Glen S. Mattioli, Ph.D.
Director of Geodetic Infrastructure and PBO Director

EARTHSCOPE PLATE BOUNDARY OBSERVATORY IN AK:
SCIENCE HIGHLIGHTS, CURRENT STATUS, CAPABILITIES AND FUTURE BEYOND GAGE IN 2018

USArray Sustainability Workshop, Nov. 9-10, 2016 - ARCUS, Washington, DC
• Overview of UNAVCO GI program in NSF GAGE Facility

• EarthScope overview: PBO infrastructure, current status, and data products

• Science Drivers and Value of PBO for earthquake and other studies: some examples from AK

• Vision for the future: PBO as a basis for a multi-hazard network of networks across the Americas - planned upgrades and enhancements (i.e. new investments) to PBO?

• Sustainability - Possible Scenarios and Costs: PBO as a platform to support real-time, multi-hazard monitoring for NOAA and USGS, civil infrastructure, and the commercial sector

• Summary and challenges going forward...
Geodetic Infrastructure Directorate

Community & Continuously Observing Networks

Plate Boundary Observatory

- GPS/GNSS and Metpack Operations
- Borehole Geophysics Operations

NASA Global GNSS Network (GGN)
POLENET: GNET & ANET
COCONet, TLALOCNet, and Africa Array

Principal Investigator support

NSF - EAR, PLR funded

Campaign and longer term GPS deployments

Terrestrial Laser Scanning Projects
Emerging Imaging Geodesy Tools
Development & Testing
The EarthScope Plate Boundary Observatory

Focused, dense deployments of cGPS and strainmeter arrays
- 1100 continuous Global Positioning Systems around tectonic clusters
- 78 borehole tensor strainmeters and 3 component short-period seismometers
- 6 long baseline laser strainmeters
- 25 tiltmeters
- 120 meteorological instruments

Portable GPS receivers
- Pool of 100 portable GPS receivers for temporary deployments to areas not sufficiently covered by continuous GPS

Geo-EarthScope
- InSAR imagery covering the western US
- LIDAR imagery covering the northern and southern San Andreas Fault, Yellowstone Caldera, and faults in Cascadia and Alaska

• Funded by NSF
• Project started in 2003 - continues through 2018
• Total EarthScope Budget: ~$500M over the lifetime of the project

PBO Investment:
- $100M - Construction Phase (2003-2008)
- $54M - Operations and Maintenance Phase 1 (2009-2013)

Funded by NSF
Project started in 2003 - continues through 2018
Total EarthScope Budget: ~$500M over the lifetime of the project
PBO: A NUCLEUS FOR A NETWORK OF GEODETIC NETWORKS

PLATE BOUNDARY OBSERVATORY

Governance and Community
GAGE Impact
Geodetic Infrastructure
Geodetic Data Services
Education & Community Engagement
Beyond 2018
Strong interest in NASA/USGS/NOAA earthquake, volcano, and tsunami early warning communities to upgrade PBO-AK sites to RT-GPS (1 Hz, <1 s latency) with accelerometers (MEMS).

Surveying and AK state-wide spatial reference system could also benefit from these upgrades, but appropriate funding partners have yet to be determined.

PBO-AK stations logging at 1 Hz - Only downloaded on demand

PBO-AK logging L2C at 1 Hz - Data downloaded hourly at times
EarthScope PBO geodetic assets make up the vast majority of all cGPS/cGNSS stations in AK.

PBO stations are vital for:

1) hazard monitoring and early event characterization
2) civil infrastructure monitoring
3) support of commercial sector for construction, navigation, remote sensing, etc.
The Plate Boundary Observatory in Alaska Highlights from 2003-2015

- Before the PBO came to Alaska in 2003, fewer than 5 continuous GPS reference stations were operating in Alaska with reliable telemetry.

- Today, 140 PBO stations in Alaska provide reliable, continuous access to GPS, tiltmeter, and meteorologic data.

- PBO sites installed prior to 2006 eruption of Augustine Volcano.

- Since 2003, UNAVCO has spent $30M on PBO-Alaska network construction and operations/maintenance ($2.5M/yr).

- Alaska-based UNAVCO staff (currently 3.5 FTE, as many as 6 FTE during construction phase), located in Anchorage and Fairbanks.

- ~80 field visits per year required to maintain the PBO Alaska network.

- UNAVCO has a proven record of success in Alaska: PBO construction and maintenance has been completed safely, on-schedule, and within budget.
PBO SENSOR DATA RETURN

Metrics complete through September 30, 2016 (Y8Q4 - GAGE Y3Q4)
PBO SENSOR DATA RETURN

Cumulative data return for the PBO network since the beginning of the GAGE O&M period (FY2014) is:

- 96% for GPS/Met
- 99% for seismic
- 99% for BSM
- 100% for LSM
- 94% for pore pressure
- 91% for tilt

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Metrics complete through September 30, 2016 (Y8Q4 - GAGE Y3Q4)
GAGE Processing Centers - Positioning Data Quality

Vertical Position WRMS

Phase RMS
THE PLATE BOUNDARY OBSERVATORY IN ALASKA
SCIENCE AND OTHER DRIVERS

• Tectonic block definition and motion - examination of oblique convergence and slip partitioning

• Strain accumulation and locking along the megathrust interface between NAM-PAC

• Post-seismic visco-elastic response from the 1964 M9.2 Anchorage and 2002 Mw7.9 Denali earthquakes

• Static and dynamic forcing of volcanic systems and changes in state of from seismic- and ice-loading

• Short to medium-term characterization of crustal magma dynamics and volcanic eruptions (e.g. dike intrusion and propagation)

• Support of hazard missions of USGS and NOAA - EEW/TEW and NGS CORS - PBO AK contributes 76 of ~100 stations

• With deployment of USArray in AK - integration of crustal and lithospheric structure with surface deformation field
Data from M9.2 1964 event (Suito and Freymueller, JGR, 2009) was used to drive 2014 AK Shield simulation for NASA READI prototype earthquake early warning system.
JPL tsunami simulations based on RT-GPS (1 Hz) coseismic displacements for M9.2 1964-type event (FFM of Suito and Freymueller, JGR, 2009).

NASA READI TEAM PRODUCTS FOR AK SHIELD

From T. Song, JPL

NASA READI team: JPL, UCSD-SIO, CWU with PBO as key data provider
GAGE: RT-GPS/GNSS UPGRADE PLAN

Real-Time Stations

Governance and Community
GAGE Impact
Geodetic Infrastructure
Geodetic Data Services
Education & Community Engagement
Beyond 2018
GAGE: RT-GPS/GNSS UPGRADE PLAN

- Governance and Community
- GAGE Impact
- Geodetic Infrastructure
- Geodetic Data Services
- Education & Community Engagement
- Beyond 2018

Real-Time Stations

Graph showing the growth of Real-Time Stations from 2008 to 2018:
- 2008: 0
- 2009: 175
- 2010: 350
- 2011: 525
- 2012: 700
- 2013: 0
- 2014: 175
- 2015: 350
- 2016: 525
- 2017: 700
- 2018: 0
GAGE: RT-GPS/GNSS UPGRADE PLAN

Governance and Community

GAGE Impact

Geodetic Infrastructure

Geodetic Data Services

Education & Community Engagement

Beyond 2018

Real-Time Stations

0 175 350 525 700

Beyond 2018

Real-Time Stations

0 175 350 525 700

Geodetic Data Services

Education & Community Engagement

Beyond 2018

Real-Time Stations

0 175 350 525 700

Geodetic Data Services

Education & Community Engagement

Beyond 2018
ABOVE: Based on the NUMBER OF NEW USERS (new requestors) per year, the percentage of commercial users relative to academic and agency users has increased consistently over the past four years.

BELOW: Based on the VOLUME OF DATA DOWNLOADED per year, the percentage of commercial users relative to academic users has decreased consistently over the past several years.

Interpretation: there are more commercial users than academic users of RTGPS data, but academic users access larger volumes of data.

Trends in PBO RT-GPS usage:

Increase in the number of new commercial sector users from 2010 to 2013

Increase in the amount of RT-GPS data downloaded by academic groups
RT-GPS - CURRENT NETWORK
Originally only 13 RT-GPS PBO sites in AK
Recent efforts have increased this to 40...
Originally only 13 RT-GPS PBO sites in AK
Recent efforts have increased this to 40...

Trimble PIVOT
PPP-AR solutions
RT-GPS: WHAT COULD BE DONE WITH PBO-AK UPGRADES

Network Background – Seismic & hr-GPS

- ≈1 cm or less
- hr-sites only
- event at 128 km

Processing Strategy

- baselines w/ track (GAMIT/MIT)
- PPP possible, but small displacements

Test Case: 2016 Mw7.1 Iniskin, Alaska
From R. Grapenthin et al. (ms. in prep)

This is GPS only - not a seismogeodetic combination
RT-GPS: WHAT COULD BE DONE WITH PBO-AK UPGRADES

PGD – Magnitude evolution

Better estimate of PGD in ~60 s!

Based on Crowell et al. (2013), Melgar et al. (2015) developed a scaling relationship to infer Mw from PGD & hypocentral distance (R):

\[
\log(\text{PGD}) = A + B \times Mw + C \times Mw \times \log(R)
\]

This is GPS only - not a seismogeodetic combination

Test Case: 2016 Mw7.1 Iniskin, Alaska
From R. Grapenthin et al. (ms. in prep)
Emerging technique exploiting Doppler shift of L1 or L2 GPS phase observable to create velocigrams - no ‘positioning’ estimation needed…

Test Case: 2016 Mw7.1 Iniskin, Alaska
From R. Grapenthin et al. (ms. in prep)
Workshop held in May 2015 in Leesburg, VA
>100 participants

- Report divides into three components related to US NSF-funded geophysical & seismo-geodetic facilities:
  
  **Existing Foundational**
  
  Maintained permanent seismic, strainmeter, and geodetic networks
  - A global very broadband seismographic network
  - Permanent and continuously recording GPS (GNSS) networks
  - A network of borehole strainmeters

  **Emergent Foundational**
  
  Development of operational RT-GNSS processing at >1 Hz

  **Frontier**
For example, the community envisions a future that includes:

(1) near-real-time and daily maps of deformation derived from integrated seismic, Global Navigation Satellite System (GNSS) instrumentation, and orbiting radar satellite data;

(2) anchored and drifting seafloor and water column geophysical instrumentation distributed around the globe;

(3) arrays of fiber optic cables providing spatially continuous high-rate sampling of surface strain;

(6) global telemetry providing high-rate and low-latency sampling from any number of remote instruments; and

(7) routine access to high performance computing (HPC) and associated capabilities for data reduction and model inference on an unprecedented scale.
**GPS MODERNIZATION - IMPLICATIONS FOR PBO**

- Total of **19 L2C-capable SVs** in orbit now
- Total of **12 L5-capable SVs** in orbit now
- Block III SVs available for launch in 2016
- DoD/DoC announced phase-out of civil access to P(Y) on L1/L2 effective 2020 to drive commercial sector to L2C/L5 applications

- **PBO has ~900 Trimble NetRS deployed** - only can encode L2C & no GNSS signals (all are EOL/EOS); most EAR/PLR pool receivers are the same obsolete, legacy technology

- **PBO/COCONet/TLALOCNet has ~250 Trimble NetR9 deployed** - can encode L2C, L5, +GNSS; PBO turned on GLONASS at 140 stations

- UNAVCO selected **Septentrio** as its GNSS receiver preferred vendor. We have purchased and deployed 120 (PBO + ODOT) new PolaRx5 instruments in 2016.

<table>
<thead>
<tr>
<th>Legacy Satellites</th>
<th>Modernized Satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Block IIA</strong></td>
<td><strong>Block IIR</strong></td>
</tr>
<tr>
<td>0 operational</td>
<td>12 operational</td>
</tr>
<tr>
<td>- Coarse Acquisition (C/A) code on L1 frequency for civil users</td>
<td>- C/A code on L1 &amp; L2</td>
</tr>
<tr>
<td>- Precise P(Y) code on L1 &amp; L2 frequencies for military users</td>
<td>- All legacy signals</td>
</tr>
<tr>
<td>- 7.5-year design lifespan</td>
<td>- 2nd civil signal on L2 (L2C)</td>
</tr>
<tr>
<td>- Launched in 1990-1997</td>
<td>- On-board clock monitoring</td>
</tr>
<tr>
<td>- Last one decommissioned in 2016</td>
<td>- New military M code signals for enhanced jam resistance</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Block IIR(M)</th>
<th>Block IIF</th>
<th>GPS III</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 operational</td>
<td>12 operational</td>
<td>In production</td>
</tr>
<tr>
<td>- All legacy signals</td>
<td>- All Block IIR(M) signals</td>
<td></td>
</tr>
<tr>
<td>- 3rd civil signal on L5 frequency (L5)</td>
<td>- 4th civil signal on L1 (L1C)</td>
<td></td>
</tr>
<tr>
<td>- Advanced atomic clocks</td>
<td>- Enhanced signal reliability, accuracy, and integrity</td>
<td></td>
</tr>
<tr>
<td>- Improved accuracy, signal strength, and quality</td>
<td>- No Selective Availability</td>
<td></td>
</tr>
<tr>
<td>- 12-year design lifespan</td>
<td>- Satellites 11+: laser reflectors; search &amp; rescue payload</td>
<td></td>
</tr>
<tr>
<td>- Launched in 2010-2016</td>
<td>- 15-year design lifespan</td>
<td></td>
</tr>
<tr>
<td>- Available for launch in 2016</td>
<td>- Learn More</td>
<td></td>
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UPGRADES TO PBO INSTRUMENTS
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UPGRADED TO GPS+GLONASS ON TRIMBLE R9 (n=134)
UPGRADES TO PBO INSTRUMENTS

UPGRADED TO GPS+GLONASS ON TRIMBLE R9

UPGRADED TO MULTI-GNSS SEPTENTRIO PolaRx5 (n=129)
PBO: STATION IN AK - DESIGN AND CHALLENGES

PBO stations are an established, long-term platform for additional sensors!

- DDBM/SDBM - most stable
- Battery/Instrument enclosure
- Solar array
- Telemetry (VSAT/CDMA/microwave)
- Helicopter LZ
- Bears, weather…
**Operational definition:** A GPS station is considered “up” if less than 3 days have passed since data arrived in the UNAVCO archive.
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OPERATIONS AND MAINTENANCE COSTS: CONUS AND AK
GPS/GNSS stations will be prioritized into three categories based on the science goals and the number and diversity of stakeholder interests, guided by advisory committees and community:

1) **highest** - problems will receive attention and remediated as rapidly as possible;

2) **intermediate** - problems will be diagnosed and will receive attention as resources permit;

3) **lowest** - problems will be diagnosed, but any required service will only occur if periodic maintenance is scheduled for that station during the upcoming annual field season.

Under GAGE, engineers visited each station approximately every five years for scheduled battery and hardware maintenance and unscheduled maintenance was performed on a best-effort basis. *Our new O&M model will allow more efficient use of available resources*, and most importantly, focus them on the stations that are deemed the highest priority by stakeholders.
NSF EarthScope
Plate Boundary Observatory Network in Alaska:

Real-time capabilities and potential:

- GPS - NetRS (129)
- GNSS - NetR9 (8) - GLONASS only
- GNSS - PolaRx5 (3) - all SVs
- RT - PIVOT (13)
- RT - BKG (34)
- Metpacks (2)
Example Scenario:
Tsunami Early Warning sensor network for constraining earthquake source parameters:

a straw-man plan to upgrade to 30 real-time stations proximal to the subduction interface to support NOAA-NTWC, USGS, and AEC hazard missions

UNAVCO has a proposal pending at NOAA
Example Scenario:
Tsunami Early Warning sensor network for constraining earthquake source parameters:

- A straw-man plan to upgrade to 30 real-time stations proximal to the subduction interface to support NOAA-NTWC, USGS, and AEC hazard missions.

Note that a particular science- or hazard monitoring-driven subset of sites selected for RT upgrades, will not perfectly overlap the subset of already-upgraded, or even easily-upgradable, RT stations.

Example TsEW subset (total = 30 sites)
Current PBO-AK RT Status (total = 140 sites)

UNAVCO has a proposal pending at NOAA
ONE SCENARIO FOR PBO ENHANCEMENT

- Budget includes one time costs to upgrade 30 key stations, staffing and development and set up of local monitoring.

- Annual costs include staffing for near-real-time monitoring, triage, and responding to station outages, associated travel, and all recurring communications costs with satellite uplink failover.

<table>
<thead>
<tr>
<th></th>
<th>One Time</th>
<th>Annual</th>
</tr>
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<tbody>
<tr>
<td>Salaries</td>
<td>$328,194</td>
<td>$88,317</td>
</tr>
<tr>
<td>Fringe</td>
<td>$189,171</td>
<td>$50,906</td>
</tr>
<tr>
<td>Materials/Supplies</td>
<td>$398,820</td>
<td>$10,000</td>
</tr>
<tr>
<td>Helicopter Services, etc.</td>
<td>$315,000</td>
<td>$50,000</td>
</tr>
<tr>
<td>Travel</td>
<td>$101,003</td>
<td>$20,000</td>
</tr>
<tr>
<td>Other Direct Costs</td>
<td>$107,790</td>
<td>-</td>
</tr>
<tr>
<td>Communications</td>
<td>$456,000</td>
<td>$456,000</td>
</tr>
<tr>
<td>Total Direct Costs</td>
<td>$1,895,978</td>
<td>$675,223</td>
</tr>
<tr>
<td>Indirect Costs</td>
<td>$304,494</td>
<td>$108,441</td>
</tr>
<tr>
<td>Total</td>
<td>$2,200,472</td>
<td>$783,663</td>
</tr>
</tbody>
</table>

UNAVCO submitted a proposal to NOAA-NFA-NFAP0-2016-2004791 in May 2016.
TYPICAL PBO AK STATION - CURRENT STATE

Standard PBO GPS Site

upgrade

Real-time PBO GNSS Site
TYPICAL PBO AK STATION - CURRENT STATE

Hut containing 24-32 batteries for year-round operation (space limited)

Limited solar array, 240-Watts

Lower-bandwidth telemetry designed for daily downloads of standard 15-sec frequency, GPS-only data

GPS-only receiver & antenna

Current PBO station
TYPICAL PBO AK STATION - CURRENT STATE

Higher-bandwidth telemetry systems support real-time streaming of 1-Hz GNSS (multi-constellation) data.

Larger solar array as needed

Additional battery storage can require a second hut or enclosure for 24-7 data streaming.
PBO: A CRITICAL NATIONAL AND AK RESOURCE: SUMMARY OF IMPORTANT CONCERNS

Aging PBO infrastructure - planned replacement in GAGE, not fully possible under current budget scenarios. Many EOL/EOS units will remain in place at close of GAGE Facility. **Reduced O&M for PBO means possible loss of data and likely will decrease up-time in long-run.** Future post-GAGE (under NGEO) is uncertain…

Need for **high-rate and real-time data streams** and archived products to position UNAVCO for future (NSF and non-NSF) funding and relevance. **PBO is now viewed as a “utility” by many critical stakeholders.** Cost to renew and upgrade selected PBO-AK stations to real-time would be considerable ($2.2M one-time funds and $0.8M/yr ongoing costs using current technologies).

- Geodetic Infrastructure is vital to multiple communities and agencies - **how will it be sustained?**
- NSF (and NASA/USGS to a lesser degree) has made the **initial investment** - but the need for sustaining federal and state partners remains paramount…

**Impact of loss (possible descoping by NSF) or degradation of PBO assets (physical and human)** stakeholders are charged with Safety of Life warnings, Initial Crisis Response, and development and maintenance of state-wide Spatial Reference Network systems needs evaluation and mitigation.