial performance testing was completed. An AWS virtual machine (VM) has been set up as the source FTP system and 2 months of 2016 GNSS (RINEX) data have been staged to that system,
completing one of the GeoSciCloud year 1 tasks. These data will be used by the analysis centers in reprocessing using cloud-based VMs. A metrics rubric definition that will be used to measure multiple aspects of setting up and operating in cloud environments versus on premises operation was developed.

The “Discovery through Semantic Connections” (EarthCollab) EarthCube-funded project is based on the Cornell-developed “VIVO” semantic web ontology and web presentation software. Cross-institutional efforts to coordinate ontologies is a focus of this effort, as is “cross-linking” of VIVO instances so that an individual’s presence within their home institution’s VIVO instance can be represented within UNAVCO’s VIVO. Development was completed for the GPS/GNSS DOI API that is needed.

The deployment of OGC (Open Geospatial Consortium) web services based delivery of IGS Site Log metadata in GeodesyML, described under section 3.4.6 is also a significant cyberinfrastructure accomplishment. With respect to the GeodesyML and Site Log XML schemas, we have been identifying how our vocabulary for UNAVCO site information and time series web services dovetails with GeodesyML, and how best to standardize our own vocabulary.

The infrastructure software development team developed software to combine GPS and other station data into a single repository using the open source tool DataTurbiné originally developed as part of NSF SII-SSI. After running into many issues with the open source software and discovering that software did not meet needs, the UNAVCO team consulted with DataTurbiné support resources and was not able to get resolution. In August it was announced that DataTurbiné was no longer going to be supported. At that time the decision was therefore made to abandon any further development using DataTurbiné and to look for an alternative. Efforts on this front will continue into Y5.

New software to monitor GPS station state of health (SOH), including receiver temperature and voltage, was developed and deployed in Y3Q4. This was necessary to support the new Septentrio receivers, as the previous software version only supported Trimble receivers.

A new system to manage and deliver accelerometer data to the IRIS DMC was deployed in Y4. The new system features modified software and runs in a virtual environment. This was done to address performance and stability issues related to older, unstable hardware. In addition, communication with IRIS was moved to a different Antelope ORB. The platform has been stable since migration, and data flow no longer requires constant monitoring.

3.6 Internal Computing Initiatives and Support

3.6.1 IT Highlights

UNAVCO uses two SANs (storage area networks) to support our computing environment. During this past year, several major outages for production and real-time data flow occurred as a result of having to replace internal batteries or controllers within the older SAN hardware. After the first outage, additional storage was purchased, installed and the storage for production and real-time servers was moved onto the new SAN. The new SAN is better able handle such events that caused the earlier outages along with many other device outages without impacting data flow. Storage for development and testing systems remains on the old SAN. In addition, Network File System (NFS) access was configured for file storage on the new SAN that is used by many of UNAVCO’s production systems. This feature allows any system connected to the new SAN to access all file system storage on the SAN directly. Enabling NFS on the new SAN improved overall system performance, reduced network traffic and reduced computing power consumption.
The IT group initiated the move to the 6.0 release of VMWare in Y4Q2, replacing a release that was more than 5 years old and limited in supporting file systems larger than 2 TB. This resulted in the need to divide the UNAVCO archive into multiple file systems within VMWare, which introduced performance and space usage issues. In addition, a Linux version was installed, eliminating the need for a Microsoft Server and reducing overall VMWare platform support costs. Remote maintenance hardware modules were also added to all of the real-time systems for remote access, should indirect network access not be available. SD cards were also installed to eliminate the need for on-system hard drives and to support platform resilience should a single system fail. These upgrade activities will continue in Y5.

At the beginning of Y4Q1, the servers used to support UNAVCO's production virtual environment were more than four years old, with increasing maintenance requirements. Four new servers have now replaced these older systems, providing greater computing power and network bandwidth. The higher network bandwidth also better supports circuit bandwidth of 1GB to 10GB capabilities.

All virtual servers supporting UNAVCO's production environment (except real-time GNSS) were moved to new servers in Y4. It now resides as a single cluster within UNAVCO's VMWARE environment. This allows VMWare to move resources within the production hardware environment to improve performance and resiliency. This dedicated cluster also isolates production systems from development, removing inadvertent impact of development on the production environment. It also isolates production from the real-time streams, protecting each environment from resource limitations in the other environment.

The phone system used by UNAVCO since its inception in 2003 became obsolete in Y4Q1. The IT group evaluated several replacement systems, and a new phone system was successfully installed by the end of Y4Q1. The new system is IP based and relies on existing ethernet connectivity, eliminating the need for extra dedicated phone wiring to support office phones.

The HP Servers and storage arrays supporting the New Mexico Tech (NMT) GPS data analysis center were moved to the Boulder Data Center. UNAVCO personnel helped in the network documentation, un-racking, packing and shipping of the servers from NMT to Boulder. Several VMs were created and used to support the processing needed for the subward while the move was occurring. Once the servers were installed in Boulder, processing moved back back to the HP servers.

Several open source software packages along with a server were installed, configured and tested to automate the process of configuring/installing new Macintosh laptops for employees at UNAVCO. This automation replaces manual installations, reducing the time required by IT staff who previously performed this task. It installs a from a gold master and provides a centralized software point of distribution that allow for patch upgrades as required.

UNAVCO began moving to a single, centralized Active Directory user authentication system in Y4 for the UNAVCO ONE-ID project. This which replaces several user authentication applications that were previously used. The new Active Directory structure better supports internal and external users and allows UNAVCO designated group administrators outside of IT to manage their designated groups.

### 3.6.2 Software Development

Internal software development supports the maintenance and development of software systems used only by UNAVCO staff to perform jobs functions. These systems support the tracking of equipment at field sites, metadata entry, tracking of travel requests, tracking of PI requests and support, automating formerly manual processes, registration for UNAVCO classes and conferences, installation of 3rd party systems used for tracking time and financial data within the company, and other systems used by UNAVCO personnel for internal business purposes. Web services are also developed to support the backend of the UNAVCO web site.
The automated collection and display of GDS metrics for GPS data was implemented in Y4. The backfilling of data metrics for previous periods was also completed. Some GI metrics were automated as well. Comparisons were performed each quarter to compare results against those still being reported manually to make sure they agreed. This new automated metrics system significantly improves the tracking and reporting of key metrics as reported to sponsors.

Software development staff worked on an enhancement to the UNAVCO MDM (Metadata Management System) to support the tracking of cellular data usage by tracking SIM cards used in cell modems. These enhancements can track SIM cards added to the system. Notifications are sent to accounting once a card is no longer in use and is then removed from billing, reducing data usage charges for cards between uses. This new feature is currently being tested and should be available early next year. The tracking of ESNs (Electronic Serial Numbers) was added to support tracking of accounts for G3 (Third Generation) data network providers. A variety of different equipment and IP billing accounts have made this capability difficult to develop and test. Scrubbing and correcting inconsistencies within the existing database now supports the required tracking. In addition, other enhancements requested by field engineers are being addressed and will soon be released.

A common task performed by IT staff is the creation and configuration of VPN connections for field stations. A single script was developed in Y4 support significant efficiencies in implementing these requests. A script performs the required configuration changes within seconds, thereby reducing IT staff time to input requests and eliminating added expense/time to verify or correct data entry errors.

Software engineering staff performed testing of the 9.6 Postgres release. This release provides improved performance when using data from multiple tables across different Postgres databases, something IT staff hopes to take advantage when the archive team completes their migration from Oracle to this same release on Postgres. Web services were developed to allow for retrieval of station page photos from the existing system. This will reduce verification of migration for new Postgres releases, as it replaces outdated software.

### 3.6.2 Web Software Developments

A new tool used by field engineers to monitor station operations was developed in Y4. This tool was created by web developers in close collaboration with field engineers to ensure speed, ease of use, customization and robustness as well as new functionality compared to the old system that is still running on the deprecated pbo.unavco.org web site.

Web pages for stations operated by UNAVCO were updated throughout Y4. Borehole station pages were updated with a new layout developed exclusively for borehole stations, for example, eliminating fields that applied only to GPS stations. Software enhancements also support a new map interface for all station pages. The new interface will allow users to interactively query information for all types of instruments managed by UNAVCO.

### 3.7 GDS PROGRAM SUMMARY

The Geodetic Data Services program manages all the steps from station metadata management and downloading, to data flow, product generation, archiving and advanced cyberinfrastructure developments, for a heterogeneous mix of sensors. The total volume of data, as well as the types of data and products, continues to grow, as does the user base. The complexity is also increasing with developments in RT-GPS, implementation of GNSS, handling of geophysical event data sets, refinements to TLS archiving processes, and new satellite SAR systems coming online. There is greater emphasis on classroom and field course support, including development of online tools. UNAVCO GDS activities continue to be international and collaborative in scope and participation. In
addition to participating in the International GNSS Service (IGS), the International Earth Rotation Service (IERS) governance, and supporting the IGS Central Bureau, UNAVCO has been working to help remove technical barriers to data sharing by defining best practices and developing software tools such as the Geodetic Seamless Archive Centers (GSAC) software to facilitate international data sharing and discovery from a broad community of international data repositories. Dataworks software was developed to provide an additional capability for network data management. Data web services, both those that are operational and those under development, are the framework for UNAVCO contributions to multi-technique, interdisciplinary, and integrative activities such as CooPEUS, GEO Supersites, EarthScope, and EarthCube. While developing new capabilities, UNAVCO is at the same time engaged in continual upgrades and modernization of its core services to streamline operations, to maintain a varied suite of software, hardware and databases, and to explore new ways to increase efficiencies such as by using using private and public cloud services.

4. Education and Community Engagement

The UNAVCO ECE program provides technical and educational professional development, materials, tools, and resources for students, teachers, university faculty, researchers and the general public. ECE promotes community science through outreach and broader impacts support and provides support to students and early career professionals through mentoring and internships for those interested in careers in geodesy and geosciences.

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4.1 ECE PROGRAM SUMMARY

Dedicated staff with expertise in geodesy, science education, journalism and communications, instructional design, and broadening participation in science four areas of focus aligned to the UNAVCO Strategic Plan and guided by a Logic Model (Figure 4-1). (A Logic Model is a graphical depiction of resources, audiences, and outcomes and guides program planning and implementation.)
Figure 4-1. Logic Model for the ECE Program.

The ECE outcomes for GAGE are articulated in Table 4-1 and are identified in column 7 of the logic model. Activities conducted in support of these outcomes were reported quarterly (see Quarterly Reports).

Table 4-1. ECE Outcomes expected during GAGE.

<table>
<thead>
<tr>
<th>Priority Area</th>
<th>Expected GAGE Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Professional Development</td>
<td>We will broaden the community using UNAVCO-supported tools, data, and instrumentation through technical training and online resources.</td>
</tr>
<tr>
<td>Education Resources</td>
<td>We will facilitate the development and dissemination of geodesy-focused educational materials.</td>
</tr>
<tr>
<td>Community Communications</td>
<td>We will facilitate greater communication of, access to, and dissemination of UNAVCO science and education to both the UNAVCO and broader community.</td>
</tr>
<tr>
<td>Geosciences Workforce Development</td>
<td>We will facilitate the development of a robust, well-trained and diverse geoscience workforce with the knowledge, skills, and abilities to tackle emerging scientific and societal issues.</td>
</tr>
</tbody>
</table>

Geodesy, Community and Society

As we approach the final year of the GAGE award, the ECE program continues to thrive in conducting outreach to the community, supporting education efforts across much of the K-16 spectrum, and engaging the next generation of geoscientists in professional development and research opportunities. Y4 effort centered on improving dissemination of materials and broadening the audiences we reach through our multiple activities.
Education and outreach materials continue to reach a broad audience including teachers, students, UNAVCO community members, and landowners who host UNAVCO supported instrumentation. An updated poster of the Tectonic Map of Alaska was distributed to 14,000 teachers across the U.S. as part of the AGI Earth Science Week, with another 2,000 posters reserved for general distribution. Geodesy-focused curricular materials for incorporation into undergraduate program were published and disseminated to university faculty as part of the GEodesy Tools for Societal Issues (GETSI) and the SERC InTeGrate projects. The PBO SiteLog was distributed to hundreds of private landowners and has resulted in greater understanding by landowners and notably a reduction in our permitting costs as landowners were willing to either reduce or eliminate the permitting costs.

More than 200 community members and students participated in short courses and workshops primarily on geodetic imaging and InSAR in courses held at UNAVCO, at partner organizations (Scripps Institute of Oceanography; OpenTopography), professional meetings (AGU and AGU), and through online technologies. Students benefited from UNAVCO support for participation in short courses as well as informal meetings and networking at the AGU and AGU annual meetings. Three summer internship programs brought a record number of 24 students to work with UNAVCO offering them a glimpse into the world of science as well as providing professional development in the areas of scientific writing, formal and informal communications, and skills needed for professional success.

**Partnerships**

ECE developed new collaborations and strengthened and refined the focus of existing partnerships with the following organizations and institutions of higher education:

**Organizations:** American Geosciences Institute (AGI), American Geophysical Union (AGU), EarthScope National Office, ExxonMobil Foundation, Federation of Earth Science Information (ESIP), Geological Society of America (GSA), Hatfield Museum Science Center, Incorporated Research Institutions for Seismology (IRIS), Mt. St. Helens Institute, Mt. St. Helens National Volcanic Monument - U.S. Forest Service, National Earth Science Teachers Association (NESTA), National Ecological Observatory network (NEON), National Oceanic and Atmospheric Administration-Earth System Research Laboratory (NOAA-ESRL), Pacific Northwest Seismic Network, Pacific Science Center, Science Education Resource Center (SERC), Smithsonian National Museum of Natural History, Southern California Earthquake Center (SCEC), University Corporation for Atmospheric Research (UCAR), USGS Cascade Volcano Observatory.

**Colleges and Universities:** Austin Community College, Baylor University, Carleton College, College of the Atlantic, College of William and Mary, Colorado State University, Colorado School of Mines, Front Range Community College, Idaho State University, Indiana University, Lamont Doherty Earth Observatory, Mt. San Antonio College, Oregon State University, Pennsylvania State University, University of Arizona, University of Colorado-Boulder, University of Houston, University of Michigan, University of North Texas, University of Northern Colorado, University of Oklahoma, University of Victoria, Syracuse University, Virginia Tech, Wesleyan University.

**5. Summary**

GAGE Y4 was another exciting and productive year, and much has been accomplished. The membership continues to grow, as does UNAVCO's national and international impact.

During GAGE Y4, the Geodetic Infrastructure Program focused on completing the challenging borehole strainmeter installations in Turkey with the final installation of uphole electronics, including power and telecommunications systems (5 of 6 stations are delivering data to the UNAVCO archive), the closing out the cGPS/Met station installations in Mexico for TLAOCNet, which now is finished in accordance with the original MRI plan, and continued efforts keep COCONet funded and operational.
through the close of the GAGE Facility. Continuing O&M for the PBO GNSS and BSM networks remain a high priority and these tasks account for much of the effort and resources available to the GI Program under the GAGE Facility. The PBO GNSS Operations team continues to implement the recommendations from the “PBO Futures” workshop report during GAGE Y4, including installing 104 out of 120 new Septentrio PolaRx5 multi-constellation GNSS instruments at PBO stations. At the time of the writing of this report, 244 multi-constellation GNSS receivers (140 Trimble NetR9 GPS+GLONASS and 104 Septentrio PolaRx5) along with broad-band GNSS choke ring antenna have been deployed across PBO, resulting in a modernization of ~22% of the network.

The GI Director continued efforts on the writing committee for the NASA Challenges and Opportunities for Research in ESI (CORE) workshop held in Arlington, VA 2-3 November 2015; this report was published by NASA and made available to the scientific community in early December 2016 (Davis et al., 2016). In GAGE Y3, GI Director Mattioli acted as PI with GDS Director Meertens as Co-PI on a solicited proposal to the USGS Earthquake Hazards Program ShakeAlert FY2016 Program Announcement GA16AS00042 entitled “Incorporating Real-time GNSS into ShakeAlert: Collaborative Proposal between Central Washington University and UNAVCO, Inc.,” with a requested budget of $2.46M for 2 years. The UNAVCO component of this Collaborative Proposal unfortunately was declined. In GAGE Y4, Mattioli and Meertens used the feedback from the USGS panel along with additional guidance from existing ShakeAlert Centers and USGS staff to develop and submit a substantially revised proposal to the FY2017 USGS Program Announcement G17AS00042 entitled “Incorporating Real-time GNSS into ShakeAlert: Improving telemetry, reducing latency, and enhancing robust GNSS data flow at existing PBO stations in CA, OR, and WA,” with a requested budget of $698K for 2 years. This proposal was selected for funding and a new Cooperative Agreement between the USGS and UNAVCO, Inc. was executed in early August 2017. The USGS effort leverages the significant NSF investment in PBO RT-GNSS assets in CA, OR, and WA.

At the close of Y4, the GI group headcount is 38 with 36.40 FTE, including staff supported by NSF EAR and OPP and NASA. The overall headcount as well as FTE are down 2.0 relative to the close of GAGE Y3 as a result of the resignation of Mr. J. Sandru, an Engineer II in the EAR PI Support group in late October 2016, and resignation of Mr. H. Berglund, an Engineer III in the D&T group in February 2017. There are no plans to add additional staff to the GI group at this time.

During GAGE Y4, the Geodetic Infrastructure Program advanced its primary task of operations and maintenance for the PBO GPS and borehole geophysics networks, accounting for much of the effort and resources available to the GI Program under the GAGE Facility. The PBO GNSS Operations team continued installment of 104 new Septentrio PolaRx5 multi-constellation GNSS instruments at PBO stations. Now 244 multi-constellation GNSS receivers (140 Trimble NetR9 GPS+GLONASS and 104 Septentrio PolaRx5) with broad-band GNSS choke ring antenna are deployed across PBO, resulting in a modernization of ~22% of the network.

The Geodetic Data Services program strengthened and updated the systems that support station metadata management, data flow, development and production of data products, archiving and advanced cyberinfrastructure developments, for the heterogeneous mix of supported sensors. The total volume of data, as well as the types of data and products, continued to grow, as does the user base. New capabilities in real-time GPS, refinements in archiving and user support, and participation in IGS governance continued as important areas of contribution in Y4.

UNAVCO GDS activities continue to be international and collaborative in scope and participation. In addition to contributions to the International GNSS Service (IGS), the International Earth Rotation Service (IERS) governance, and supporting the IGS Central Bureau, UNAVCO works to remove barriers to data sharing by defining best practices and developing new software tools to facilitate international data sharing and discovery from a broad international community. While developing new capabilities, UNAVCO is at the same time engaged in continual upgrades and modernization of its core services to streamline operations, to maintain a varied suite of software, hardware and
databases, and to explore new ways to increase efficiencies such as by using private and public cloud services.

The Education and Community Engagement Program continued to expand its reach through internal collaborations with GI and GDS, as well as establishing new external partnerships in the science education and outreach community. Activities promoted the expanded use of UNAVCO-supported tools, data sets, and instrumentation; disseminated innovative, geodesy-focused educational resources; enhanced visibility and impact for UNAVCO science and education; and created innovations while contributing to capacity for geoscience workforce development.
**Geodesy Advancing Geosciences and EarthScope: GAGE Annual Project Report**

**Year 4 reporting period: 01 July 2016 - 30 June 2017**

**Appendix A: Continuous GPS networks for which UNAVCO is providing support.**

UNAVCO provides operations and management (O&M) support at various levels to continuously operating GPS stations in PI networks. The O&M support includes data downloading, state of health monitoring and reporting, resolving communications and equipment issues, shipping replacement equipment, and working with PIs and local contacts to resolve problems. UNAVCO, working closely with PIs and their collaborators, provides this O&M support at three broad levels of effort:

- **High**—UNAVCO provides centralized O&M support that may include retrieving the data, monitoring station data flow, and proactively responding to problems with data flow or station hardware. Problems are fixed remotely working with collaborators if necessary. If maintenance trips or materials are required for O&M, these are provided by the PI’s project.

- **Medium**—PI or collaborators download the data from the stations, monitor station data flow, and handle most problems themselves. UNAVCO provides engineering and technical support on a request basis. Any UNAVCO Engineering maintenance trips and materials required for O&M are provided by the PI's project.

- **Low**—UNAVCO provides only archiving support and a low-level of technical support. UNAVCO does not monitor or download data from the stations. UNAVCO provides engineering and technical support on a request basis.

<table>
<thead>
<tr>
<th>Network Name or Location</th>
<th>Principal Investigator</th>
<th># Stations</th>
<th>PI Funding Source</th>
<th>Level of Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa Array</td>
<td>Andy Nyblade, Penn State University</td>
<td>18</td>
<td>NSF-EAR: Geophysics</td>
<td>high</td>
</tr>
<tr>
<td>Caltech Nepal</td>
<td>Jean-Philippe Avouac, California Institute of Technology</td>
<td>27</td>
<td>NSF-EAR</td>
<td>high</td>
</tr>
<tr>
<td>COCONet</td>
<td>John Braun, UCAR et al</td>
<td>129</td>
<td>NSF-EAR: IF</td>
<td>high</td>
</tr>
<tr>
<td>Costa Rica - Nicoya</td>
<td>Tim Dixon, University of Miami</td>
<td>16</td>
<td>NSF-EAR: Tectonics</td>
<td>high</td>
</tr>
<tr>
<td>Hastings</td>
<td>Timothy Dixon, USF</td>
<td>4</td>
<td>Community Other</td>
<td>high</td>
</tr>
<tr>
<td>HoustonNet</td>
<td>Guoquan Wang, University of Houston</td>
<td>65</td>
<td>NSF-EAR: IF</td>
<td>high</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>Rob Reilinger, Massachusetts Institute of Technology</td>
<td>12</td>
<td>NSF-EAR: Tectonics</td>
<td>high</td>
</tr>
</tbody>
</table>

Table A-1. List of continuous GPS networks supported by UNAVCO in GAGE Y4 for EAR and Community investigators.
<table>
<thead>
<tr>
<th>Region</th>
<th>Institution details</th>
<th>Number</th>
<th>Category</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-America</td>
<td>Bob Smalley, University of Memphis</td>
<td>15</td>
<td>NSF-EAR: IF</td>
<td>high</td>
</tr>
<tr>
<td>Mississippi Delta</td>
<td>Tim Dixon, USF</td>
<td>3</td>
<td>Community</td>
<td>high</td>
</tr>
<tr>
<td>Pakistan</td>
<td>Roger Bilham, University of Colorado</td>
<td>4</td>
<td>NSF-EAR: Tectonics</td>
<td>high</td>
</tr>
<tr>
<td>Oklahoma Deformation</td>
<td>Robert Smalley, University of Memphis</td>
<td>8</td>
<td>NSF-EAR: RAPID</td>
<td>high</td>
</tr>
<tr>
<td>Pacaya Volcano</td>
<td>Gregory Waite, MTU</td>
<td>1</td>
<td>NSF-EAR: Geomorphology and Land Use Dynamics</td>
<td>high</td>
</tr>
<tr>
<td>Panama</td>
<td>Peter LaFemina, Penn State University</td>
<td>4</td>
<td>NSF-EAR: CAREER</td>
<td>high</td>
</tr>
<tr>
<td>RAPID-Bolivia</td>
<td>Mike Bevis, Ohio State University</td>
<td>11</td>
<td>NSF-EAR: RAPID</td>
<td>high</td>
</tr>
<tr>
<td>RAPID-Mineral</td>
<td>Seth Stein, Northwestern University</td>
<td>2</td>
<td>NSF-EAR: RAPID</td>
<td>high</td>
</tr>
<tr>
<td>Rio Grande Rift</td>
<td>Anne Sheehan, University of Colorado</td>
<td>22</td>
<td>NSF-EAR: EarthScope</td>
<td>high</td>
</tr>
<tr>
<td>Susitna-Watana</td>
<td>Jeff Freymueller, University of Alaska</td>
<td>1</td>
<td>Community - UAF</td>
<td>high</td>
</tr>
<tr>
<td>Tanzania Volcano Observatory</td>
<td>Sarah Stamps, Virginia Tech</td>
<td>5</td>
<td>Community</td>
<td>high</td>
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<tr>
<td>Telica Volcano</td>
<td>Peter LaFemina, Penn State University</td>
<td>16</td>
<td>NSF-EAR: Petrology and Geochemistry</td>
<td>high</td>
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<tr>
<td>TLAOCNet</td>
<td>UNAVCO Community</td>
<td>35</td>
<td>NSF-EAR: IF</td>
<td>high</td>
</tr>
<tr>
<td>Oak Ridge Earthflow Observatory</td>
<td>Noah Finnegan</td>
<td>1</td>
<td>NSF-EAR: Geomorphology and Land Use Dynamics</td>
<td>medium</td>
</tr>
<tr>
<td>Alaska</td>
<td>Jeff Freymueller, University of Alaska, Fairbanks</td>
<td>9</td>
<td>NSF-EAR</td>
<td>medium</td>
</tr>
<tr>
<td>Andaman Islands</td>
<td>John Paul, Memphis State University</td>
<td>3</td>
<td>NSF-EAR: Geophysics</td>
<td>medium</td>
</tr>
<tr>
<td>Azerbaijan Continuous</td>
<td>Rob Reilinger, Massachusetts Institute of Technology</td>
<td>3</td>
<td>NSF-EAR: Geophysics</td>
<td>medium</td>
</tr>
<tr>
<td>BARGEN</td>
<td>Brian Wernicke, California Institute of Technology</td>
<td>8</td>
<td>NSF-EAR</td>
<td>medium</td>
</tr>
<tr>
<td>Calabria</td>
<td>Michael Steckler, LDEO, Columbia University</td>
<td>2</td>
<td>NSF-EAR: IF</td>
<td>medium</td>
</tr>
<tr>
<td>Region</td>
<td>Principal Investigator</td>
<td>Credits</td>
<td>Program Area</td>
<td>Intensity</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------------------------------------------------------------</td>
<td>---------</td>
<td>--------------------------------------------------</td>
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</tr>
<tr>
<td>Central Asia</td>
<td>Tom Herring, Massachusetts Institute of Technology</td>
<td>6</td>
<td>NSF-EAR: Continental Dynamics</td>
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<tr>
<td>Central Iceland</td>
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<td>Colorado Plateau</td>
<td>Corné Kreemer, University of Nevada Reno</td>
<td>33</td>
<td>NSF-EAR: EarthScope</td>
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<td>CORS</td>
<td>Giovanni Sella, NGS/CORS</td>
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<td>Community NGS/CORS</td>
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<tr>
<td>E. Med and Red Sea</td>
<td>Rob Reilinger, Massachusetts Institute of Technology</td>
<td>2</td>
<td>NSF-EAR: Tectonics</td>
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<td>Continuous</td>
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<tr>
<td>Ecuador</td>
<td>Peter La Femina, Penn State University</td>
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<td>Community Other</td>
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<tr>
<td>Ecuadoe- IGEPN</td>
<td>Patricia Mothes. IGEPN</td>
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<td>El Salvador</td>
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<tr>
<td>Ethiopia Tectonics</td>
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<td>Dennis Geist, University of Idaho</td>
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<tr>
<td>GPS Soil Moisture</td>
<td>Kristine Larson, University of Colorado</td>
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<tr>
<td>GULFNET</td>
<td>Roy Dokka, Louisiana State University</td>
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<td>HOPRnet</td>
<td>Ronni Grapenthin</td>
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<td>Jalisco, Mexico</td>
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<td>Las Vegas</td>
<td>Geoff Blewitt, University of Nevada, Reno</td>
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<td>Malawi Rifting</td>
<td>Donna Shillington, Columbia University</td>
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<td>Mauna Loa</td>
<td>James Foster, University of Hawaii</td>
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<td>Nepal</td>
<td>Jean-Philippe Avouac, California Institute of Technology</td>
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<td>Oaxaca, Mexico</td>
<td>Chuck DeMets, University of Wisconsin-Madison</td>
<td>1</td>
<td>NSF-EAR: Geophysics</td>
<td>medium</td>
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<tr>
<td>PLUTONS</td>
<td>Matt Pritchard, Cornell University</td>
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<td>NSF-EAR: Continental Dynamics</td>
<td>medium</td>
</tr>
<tr>
<td>Location</td>
<td>PI/Institution</td>
<td>Number</td>
<td>Key</td>
<td>Level</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------------------------------------------</td>
<td>--------</td>
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<td>Salmon Falls Creek</td>
<td>Bejamin Crosby, ISU</td>
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<td>Southeast Montana</td>
<td>Becky Bendick, University of Montana</td>
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<td>Tajik-Kyrgyz-Pamir</td>
<td>Becky Bendick, University of University of Montana</td>
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<td>University of Houston Field Camp</td>
<td>Guoquan Wang, University of Houston</td>
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<td>NSF-EAR</td>
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<td>Andaman Islands</td>
<td>John Paul, Memphis State University</td>
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<td>NSF-EAR: Geophysics</td>
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<td>CAP Andes</td>
<td>Mike Bevis, Ohio State University</td>
<td>38</td>
<td>NSF-EAR: RAPID</td>
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<td>Caltech Andes</td>
<td>Mark Murray, California Institute of Technology</td>
<td>10</td>
<td>NSF-EAR</td>
<td>low</td>
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<td>Denali Fault</td>
<td>Jeff Freymueller, University of Alaska, Fairbanks</td>
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<td>EBRY</td>
<td>Bob Smith, University of Utah</td>
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<td>Community USGS</td>
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<td>Eritrea</td>
<td>Rob Reilinger, Massachusetts Institute of Technology</td>
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<td>NSF-EAR: Tectonics</td>
<td>low</td>
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<td>Idaho National Laboratory</td>
<td>Suzette Payne, Idaho National Laboratory</td>
<td>15</td>
<td>Community INEL</td>
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<td>MacKenzie Mountains</td>
<td>Jeff Freymueller, University of Alaska</td>
<td>3</td>
<td>NSF-EAR: Geophysics</td>
<td>low</td>
</tr>
<tr>
<td>Popocatepetl</td>
<td>Enrique Cabral-Cano, UNAM</td>
<td>1</td>
<td>Community Other</td>
<td>low</td>
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<td>Puerto Rico</td>
<td>Alberto Lopez, UPRM</td>
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<td>Community Other</td>
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<tr>
<td>SAGE, New Zealand</td>
<td>Peter Molnar, University of Colorado</td>
<td>10</td>
<td>NSF-EAR: Tectonics</td>
<td>low</td>
</tr>
<tr>
<td>Santorini</td>
<td>Andrew Newman, Georgia Tech</td>
<td>4</td>
<td>NSF-EAR: Geophysics</td>
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<tr>
<td>Socorro</td>
<td>Ronni Grapenthin, NMT</td>
<td>1</td>
<td>Community Other</td>
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<td>Solano County</td>
<td>UNAVCO Community</td>
<td>2</td>
<td>Community Other</td>
<td>low</td>
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<tr>
<td>SuomiNet-A</td>
<td>Various EAR/ATM PIs</td>
<td>5</td>
<td>NSF-ATM</td>
<td>low</td>
</tr>
<tr>
<td>SuomiNet-G (Geodetic)</td>
<td>Various EAR/ATM PIs</td>
<td>2</td>
<td>NSF-ATM</td>
<td>low</td>
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<tr>
<td>USGS Volcano Science Center</td>
<td>Alaska, Hawaii, and Cascade Volcano Observatories</td>
<td>134</td>
<td>Community - USGS</td>
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### Table A-2. List of continuous GPS networks supported by UNAVCO in GAGE Y4 for PLR investigators.

<table>
<thead>
<tr>
<th>Network Name or Location</th>
<th>Principal Investigator</th>
<th># Stations</th>
<th>PI Funding Source</th>
<th>Level of Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arctic Networks</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>GNET</td>
<td>Michael Bevis, Ohio State University</td>
<td>42</td>
<td>NSF Polar Programs</td>
<td>High</td>
</tr>
<tr>
<td>Collaborative Research: Impact of subglacial discharge on turbulent plume dynamics and ocean-glacier heat and mass transfer</td>
<td>Jason Amunden, University of Alaska</td>
<td>3</td>
<td>NSF Polar Programs</td>
<td>Med</td>
</tr>
<tr>
<td>Arctic UNAVCO operated cGPS reference stations (Located at Barrow, Toolik Lake Camp, Atqasuk in Alaska and Summit Camp in Greenland.)</td>
<td>UNAVCO</td>
<td>4</td>
<td>NSF Polar Programs</td>
<td>Med</td>
</tr>
<tr>
<td>GLISN</td>
<td>IRIS/PASSCAL</td>
<td>3</td>
<td>NSF-EAR</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Antarctic Networks</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LARISSA</td>
<td>Eugene Domack, Hamilton College</td>
<td>9</td>
<td>NSF Polar Programs</td>
<td>Med</td>
</tr>
<tr>
<td>ANET</td>
<td>Terry Wilson, Ohio State University</td>
<td>42</td>
<td>NSF Polar Programs</td>
<td>High</td>
</tr>
<tr>
<td>Collaborative Research: Integrative Study of Marine Ice Sheet Stability and Subglacial Life Habitats - Lake and Ice Stream Subglacial Access Research Drilling (LISSARD/WISSARD)</td>
<td>Slawomir Tulaczyk, UC Santa Cruz</td>
<td>8</td>
<td>NSF Polar Programs</td>
<td>Med</td>
</tr>
<tr>
<td>Antarctic UNAVCO operated cGPS reference stations (Located at McMurdo Station, South Pole Station, Palmer Station.) Plus one Development and Test site.</td>
<td>UNAVCO</td>
<td>5</td>
<td>NSF Polar Programs</td>
<td>Low</td>
</tr>
<tr>
<td>Collaborative Research: Role of the Central Scotia Sea Floor and North Scotia Ridge in the Onset and Development of the Antarctic Circumpolar Current</td>
<td>Ian Dalziel, University of Texas, Austin</td>
<td>3</td>
<td>NSF Polar Programs</td>
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</tr>
</tbody>
</table>
Geodesy Advancing Geosciences and EarthScope: GAGE Annual Project Report

Year 4 reporting period: 01 July 2016 - 30 June 2017

Appendix B: Impacts

1. What is the impact on the development of the principal discipline(s) of the project?

UNAVCO is the geodetic facility for NSF supporting geoscience research and education using geodesy. Scientific investigations supported include the study of earthquake processes, mantle properties, active magmatic systems, plate boundary zone deformation, intraplate deformation and glacial isostatic adjustment, global geodesy and plate tectonics, atmospheric science, global change, and polar processes. Details of projects supported are given in the accomplishments section of this report.

2. What is the impact on other disciplines?

UNAVCO facilitates cutting edge, interdisciplinary science using geodesy within the broader realm of science, technology, engineering and mathematics (STEM). In addition to the core discipline of geodesy, the instrumentation, data, tools, and data products provide scientific researchers from a wide variety of geoscience disciplines to several UNAVCO services. This provides a plethora of disciplines with cutting edge technology to support scientific investigations.

In addition, geoscience applications are included in STEM education materials and distributed at both the K-12 level and in higher education. The inclusion of UNAVCO data into education materials is transforming instruction. It provides students with an unprecedented opportunity to be immersed in the science using real world data. This is critical in training the next generation of scientists at the university level and is an emerging focus of K-12 education with the development and adoption of the Next Generation Science Standards (NGSS).

3. What is the impact on the development of human resources?

UNAVCO supports a highly popular short course series each year whereby community experts teach a short course in their disciplinary expertise. The courses provide training in cutting edge scientific techniques and software for processing and analyzing data from the UNAVCO data archive. UNAVCO provides financial support for students to attend to ensure training of the next generation of scientists. During this reporting period, UNAVCO formalized short courses for university faculty to assist in their incorporating geodetic data and instrumentation into courses and field experiences.

UNAVCO sponsored two short courses serving nearly 100 participants including researchers, university faculty, graduate students, postdoctoral scholars, undergraduate students, and K-12 faculty. When possible, courses are offered in a hybrid format (synchronous online and face-to-face), in essence doubling the capacity of courses and enabling us to reach a broader - global - audience.
UNAVCO staff provided mentoring support for three summer research internships. The Research Experiences in Solid Earth Science for Students (RESESS) program serves underrepresented minorities in geosciences. Eight undergraduate students participated in the program in 2017. UNAVCO hosted a science colloquium featuring the research of each student, providing them the opportunity to develop their research presentation skills. The Geo-Launchpad internship program is a work-experience internship for Colorado community college students. UNAVCO hosted eight students, four of whom worked at the U.S. Geological Survey in Lakewood, Colorado. They worked under the supervision of USGS staff, providing staff with both the opportunity to engage with community college students and learn more about the work UNAVCO conducts and supports. UNAVCO engineers directly mentored four Geo-Launchpad interns. UNAVCO also supports the UNAVCO Student Internship Program (USIP) where interns from undergraduate and graduate programs conduct work directly on UNAVCO-GAGE scope of work. Seven USIP interns worked under the supervision of six UNAVCO staff, some of whom do not have regular management responsibilities.

UNAVCO supports the maintenance of a GPS/PBO focused museum display at the Hatfield Marine Science Center in Newport, Oregon, a Sea Grant Institution. The exhibit highlights the EarthScope Plate Boundary Observatory network in the Pacific Northwest with its upgraded realtime data streaming capabilities. The museum hosts over 150,000 visitors annually. Monitoring a Shifting Earth is a hands-on exhibit designed to reach a broad audience, including students either on field trips or after school programs, families, and senior groups. The exhibit offers a regional perspective on the processes responsible for earthquakes and tsunamis in the Pacific Northwest. Museum visitors explore and learn about basic plate tectonics concepts and natural hazards relevant to the Pacific Northwest, how the GPS in a smartphone compares to a high precision GPS receiver used by the EarthScope Plate Boundary Observatory, and how land near the coastline is being squeezed inland and building potential energy that could be released as an earthquake, resulting in strong ground shaking and tsunamis. Additionally, visitors learn about the role that the upgraded PBO GPS network is expected to play in hazard mitigation with a combined real time GPS and seismometer earthquake early warning system.

Education materials provided via the UNAVCO and Science Education Research Center (SERC) at Carleton College were accessed by K-12 teachers and college faculty and incorporated into their classes. The implementation of these materials into the classroom has impacts upward of 2,500 undergraduate students per year.

UNAVCO staff provided exposure of the facility work through outreach to local community groups, park service professionals and interpreters, K-12 students and teachers, and undergraduate students. Outreach activities include science cafes, formal and informal presentations, participation in community organized science fairs, and field camps and field education experiences. Details of the specific number of individuals reached in various audience groups is provided above.

4. What is the impact on physical resources that form infrastructure?

As described in the accomplishments, the equipment, engineering, data, and educational resources provided by UNAVCO ensure high quality data are acquired, archived and curated. UNAVCO is a leader in NSF facilities in leveraging emerging technologies and best practices, including transforming the physical resources to support the community including cloud computing, virtual machines, online short course instruction, and an expanded online database for engineers and researchers.
5. What is the impact on institutional resources that form infrastructure?

As described in the accomplishments, equipment, engineering, data and educational resources provided by UNAVCO ensure high quality data are acquired, archived and curated. UNAVCO follows best practices expected of an NSF Large Facility and is a leader in establishing best practice for business affairs. UNAVCO has been referenced as an exemplary of large facilities for business execution.

6. What is the impact on information resources that form infrastructure?

Same as above.

7. What is the impact on technology transfer?

UNAVCO staff under GAGE provided support for community networks including the Caribbean network (Continuously Operating Caribbean GPS Observational Network, COCONet) and Mexican GPS-Meteorological Observational Network (TLALOCNet). Regional Data Centers and Regional Mirror Data Center Sites provide additional community capacity in the Caribbean as a result of UNAVCO training and assistance with infrastructure development. Software developed for the Regional Data Centers (Dataworks) is available to any group having data to share.

8. What is the impact on society beyond science and technology?

UNAVCO outreach efforts have a broad impact on a large segment of society, beyond our key research and academic stakeholders. The PBO SiteLog and customized site inserts is distributed to citizens who currently host UNAVCO-maintained instrumentation on their land. The SiteLog provides an overview of the PBO Network highlighting the value to the citizens of the U.S. A museum display in Oregon featuring GPS and the Plate Boundary Observatory improves public knowledge about the basic of GPS and the value of GPS to earthquake early warning and tsunami warning. Through social media (Instagram, Pinterest, YouTube, Facebook and Twitter) UNAVCO has reached tens of thousands of individuals beyond our core stakeholders. Instagram posts share the work UNAVCO supports in a visual manner with the ability to tag and search easily. Pinterest is used by a high percentage of K-12 educators, thereby increasing our reach to the next generation of scientists with visual representation of what science supports. YouTube videos provide explanations and show animations of complicated scientific concepts related to UNAVCO supported science. Videos are also available of seminars focused on community science. The UNAVCO Twitter feed reaches an audience interested in science news, policy, and geo-related opportunities. The UNAVCO Facebook page engages a broad spectrum of the geoscience interested public through geoscience news, interesting facts, summaries and photos of UNAVCO activities in support of the community, and geo-focused humor. Communications are framed in “plain English” and easy to understand terms to reach the broadest audience. The combination of these media channels has resulted in more people than ever being aware of and engaged in the conversation about UNAVCO supported science.
Geodesy Advancing Geosciences and EarthScope: GAGE Annual Project Report - NASA Scope

Year 4 reporting period: 01 July 2016 - 30 June 2017

Appendix C: NASA Project Support

1. Introduction

Herein we report the activities of the NASA component of the 4th year (GAGE Y4) of the 5-year UNAVCO Cooperative Agreement 2013 – 2018 UNAVCO Community Proposal Geodesy Advancing Geosciences and EarthScope (GAGE) (NSF EAR – 1261833). The GAGE Facility, through this Cooperative Agreement (CA), provides engineering, equipment and data services that support research projects for investigators using a spectrum of geodetic techniques to conduct scientific investigations that include the study of earthquake processes, mantle properties, active magmatic systems, plate boundary zone deformation, intraplate deformation and glacial isostatic adjustment, global geodesy and plate tectonics, atmospheric science, global change, polar science, and hydrogeodesy. These projects are NSF-EAR, NSF-OPP Arctic and Antarctic, and NASA-funded and include individual Principal Investigator (PI) projects, as well as large interdisciplinary collaborative community projects for shared infrastructure and open data sets. Core infrastructure supported under GAGE includes operation of the NSF EarthScope Plate Boundary Observatory (PBO), COCONet, TLALOCNet and the NASA Global GNSS Network (with JPL). Larger PI projects include AfricaArray, GNET and ANET, collectively known as POLENET.

Geodesy is a global science and through its NASA-funded GAGE components UNAVCO has played an important role in international collaborations required to realize the modern terrestrial reference frame, share global data, and produce products needed for high-precision space geodesy. With NASA support and in collaboration with JPL, UNAVCO operates the Global GNSS Network (GGN). The GGN is a major contributor to the International GNSS System (IGS) and has sites located in some of the more remote but important locations around the globe. UNAVCO also participates in governance of the IGS and in working groups and supports the operations of the IGS Central Bureau including network coordination. UNAVCO participates in the European Geophysical Union, American Geophysical Union, WEGENER, and the Scientific Committee on Antarctic Research (SCAR). Recent NSF cyberinfrastructure projects such as COOPEUS and EarthCube and the NASA ROSES ACCESS program have augmented GAGE core resources and contributed towards building a framework for a sustainable, transatlantic, environmental-research infrastructure and fostered collaboration here and abroad. NASA contributes to UNAVCO development and testing activities that range from testing of new receivers for the GGN and implementation of multi-constellation GNSS observations to investigating ways to mitigate effects of radio interference. Finally NASA contributes to the UNAVCO support of WInSAR, the consortium of institutions using SAR and InSAR and UNAVCO Education and Community Engagement.

This annual report presents the NASA highlights, activities, and performance metrics for Year 4 of the GAGE award. To ensure timely submission, and because the report must be approved prior to the actual year end, the narrative below describes work from Y3Q4 through Y4Q3, and metrics include a complete summary of years 1 and 2 and 3, and a roll up Y4Q1-3. The narrative may also report on some events from Y4Q4. The content of this report will be rolled into the full NSF/NASA GAGE annual report and submitted for the record into Research.gov.

2. Geodetic Infrastructure Program
2.1 OVERVIEW

This UNAVCO program integrates all geodetic infrastructure and data acquisition capabilities for continuously operating observational networks and shorter term deployments of geodetic instruments. Supported activities include development and testing, advanced systems engineering, the construction, operation, and maintenance of permanent geodetic networks around the globe, and engineering services tailored to PI project requirements. The GI program coordinates closely with Geodetic Data Services program (Section 3) to ensure the highest standards of data quality control, integrity of metadata, ease and transparency of data access for the UNAVCO user community, and to provide appropriate and timely metrics on data usage for sponsors. Major projects currently supported by the GI program include the 1,131 station Plate Boundary Observatory (PBO) core and affiliated stations, NASA’s Global GNSS Network (GGN), polar networks in Greenland and Antarctica (GNET and ANET, together known as POLENET), COCONet spanning the Caribbean plate and its boundaries, and TLALOCNet in Mexico, the multidisciplinary AfricaArray, and several other smaller continuously observing geodetic networks. UNAVCO now supports operations and management (O&M) of more than 900 cGPS stations globally in 63 different PI networks.

The GI program provides engineering services to individual PIs for shorter term GPS and TLS projects, and other investigator-led data acquisition that had been previously managed by the UNAVCO Facility. A large share of GI resources in GAGE are tied to ongoing O&M of the PBO, GGN, and POLENET continuous GPS (cGPS) networks and ongoing support to PI projects. Individual NASA PIs normally are supported on a full-cost recovery basis.

The GI Director and GAGE Facility Co-PI G. Mattioli was part of the organizing committee for the NASA Earth Surface and Interior (ESI) Focus Area Workshop held November 2-3, 2015 in Arlington, VA. Mattioli continued his service to NASA during GAGE Y4 as part of the writing team that produced the final report entitled “Challenges and Opportunities for Research in ESI (CORE),” Davis et al., 2016, which was published in print and distributed electronically by NASA and UNAVCO in December 2016 (See NASA’s report: CHALLENGES AND OPPORTUNITIES FOR RESEARCH IN ESI (CORE).

2.2 NASA GLOBAL GNSS NETWORK (GGN) FIELD SUPPORT

2.2.1 GGN Support Overview

UNAVCO, under the direction of the Jet Propulsion Laboratory (JPL), is responsible for the operations and maintenance of 59 permanent GNSS stations that contribute to the NASA Global GNSS Network (GGN) (Figure 2-1). Eighty-eight receivers are operated, as 19 stations have multiple receivers sharing single antennas, including new multi-constellation-capable instruments. The new instruments operate side-by-side with legacy hardware and receivers that are part of the NASA Space Geodesy Program (SGP). It is important to note that these station and receiver counts change over time as determined by JPL’s requirements (e.g., decommissioning of legacy receivers, adding new receivers, changes in monitoring responsibilities, etc.)

UNAVCO staff members, including two full-time Engineers and 20% FTE Project Manager, monitor station network connections, ship replacement equipment to site operators as necessary, and construct new permanent sites as specified by JPL. UNAVCO staff work closely with local collaborators at each station for routine maintenance and troubleshooting data flow interruptions, and perform field maintenance and upgrades. UNAVCO GGN network support metrics are summarized in Table 2-1.

UNAVCO’s primary objective is to keep the GGN running at full capacity, and this past year was very successful, with network health remaining at or above 95% during the entire reporting period. Many computer and power system upgrades at GGN stations were done by local collaborators using hardware provided by UNAVCO and directed by our engineering staff. Notable field projects
completed this year included the installation of a new GGN station in Fairbanks, AK, and major hardware upgrades at stations in Cachoeira Paulista, Brazil, the Galapagos Islands, the Harvest oil platform in Southern California, and Santiago, Chile. In addition, new computers and multi-constellation capable receivers were deployed to various other GGN sites around the globe.

Figure 2-1. Operational state of the NASA GGN on June 30, 2017. Green stations are online; red stations have been offline for more than a week; grey stations offline for more than one month.

<table>
<thead>
<tr>
<th>Period</th>
<th>GNSS Stations Monitored (Qty)</th>
<th>GNSS Receivers Monitored (Qty)</th>
<th>Troubleshoots (Qty)</th>
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<td>July - September, 2016</td>
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<td>April - June, 2017</td>
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<tr>
<td>Total July 2016 - June 2017</td>
<td>59</td>
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<td>579</td>
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</table>

2.2.2 GGN Support Highlights: July - September, 2016

In GAGE Y3Q4, UNAVCO staff completed construction of station GCGO, a new continuously operating GNSS station at the NOAA Fairbanks Command and Data Acquisition Station (FCDAS), Alaska. The new antenna monument is 100 feet due NW of existing GGN station FAIR, which has been operating at the site since 1991. The addition of the new antenna and receiver allows the long-running time series of FAIR to remain undisturbed, while augmenting the site with next generation, multi-GNSS capable equipment. GCGO contributes data to the GGN and the IGS. The new monument consists of 6 inch diameter steel pipe grouted in bedrock to a depth of 60 feet (Figure 2-2a). The single-mast style mount was chosen in order to anchor into competent bedrock, which begins at ~40 feet below the surface. The pipe protrudes 5 feet above the ground surface, and is fitted with a self-leveling adapter to which the antenna is fixed (Figure 2-2b). Additional designs were also incorporated to help limit the near-surface effects of freeze-thaw action on the pipe, which should add additional stability to the monument and antenna.
GAGE Y3Q4 activities also included a new station computer installation at SUTH, in Sutherland, South Africa. The swap was completed by local collaborators and marked the removal of the last legacy rack-mounted machine left in the NASA GGN. All GGN stations are now networked via small, low power, mini-computers with modern operating systems. GGN computers are now replaced on an as-needed basis when hardware fails at any station.

Lastly, UNAVCO implemented a bandwidth monitoring method for tracking traffic to and from the GGN station computers throughout the network. Six new stations were set up to be monitored during GAGE Y3Q4. Both UNAVCO and JPL have access to the resulting detailed data plots, which have improved network monitoring to support optimization of station link performance.

2.2.3 GGN Support Highlights: October - December, 2016

During GAGE Y4Q1, the GPS receivers at station SANT (Santiago, Chile) was no longer able to track satellites as a result of a grass fire that engulfed the antenna and monument (Figures 2-3a, b). The plastic radome, antenna ring mount (made of a composite resin material), and cable end were consumed by the fire and the internal electronic components of the antenna were destroyed. Fortunately, the monument and reference mark were undamaged. Local collaborators had another antenna and aluminum ring mount available which were installed shortly after the fire. This backup antenna was subsequently replaced in early January 2017 with a new Javad JAVRINGANT_DM choke-ring.

During Y4Q1, UNAVCO also acquired five new Septentrio PolaRx5 GNSS receivers, procured by JPL for deployment at selected NASA GGN stations. These receivers are the first set of more than 20 multi-constellation capable units, which will continue to be deployed in across the GGN during late 2017 and in to 2018. The GNSS capabilities are fully enabled, and the receivers are able to track all available GNSS signals including GLONASS, Galileo, BeiDou, and QZSS. These receivers were shipped out during the quarter to stations FALK (Falkland Islands), IISC (India) CHPI (Brazil), ARUC (Armenia), and ABPO (Madagascar).

In addition, UNAVCO implemented a new update process for the computer systems deployed in the GGN. Beginning in November of 2016, the entire network now receives software system and security updates on a bi-monthly basis (with half of the network updated one month, and the other half updated in the following month). These updates are now incorporated into the network maintenance routine and are ongoing.
2.2.4 GGN Support Highlights: January - March, 2017

During Y4Q2, station CHPI in Cachoeira Paulista, Brazil was visited by UNAVCO personnel for a major equipment upgrade (Figures 2-4a, b). The GNSS receiver, uninterruptable power supply, meteorological package, and wireless radio communications system were replaced. The newly installed Septentrio PolaRx5 receiver is capable of tracking all modern GNSS signals, as well as streaming the RTCM format, which is the IGS standard for real time data. The new wireless radios provide a significant increase in bandwidth, which allows for a more robust link that can handle increased data throughput. The upgrades were made possible thanks to collaborations with personnel from the Brazilian Institute for Space Research (INPE), who arranged for site access, transportation, and local assistance.

Other travel to support the NASA GGN during Y4Q2 included a visit to station HARV on the Harvest Oil Platform (Figure 2-5) off the coast of Santa Barbara, CA, in order to improve the performance of the wireless radio/VSAT communications system. The VSAT access point at the onshore VNDP GNSS station (Figure 2-6) on Vandenberg Air Force Base also was visited, and all VSAT hardware replaced. The VSAT hardware replacement resulted in notable improvement in signal robustness. The signal strength of the link between HARV and VNDP was also improved by 20 dB with the installation of new dual-polarity radio transceivers.
2.2.5 GGN Support Highlights: April - June, 2017

In GAGE Y4Q3, a UNAVCO engineer visited station GLPS in Puerto Ayora, Galapagos Islands, to troubleshoot the metpack and meet with the local support staff to maintain engagement and good relations. A new point of contact was established for general site maintenance, and arrangements were made to clear the overgrowth from around the antenna and install a new AC unit in the equipment room. The antenna was inspected and found to be in good condition and the metpack was brought back online with the installation of a new cable.

In addition, UNAVCO began developments for a DC/DC uninterruptible power system to enable a clean shutdown of the GGN linux computer systems used for managing data downloads from GPS receivers (Figure 2-8). Nearly all GGN stations experience power outages one or more times during a year. Uninterruptible power systems (UPS) are used to manage these outages. Most of the time these outages are brief and do not cause any significant interruptions in data flow. However, there are
several stations that are more prone to extended outages, which can last several days to a week or more; well beyond the capacity of the standard GGN UPSs. In order to bridge the power gap and minimize data loss, deep cycle Pb-acid batteries can be used. If the batteries are drained before utility power is restored, however, the computer will ungracefully shutdown, risking damage to the file system. Code has been developed to work with a new supercapacitor/low-voltage-disconnect serial device that will enable a clean shutdown process. Once testing has been completed, UNAVCO will embed these devices into custom UPS systems, which will be deployed to problematic GGN stations that include IISC (India), and ISPA (Easter Island).

2.2.6 Development and Testing

The GAGE Facility Development and Testing (D&T) team is now staffed by 1.8 FTE at the Project Manager III and Engineer III levels, following the departure of D&T Engineer H. Berglund in February, 2017, whose position will not be filled for the foreseeable future. UNAVCO’s Development and Testing effort incorporates the PBO BSM and GNSS testing tasks. Ad hoc contributions to individual D&T projects from other UNAVCO groups have been critical to the effort, with individuals participating in projects of direct interest to their operational needs. The ongoing development of teqc software and implementation of receiver- and server-based real-time GNSS positioning capabilities in close collaboration with GDS are important ongoing projects undertaken by D&T staff. Under guidance from the Development and Testing Product Council, the group’s activities continue to be oriented toward six important strategic goals: 1) development of battery monitoring tools, which can help realize economy and efficiency of field operations; 2) evaluation of data communications systems suitable for use anywhere in the world; 3) evaluation of real-time positioning methods, both receiver- and server-based, for use in earthquake early detection and other geohazard monitoring applications; 4) review and improvement of GNSS receiver firmware and capabilities in collaboration with Septentrio and Trimble; 5) Evaluation of new GNSS antenna designs that may result in economical network upgrades in the future; and 6) evaluation of long-term GNSS monument stability. Development and Testing is a cross-program allocated activity at UNAVCO, funded by NASA, and NSF EarthScope, NSF OPP Arctic, and Antarctic programs to the benefit of the entire organization and the geodetic community.

The D&T group continues to lead integration of new PolaRx5 GNSS receivers into UNAVCO-operated cGNSS networks, including the NASA GGN, which now has 4 of the Septentrio receivers in operation. As we collaborate with Septentrio on the prioritization and implementation of new features to the receiver’s firmware and configuration software on an ongoing basis, PolaRx5 receivers are now being routinely installed at PBO stations. 120 PolaRx5 receivers have been installed at UNAVCO-operated stations with an additional five at community-operated stations, with only four failures having been reported to date, two of which were caused by lightning strikes.

New PolaRx5 firmware, version 5.1.0 with BINEX data logging capability, archival quality streaming (based on the linux “rsync” utility), onboard PPP positioning and other critical features was released at the end of Y4Q1. This version is the result of extensive collaboration between the UNAVCO D&T group and Septentrio; indeed the majority of D&T’s effort in Y4Q1 was devoted to testing and refining the PolaRx5 BINEX compatibility with our current real-time data system, and the performance of the onboard PPP capability. Two decimal updates, 5.1.1 and 5.1.2 were subsequently released remediating minor issues that UNAVCO identified in the earlier releases.

2.3 GPS PI PROJECT SUPPORT

2.3.1 NASA GPS PI Project Engineering and Equipment Support Overview

UNAVCO provides state-of-the-art GPS/GNSS equipment and engineering services to PI projects. This includes project management, planning, installation, operations and maintenance of continuous,
permanent GPS/GNSS station networks around the globe. Engineers and technicians also undertake technology development, testing, and systems integration to support new project demands.

During this reporting period (July 2016 - June 2017), eleven NASA PI GPS/GNSS projects were supported including: 1 Cryospheric, 1 Earth Surface and Interior, 1 Hydrology-SnowEx, 1 Terrestrial Ecology, 1 JPL/SWOT Mission, 1 MIT, 1 Terrestrial Hydrology, and 4 ROSES projects. Highlights from some of these projects are provided below. As NASA PI project support is not a primary GAGE core-funded activity these projects are subject to full cost recovery.

2.3.2 NASA GPS PI Project Support Highlights

PI: Waleed Abdalati, University of Colorado, CIRES. NASA-ROSES, NNX15AC62G, Quantifying Firn Compaction and its Implications for Altimetry-based Mass Balance Estimates of the Greenland Ice Sheet. Description: UNAVCO provided technical planning, design and fabrication assistance for four semi-continuous GPS receivers for use in southern Greenland. UNAVCO also provided two kinematic kits for a short campaign effort. These GPS instruments are being used to monitor firn compaction in Greenland’s accumulation zone, including changes in surface height over the terrain plus horizontal strain rates at mass balance stakes on the ice. The receivers will also help to reveal crevasse surface dynamics across the glacier flow line.

PI: Lawrence Smith, University of California, Los Angeles (UCLA). NASA-Cryosphere, NNX14AH93G, Drainage Efficiency Of The Greenland Supraglacial River Network. Description: UNAVCO provided three kinematic GPS kits to help investigate answers to five science questions: To what extent does ice surface topography dominate the movement of water across the ice sheet? 2) Are fluxes of supraglacial meltwater into the Greenland icesheet subsurface uniformly distributed or do some parts of the ice sheet receive greater concentrations of meltwater than others? 3) Do supraglacial river flows attain supercritical velocities? 4) Was a 100% efficient surface water drainage pattern observed following the extreme July 2012 melt event unusual or typical for the ice sheet? 5) How efficiently is GrIS surface meltwater transported off the ice sheet surface and out to the global ocean?

PI: Lawrence Smith, University of California, Los Angeles (UCLA). NASA-Terrestrial Ecology Program, NNX17AC60A, Arctic-Boreal Vulnerability Experiment (ABoVE). Description: The Arctic-Boreal Vulnerability Experiment (ABoVE) is a NASA Terrestrial Ecology Program field campaign, conducted in Alaska and Western Canada. This is a large-scale study of environmental change and its implications for social-ecological systems. In this particular endeavor, UNAVCO provided technical design assistance and proof of concept fabrication of an immersion proof GPS drifter to be used on arctic lakes and streams. Ten GPS receivers were provided for this project, with the intent to understand the resilience of surface water features in response to thawing permafrost. These measurements will directly validate NASA AirSWOT water surface elevation measurements in lakes, rivers and wetlands.


2.4 GEODETIC IMAGING (TLS) PI PROJECT SUPPORT

2.4.1 NASA TLS PI Support Overview

UNAVCO provides state-of-the-art Terrestrial Laser Scanning (TLS), a.k.a. Terrestrial LiDAR, equipment and engineering services to PI projects. This includes project management, planning, engineering and data product support as well as technology development, testing, and systems
integration to support new project demands. From July 2016 to June 2017, UNAVCO provided field engineering support/TLS equipment loan for one TLS NASA PI terrestrial laser scanning project.

### 2.4.2 NASA TLS PI Support Highlight

**PI:** Jan Eitel, University of Idaho. NASA-ROSES, NNX15AT86A, LiDAR, passive spectral, and ecophysiological approaches to link Forest Tundra Ecotone (FTE) structure and function. **Description:** At 13,400 km in length, the Forest Tundra Ecotone is the world's largest ecological transition zone. However, little is known about how the FTE - a critical component of the ABoVE study domain - will respond to ever-increasing environmental change. Remotely sensed information could play a key role in filling portions of this critical knowledge gap, yet relatively little remote sensing work has been conducted to link the current structural status of the FTE with dynamic changes in its ecological function. The overarching objective of the proposed study is to integrate LiDAR, passive spectral, and tree ecophysiological data to link biophysical structure to ecological function in the FTE. In so doing, investigators will be able to remotely assess the vulnerability and resilience of the FTE to environmental change.

![Figure 2-9. Photo of TLS survey being conducted by graduate student Andy Maguire as part of the NASA-ROSES project led by Dr. Jan Eitel, University of Idaho, to use LiDAR, passive spectral, and ecophysiological approaches to link Forest Tundra Ecotone (FTE) structure and function. The TLS instrument is a Leica ScanStation C10 from the UNAVCO instrument pool.](image)

### 3. Geodetic Data Services Program

#### 3.1 OVERVIEW

The Geodetic Data Services (GDS) program manages a complex set of metadata and data flow operations providing a wide range of geodetic/geophysical observations to scientific and educational communities. Sensors currently include GPS/GNSS (downloaded files and streaming real time (RT-GNSS)), borehole geophysics instrumentation (strainmeters, tiltmeters, seismometers, pore pressure sensors and meteorological sensors), long baseline laser strainmeters, and terrestrial laser scanners. UNAVCO also acquires and distributes satellite synthetic aperture radar (SAR) data from foreign space agencies. GDS services include data operations (managing metadata; data downloading, ingesting and preprocessing); data products and services (generating processed results and QA/QC and state-of-health monitoring); software (such as TEQC) and training; data management and archiving (distribution and curation); cyberinfrastructure; and information technology (systems and web administration). The total volume of data, as well as the types of data and products, continues to grow, as does the user base. In order to perform this mission, GDS maintains a technical staff, onsite and offsite computer facilities with networking, servers and disc storage, and manages a number of subawards to university groups who provide additional products, software and training. In addition to GAGE core support from NSF and NASA, UNAVCO receives funding from the NSF EarthCube program, NASA ROSES ACCESS awards, and the U.S. Geological Survey.
UNAVCO GDS activities continue to be international and collaborative in scope and participation with critical support from the NASA component of GAGE. In addition to participating in the International GNSS Service (IGS) and International Earth Rotation Service (IERS) governance and supporting the IGS Central Bureau, UNAVCO has been working to help remove technical barriers to data sharing by defining best practices and developing software tools such as the Geodetic Seamless Archive Centers (GSAC) software to facilitate international data sharing and discovery from a broad community of international data repositories. Dataworks software was developed to provide an additional capability for network data management. Data web services, both operational and under development, are the framework for UNAVCO contributions to multi-technique, interdisciplinary, and integrative activities such as COOPEUS, GEO Supersites, EarthScope, and EarthCube.

### 3.2 GNSS DATA SUPPORT

#### 3.2.1 Data and Software Support

NASA’s support to UNAVCO’s GNSS data management and archiving activity provides for data handling, archiving and distribution of data and metadata from the IGS network and from NASA supported GNSS installations, including stations that are part of the GGN network and associated GGN development and testing network stations, and stations installed by PIs with NASA support. As part of our support to the IGS, we provide data flow and RINEX upload services to the NASA CDDIS archive for approximately 40 stations. Due to heightened security protocols at CDDIS, newer certificate-enabled software needed to be incorporated into the upload process. Several roadblocks were encountered and eventually solved on our test system and then implemented in production.

<table>
<thead>
<tr>
<th>Period</th>
<th>TEQC Software Downloads (Qty)</th>
<th>TEQC Software Information Requests (Qty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July - September, 2016</td>
<td>7,366</td>
<td>175</td>
</tr>
<tr>
<td>October - December, 2016</td>
<td>14,905</td>
<td>200</td>
</tr>
<tr>
<td>January - March, 2017</td>
<td>17,518</td>
<td>330</td>
</tr>
<tr>
<td>April - June, 2017</td>
<td>17,130</td>
<td>180</td>
</tr>
<tr>
<td>Total July 2016 - June 2017</td>
<td>56,919</td>
<td>885</td>
</tr>
</tbody>
</table>

An integral piece of the infrastructure is the TEQC software, which is used within UNAVCO, the US research community, the IGS, and the global geodetic research community. TEQC downloads and TEQC support requests are shown in Table 3-1; downloads over the report period increased dramatically compared to the preceding year. TEQC software development over the past year has incorporated additional raw format reading functionality; reading the receiver supplied position solution from several receivers with capability for output in the proposed BINEX ox05 record type; dynamic memory management in parts of the code; refactoring of the GLONASS orbit interpolation functionality; a complete refactoring of the data structures and logic for proper output of GNSS satellite ephemerides in RINEX NAV files; improved GNSS point positioning during QC; fixing of the delta times for compact3 QC plot files when data gaps are present; and the output of placeholder value for no data epochs within RINEX met files.

#### 3.2.2 International GNSS Service Central Bureau (IGSCB) Support

As part of its NASA component tasks, UNAVCO provided participant and logistical support to the International GNSS Service Central Bureau (IGSCB) by arranging accommodations for the GGOS
Consortium Meeting, and the IGS governing board meeting that took place in December 2016 at the Fall AGU meeting in San Francisco. In total, UNAVCO provided support for 16 community meetings at AGU, six of which were in support of NASA-sponsored activities.

All IGS Central Bureau support activities are handled by UNAVCO personnel under close coordination with NASA. UNAVCO staff member David Maggert has been performing the IGS Network Coordinator role for over a year. During this past year he regularly participated in meetings and teleconferences with personnel from the IGS CB regarding the network coordination activity, software support for the IGS Network web site, and software support for the IGS Site Log Manager metadata entry and tracking tool (SLM). The SLM is in its third year as a production tool. The IGS Network website was improved by UNAVCO software staff this year through enhancement of the network map, which now shows whether stations are actively delivering data or not; stations that have not delivered data for ten days are shown with a red icon; active stations are shown with a green icon (Figure 3-1). The SLM required minor enhancements in the past year. UNAVCO continues to act a backup site for the IGS website and the SLM should IGS's primary web hosting site became corrupted or unreachable.

The network coordination role requires significant effort in interacting with existing station operators and for the vetting of proposed new stations. With a recent change in the incumbent in the role of the Antenna Working Group chair, the work of preparing and disseminating updates to the rcvr_ant.tab and antenna.gra files now is handled by the Network Coordinator. The Network Coordinator ensures metadata integrity for metadata submissions through the SLM and provides user support for station operators using the SLM. The RINEX3 transition is well underway but continues to require ongoing interactions with numerous the IGS station operators to ensure compliant data and metadata. During the last year UNAVCO personnel assisted with the transition of the NTRIP caster from the IGSCB to the UCAR COSMIC program. Coordination with station stream providers was necessary to ensure a smooth transition to the new caster at UCAR.

UNAVCO, along with Geosciences Australia and the IGS Data Centers Working Group, is continuing to promote an effort to move IGS forward with automated exchange of metadata among IGS data centers using XML. The GeoServer application server for providing Open Geospatial Consortium (OGC) web services has been deployed at UNAVCO in a pilot mode; GeoServer facilitates delivering IGS metadata via GML (Geography Markup Language) and Geoscient Australia's GeodesyML, which contains Site Log XML. Following the release of GeodesyML version 0.4, UNAVCO completed a proof-of-concept for delivering Site Log metadata in GeodesyML format via OGC Web Feature Service. This involved utilizing the latest version of GeoServer with the Application Schema plugin and defining the Application Schema mapping file to deliver the metadata. With the completion of the proof-of-concept, UNAVCO plans to implement GeoServer enabled delivery of GeodesyML formatted IGS Station metadata sourced from the SLM database.

David Maggert and Fran Boler are members of the IGS Governing Board (Boler as elected Data Center Representative, and Maggert as Network Coordinator). UNAVCO Geodetic Data Services (GDS) Director Dr. Charles Meertens serves as an At Large member of the IGS Governing Board Executive Committee. Boler, Maggert, and Meertens attended the IGS GB meeting held before the AGU Meeting in San Francisco in December, 2016. In our role in support of IGS operations, staff prepared presentations, posters, and working group reports for the IGS Workshop in Paris, France in July 2017. Meertens, Boler and Maggert prepared materials for the Governing Board meetings in Paris. Meertens also is one of the IGS GB representatives on the board of the International Earth Rotation Service (IERS). Boler attended both IGS GB and IERS GB meetings held before the EGU meeting in Vienna in April, 2017 In related IGS activities, Dr. Louis Estey, from the UNAVCO GDS Group, serves on the IGS Infrastructure Committee. Dr. Frederick Blume serves on the IGS Antenna Working Group.
3.3 SYNTHETIC APERTURE RADAR (SAR) DATA SUPPORT

The SAR Archive component of the UNAVCO Data Center was initiated in 2006 when the Western North America InSAR (WINsAR) Consortium transitioned its operations and management to UNAVCO. The WINsAR Consortium was established by a group of practicing scientists and engineers to facilitate collaboration in, and advancement of, Earth science research using radar remote sensing. Its 834 current members are from 256 universities, research laboratories, and public agencies. During the EarthScope MREFC construction phase, a large collection of EarthScope-related SAR data was amassed as a resource for the community. Today, the WINsAR and EarthScope SAR collections total ~100 TB housed at the Texas Advanced Computing Center (TACC). Under GAGE, WINsAR was supported through core and supplemental funding from NSF, NASA, and U.S.G.S. Activities include managing tasking, ordering, distribution and archiving, hosting the WINsAR Executive Committee (a committee of the UNAVCO Board of Directors), providing support for JPL’s ISCE SAR processing software, and organizing and contributing to SAR processing for ISCE and GMTSAR short courses.

3.3.1 SAR Archive

Under GAGE, UNAVCO orders ESA (European Space Agency) and DLR (Deutschland für Luftund Raumfahrt, the national aeronautics and space research centre of the Federal Republic of Germany) scenes in response to WINsAR user requests. In addition, the WINsAR Executive Committee and UNAVCO arranged for a tasking quota with DLR for use by WINsAR. WINsAR user requested tasking orders for the TerraSARX (TSX) mission have been placed on a regular basis. UNAVCO archives WINsAR community TSX and ALOS2 data in the UNAVCO SAR Archive.
The volume of SAR data archived has grown substantially from ~2 TB in Y1 to ~115 TB in Y4, primarily because of data from ALOS2/JAXA (Japan Aerospace Exploration Agency) and to a lesser extent from TSX data. JAXA provides 50 scenes per year for PI proposals, and during Y3 there was a large surge in data ordered by PIs. Some ALOS2 data files are 50-60GB each, which accounts for the large volume of data. WinSAR scenes from ESA are available without cost under their open data policy.

UNAVCO continues to maintain the core SAR archive infrastructure, including hardware, database, software, and web presence. Data ingest capabilities have been developed to allow UNAVCO to host data from newer satellite platforms such as COSMO-SkyMed, ALOS2, RADARSAT2, and Sentinel which WinSAR community users are beginning to utilize. Search and discovery for these hosted data is possible through the UNAVCO SAR Archive GUI and API interfaces. Access to data from COSMO-SkyMed, RADARSAT2, ALOS1/ALOS2, and TSX are restricted to collaborators on proposals, and the WinSAR Portal interface permits role-based access to groups of users.

ESA is the primary archive for ERS1, ERS2, and Envisat, while the Alaska Satellite Facility (ASF) is primary archive for RADAR-SAT1. For all data not archived in ESA’s Archive4 system or at ASF, UNAVCO is now backing data up to Backblaze B2, a commercial cloud storage provider. This ensures a complete offsite backup of the full UNAVCO SAR archive while minimizing redundancy.

### 3.3.2 ISCE Software Support

UNAVCO manages access to the ISCE (InSAR Scientific Computing Environment) data processing software package for all members of the WinSAR Consortium. Originally, ISCE was only available to full WinSAR members (US institutions). Since the change to allow adjunct (non-US institutions) to access ISCE, WinSAR has seen a significant increase in institutional applications. Overall, 176 WinSAR institutional representatives have submitted an ISCE license, and of those, 113 are Adjunct members (Non-US institutions). A total of 690 registered WinSAR users that have access to the ISCE software. There were a total of 1,163 ISCE software downloads between 1 July 2016 and 30 June 2017 (Table 3-2). There have been a total of 2,885 ISCE software downloads since the beginning of GAGE in October 2013. The higher number of downloads in Summer 2016 is correlated with the UNAVCO short course for ISCE.

#### Table 3-2. Number of ISCE software downloads supported by UNAVCO from 1 July 2016 through 30 June 2017.

<table>
<thead>
<tr>
<th>Period</th>
<th>NASA ISCE Software Downloads (Qty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July - September, 2016</td>
<td>430</td>
</tr>
<tr>
<td>October - December, 2016</td>
<td>276</td>
</tr>
<tr>
<td>January - March, 2017</td>
<td>236</td>
</tr>
<tr>
<td>April - June, 2017</td>
<td>221</td>
</tr>
<tr>
<td>Total July 2016 - June 2017</td>
<td>1,163</td>
</tr>
</tbody>
</table>

### 3.3.3 GEO Supersites support

For the GEO Supersites and Natural Laboratories (GSNL) initiative, UNAVCO provides data ordering from ESA together with data management (download and repackaging) of the orders received, and upload of the orders to the ESA supported cloud storage (Level 4 archive). UNAVCO continues to support GSNL as needed and Meertens serves on the GSNL Supersites Advisory Committee. As noted above, UNAVCO now supports TSX, COSMO-SkyMed, RADAR-SAT2, and ALOS2 data collected under the Supersites initiative. For these datasets, the list of PIs with access to the data include international collaborators as well as WinSAR community members. To address this expanded community of users and associated access constraints, UNAVCO has made several modifications to the WinSAR Portal system to allow registration by international partners.
Through recently completed NASA ROSES ACCESS-funded work to develop a Seamless SAR Archive (SSARA), UNAVCO staff members have engaged in joint planning with the European SAR community (DLR, ESA, CEOS, etc.) regarding federated access to data, data processing environments, and metadata and product formats. The goal is to leverage the SSARA work to build federated access to data hosted by the space agencies that participate in Supersites. Federated query of Supersites SAR data (ESA’s Virtual Archive 4 and DLR’s TerraSARX Archive) along with data archived at the Alaska Satellite Facility and UNAVCO is now available due to SSARA efforts (http://webservices.unavco.org/brokered/ssara/). The archive now supports user controlled DOI assignment for products uploaded to the InSAR archive at UNAVCO (https://winsar.unavco.org/portal/insar/). InSAR products are uploaded via the API (https://winsar.unavco.org/portal/insar/api/interferometry/), and users are now able to request a DOI from UNAVCO, making the products persistent and citable.

3.4 CYBERINFRASTRUCTURE SUPPORT

UNAVCO develops cyberinfrastructure with core GAGE Facility funding, supplementary funding to GAGE, COOPEUS and EarthCube projects, and NASA ROSES ACCESS projects. UNAVCO continues to work on REST web services to support the community with alternative methods to retrieve data, in alignment with efforts to move towards REST web services with standards for services and formats coordinated internationally and nationally and within and across scientific domains. These efforts expand the cyberinfrastructure capabilities of UNAVCO geodetic data systems. These REST web services and a companion REST web service documentation system that includes a URL builder have been implemented and are now available to users from the Data section of the UNAVCO web site. Development continues to make these services an integrated part of UNAVCO core data services. UNAVCO’s web service for delivery of station position time series was enhanced to provide users with the ability to request data from any of the three GAGE analysis centers. In addition to GAGE-produced position time series, UNAVCO worked with researchers at the University of Nevada, Reno (UNR) under the NASA Plug and Play ACCESS project to add the capability to retrieve position time series located at UNR. The service optionally allows conversion the X/Y/Z data retrieved from the one of the four analysis centers to be converted to NEU and lat/long/height coordinates that are returned in the web service response.

4. Education and Community Engagement

4.1 EDUCATION, OUTREACH AND COMMUNITY SUPPORT

The UNAVCO Education and Community Engagement (ECE) program provides technical and educational professional development, materials, tools, and resources for students, teachers, university faculty, researchers and the general public. ECE promotes community science through outreach and broader impacts support and provides support to students and early career professionals through mentoring and internships for those interested in careers in geodesy and geosciences. Any education, outreach and community activities the ECE program undertakes includes broader consideration of how geodetic research is supported by NASA. Acknowledgement of NASA support is included on all digital and print materials.

NASA-focused support includes dissemination of reports and relevant NASA materials at major scientific meetings including the Fall Meeting of the American Geophysical Union (AGU), the annual meeting of the Geological Society of America (GSA), and the European Geophysical Union (EGU) meeting. During this reporting period, ECE staff led efforts to document the new web services process for data acquisition. This video series features: the IGS network in the Web Services at UNAVCO video, GNSS in the Open Access GPS Data video, and SAR data in the Synthetic Aperture Radar Data at UNAVCO video. In the less than one year since they have been published there are over 1000 views on the UNAVCO YouTube channel and have been incorporated into short courses and other instruction.
4.2 SYNTHETIC APERTURE RADAR (SAR) SHORT COURSES

The ECE program coordinates and facilitates a series of short courses focused on technical training around SAR and InSAR data processing. Short courses are taught by UNAVCO community researchers and primary participants included graduate students and postdoctoral researchers, and also include university faculty and occasionally undergraduate researchers. UNAVCO provide support for student travel and lodging and all travel expenses incurred by instructors.

During the reporting period three short courses were supported. One short course is scheduled for August 2017. All courses are offered in a hybrid model where participants can choose to participate either in person or remotely through an online interface. The online component is synchronous with an instructor dedicated to interfacing with the online participants. Typical enrollment for short courses is between 30 and 50 participants with up to 25 to 35% participating online. All course materials included recorded versions of the entire course are archived on the UNAVCO website and are freely available. The InSAR Processing and Theory with GMTSAR: Sentinel-1A Time Series will be taught again in August 2017. A short summary of 2016 short courses follows.

**InSAR Theory & Processing with ISCE, GIAnT, and StaMPS.** 1-5 August, 2016. 45 participants, held at UNAVCO Headquarters, Boulder, Colorado. The course covered basic & advanced InSAR theories, InSAR processing with JPL/Caltech/Stanford InSAR Scientific Computing Environment (ISCE), time-series InSAR processing with Generic InSAR Analysis Toolbox (GIAnT), and StaMPS (Stanford Method for Persistent Scatterers) processing. Instructors: Paul Rosen, Eric Fielding, Piyush Agram, and David Bekaert, JPL; Andy Hooper, University of Leeds, and Scott Baker, UNAVCO.

**InSAR Processing and Theory with GMTSAR: Sentinel-1A Time Series**, 10-12 August, 2016, 37 participants, held at Scripps Institution of Oceanography, La Jolla, California. The course covered the theory and application of InSAR processing with GMTSAR. Instructors: David Sandwell, Xiaohua Xu and Katia Tyroffeyeva, Scripps Institution of Oceanography; Rob Mellors, Lawrence Livermore National Laboratory; Paul Wessel, University of Hawaii at Manoa; Kurt Feigl, University of Wisconsin; Scott Baker, UNAVCO; Matt Wei, University of Rhode Island

**COMET InSAR Training Workshop.** UNAVCO supported the Centre for Observation and Modelling of Earthquakes, Volcanoes, & Tectonics short course 31 October - November 2, 2016, held at the School of Earth and Environment (SEE), University of Leeds, United Kingdom. The course covered InSAR theory, SAR data access and preprocessing, differential interferometry, interferogram creation and unwrapping, atmospheric effects & corrections, time series analysis, displacement field modeling, Sentinel-1 data processing, GAMMA, ISCE, and StaMPS software, and InSAR-related pitfalls and caveats. Instructors: Andy Hooper, Tim Wright, Susanna Ebmeier, John Elliott, and Karsten Spaans, Leeds; Juliet Biggs, Bristol; Paola Crippa and Zhenhong Li, Newcastle, Pablo Gonzalez, Liverpool; and Richard Walters, Durham.