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Geodetic monitoring of the Yucca Mountain region using continuous GPS measurements

Geoff Blewitt  
*University of Nevada, Reno, gblewitt@unr.edu*

Jonathan Price  
*University of Nevada, Reno, jprice@unr.edu*

Nevada Geodetic Laboratory

Nevada Bureau of Mines & Geology

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Geodetic Monitoring of the Yucca Mountain Region
Using Continuous GPS Measurements

Principal Investigators: Geoff Blewitt & Jonathan Price

Nevada Geodetic Laboratory (NGL)
Nevada Bureau of Mines & Geology (NBMG)
University of Nevada, Reno (UNR)

Co-Investigators:
Bill Hammond, Corne Kreemer & Hans-Peter Plag (NGL, NBMG, UNR)
Brian Wernicke, Kevin Mahan, Bernard Guest & Nathan Niemi (Caltech)
Jim Davis, Sunil Bisnath, Eric Malikowski (Harvard-Smithsonian Center for Astrophysics = CfA)

NSHE Cooperative Agreement Interim Progress Briefings
January 18, 2007 – DRI, Reno
Overview

- What Task 3 is about
- Formal objectives
- Summary of where we are
- **Highlights of progress**
- Formal status
- Conclusions
What Task 3 is About

• **Monitor current crustal deformation at YM**
  – In the broader tectonic context of the NA-Pacific plate boundary
  – In the regional context of the East California Shear Zone (ECSZ)
  – In the geological context of specific fault activity
  – Vertical motion associated with geophysical fluids

• **Using geodetic methods**
  – GPS – mature, proven
    • track the 3-D point-positions of 47 stations with < 1 mm precision
  – InSAR – new, experimental
    • regional map of displacement along the line-of-sight (accuracy??)
    • proven capability: (1) co-seismic deformation; (2) local instabilities
YM Network in Broader Context

Great Basin GPS Velocity Field:

30-station YM network
YM Network in Broader Context

North of YM: B&R extension → transition to WL shear

Analogue for Tectonics at the Latitude of YM?
YM Network in Broader Context

West of YM: East California Shear Zone (ECSZ) Shear
YM Network in Broader Context
East of YM: Extension + Colorado Plateau Rotation?
YM Network in Broader Context
East of YM: Extension + Colorado Plateau Rotation?

Local YM Network clearly in Transition Zone (extension → shear)
Formal Objectives

a) to subcontract with the California Institute of Technology (Caltech), under the supervision of Professor Brian Wernicke, for geodetic monitoring of the Yucca Mountain region;

b) to double-check the assumptions and processing done under the Caltech subcontract (by subcontract to CfA) and to assure accuracy of global positioning system (GPS) measurements by processing at the University of Nevada, Reno (UNR) using an independent analysis methodology; and

c) to incorporate interferometric synthetic aperture (InSAR) analysis into geodetic monitoring of the Yucca Mountain region.
Summary of Where We Are

• **Previous task (1998-2003)**
  – Initial data from 30-station network on-line by May 1999 (>7 yr)
  – Demonstrated < 1 mm/yr precision in velocity
  – Indications of ~ 20 nanostrain/yr across the YM region

• **Current task (Oct 2003-now)**
  – Additional 17 stations installed to densify network (~1 yr)
  – 47-station network operating continuously - only minor problems
  – 235-station campaign network installed (NEARNET)
  – Independent GPS solutions (UNR - CfA) agree to < 0.1 mm/yr
  – GPS data consistent with > 0.7 mm/yr fault slip local to YM area
  – Initial InSAR providing consistent results in the YM-ECSZ region
Highlights of Progress

- GPS network installation and operation
- GPS analysis and results
- Deformation modeling and interpretation
- Vertical deformation
- InSAR analysis and results
- Related geological studies
Progress on GPS Networks

(1) Permanent
   - for temporal resolution

(2) NEARNET
   - for spatial resolution
30 existing sites (1999)
17 expansion sites (2005-06)
47 total sites in network
Yucca Mtn network expansion

- Project begins
- Death Valley NP permit delay
- NTS construction delay
- Monument installed
- Complete logging data

New GPS sites:
- VINE
- HELL
- PHIN
- IBEX
- NOPE
- NEVA
- LICE
- REP4
- REP3
- REP2
- BATM
- CRAM
- VONS
- SIXM
- RUMP
- ASHM
- KAYO
- HURR

Timeline:
- Aug 03
- Nov 03
- Feb 04
- Apr 04
- Jul 04
- Oct 04
- Dec 04
- Mar 05
- May 05
- Aug 05
- Nov 05
- Jan 06
- Apr 06
- Jul 06
- Sep 06
- Dec 06
Final network communication plan, 1/07
NEARNET Progress to Date

http://geodesy.unr.edu/networks/

- Semi-permanent campaign network
  - Goal ~400 at 15-30 km spacing
  - 235 stations installed to date
  - Occupied by 55 mobile receivers
- Monthly campaigns April–November
  - 10-12 new sites per month
  - nominal re-occupation 2-5 yrs
- DOE Geothermal Program Funding
  - Funded installation of initial 60-station (northern) core network
  - Now funds re-occupation of 131 stations every 5-6 months (including 71 Yucca stations)
Nevada Earthquake Response GPS Network (NEARNET)

Geoff Blewitt, Bill Hammond, Corné Kreemer, and Hans-Peter Plag

Nevada Geologic Survey, Nevada Bureau of Mines and Geology,
University of Nevada, MS 179, Reno, NV 89557 United States

E-mail: gblewitt@geo.unr.edu
Web page: http://nearnet.unr.edu

[Map of Nevada with annotations and labels related to the NEARNET network, including GPS stations and geological features.]
Progress: GPS Analysis

- **Latest Solutions at CfA and UNR**
  - All data analyzed May 1999 - December 2006
  - Analysis is completely independent
    - Different software
    - Different approach
  - 7-year velocity solution
    - effect of seasonal cycles now completely negligible
    - avoid offsets due to antenna cover (radome) changes
    - avoid offsets due to Hector Mine earthquake
    - but velocity averages through post-seismic motion
Method at UNR

• **Precise point positioning every 24 hours**
  – GIPSY OASIS II software
  – Orbits and satellite clocks from JPL
  – Estimate stochastic troposphere (zenith + gradient), station clocks and integer ambiguities
  – Estimate station positions every day

• **Put daily solutions into a reference frame**
  – Transform to ITRF2000 (daily translation, rotation, and scale)
  – Option: remove the daily mean translation of regional network

• **Compute weekly positions and average velocity**
  – Correct for constant rate of rotation of stable North America
Local YM Velocities (relative to TIVA)

- right lateral velocity gradient west of YM consistent with ECSZ
- high velocity gradient east of YM requires local tectonics
  - Example: STRI – LITT shows 0.4 mm/yr contraction
  - RVFZ now showing small left-lateral E-W shear (0.2 mm/yr)
Example of Time series: MERC

Earthquake: co-seismic displacement

post-seismic effect
N-S Contraction: STRI-LITT
0.37 mm/yr

STRI: -9.28 ± 0.02 mm/yr
LITT: -9.71 ± 0.02 mm/yr
(STRI – LITT): 0.43 ± 0.03 mm/yr
E-W Extension: TATE-PERL
0.33 mm/yr

TATE: $-16.45 \pm 0.02$ mm/yr
PERL: $-16.74 \pm 0.02$ mm/yr
(TATE – PERL): $0.29 \pm 0.03$ mm/yr
Time Series Statistics

- **RMS weekly scatter: mean (min - max)**
  - North: 0.5 mm (0.3 – 0.8 mm)
  - East: 0.5 mm (0.3 – 0.8 mm)
  - Vertical: 1.7 mm (1.3 – 2.8 mm)

- **Goodness of fit to constant velocity model**
- Chi-square/DOF = 0.8
- **Formal velocity errors now < 0.1 mm/yr**
  - Velocity differences (UNR/GIPSY-CfA/Gamit) < 0.1 mm/yr
Strain accumulation from ECSZ:
Geology vs Geodesy
Velocity Analysis

Strain-Rate Analysis

TIVA fixed

CRAT fixed
Observed

Observed - Model
where
Model = ECSZ fault slip
[Hill and Blewitt, 2006]
From Hill and Blewitt (GRL, 2006)

- Western cluster marginally higher strain than predicted by ECSZ
  - Observed: $17.0 \pm 1.8$ ns/yr
  - Modeled: $13.9 \pm 0.7$ ns/yr

- Eastern cluster has statistically higher strain than predicted by ECSZ
  - Observed: $22.3 \pm 2.1$ ns/yr
  - Modeled: $8.6 \pm 0.7$ ns/yr

- Additional sources of strain more local to YM
  - must collectively accumulate $> 0.7$ mm/yr
Transient Deformation

Hector Mine
16 Oct 1999
Mₜ 7.1
Hector Mine Earthquake
(M 7.1, 16 Oct 1999)

Best-fit model that includes parameters for velocity, seasonal, and post-seismic logarithmic decay

Best-fit straight line based on 2 years of post-HM data

~7 mm
Characterization of Deformation

• Examples of postseismic deformation model
  – afterslip
    \[ \tilde{x}(\Delta t) = \tilde{a} + \tilde{b}\Delta t + \tilde{c} \ln \left( 1 + \frac{\Delta t}{\tau} \right) \]
  – viscoelastic
    \[ u(t) = vt + a\left(1 - e^{-t/\tau}\right) + c \]
  – Here \( t \) is time past quake and \( \tau \) is decay time.
  – The parameters depend on the Earth model and earthquake model
Red: GPS

Blue:
Predictions from VISCO1D based on viscosity structure of Pollitz et al. [2000, 2001] and simplified Hector Mine slip distribution

Observed velocity gradient does not match predicted
Vertical Motion
Upward Tilting Going East from Death Valley → Las Vegas ~ 1 mm/yr

- Vertical motion more difficult to characterize:
  - noisier
  - atmospheric refraction
  - highly correlated time series
  - reference frame?
  - seasonal effects
  - loading effects
Vertical Motion

- Nothing “anomalous” is apparent local to YM
  - (large signals have been observed elsewhere due to magmatism)
- Sierra Nevada uplift?
- Hydrological loading?

Relative to Mean
Scale: 5 time enlarged
Max. arrow: 0.7 mm/yr

Lake Mead Level

- [Graph showing Lake Mead level changes from 1999 to 2005]
Progress: InSAR

- Developed InSAR data processing capability at UNR
  - ERS and ENVISAT pairs
  - Produces regional scale deformation maps consistent with GPS

- Current research towards reducing the effect of atmospheric errors
  - combined GPS-InSAR analysis
  - remote sensing data (MODIS and MERIS)
Related Geological Studies

- By Caltech
- Stateline fault system
  - Net offset
  - Active trace (LIDAR studies)
  - Timing of movement (U-Th)/He studies
Most obvious trace of the Stateline fault is the probable Holocene rupture on the Pahrump segment, between the two black arrows below.
Whole fault system (red) is remarkably straight, >200 km long, and has net offset of 30 km (white arrows) since 13 Ma, giving an average slip rate of ~2.2 mm/yr
Young apatite Helium ages characteristic of restraining bends in Eastern California Shear Zone have now been identified along SE trace of Stateline Fault Zone.
Formal Status of Task 3

• **All milestones have been met**
  – installation of new GPS receivers
  – quarterly checks that installed receivers are collecting data as anticipated
  – quarterly evaluation of new information from GPS and InSAR along with copies of peer-reviewed reports and articles

• **Subtask completion**
  – GPS site selection, permitting, & installation 100% complete
  – GPS data management and analyses 65% complete
  – InSAR data analyses 65% complete
  – Scientific interpretation 65% complete

• **Technical problems to report**
  – none
Conclusions (1/2)

• **GPS network (47 stations)**
  – no significant problems to report through 7-years of acquisition
  – new 17 stations performing well

• **GPS data processing**
  – 7-yr velocity solutions insensitive to seasonal variations
  – 0.5 mm weekly horizontal precision (2 mm vertical)
  – estimated < 0.1 mm/yr velocity precision
  – significant lack of “smoothness” now detected in velocity field
  – significant non-linear motions can now be investigated
  – unresolved question is the long-term strain accumulation
    • will take time to model post-seismic effects and thus resolve the interseismic secular velocity field
Conclusions (2/2)

• **InSAR**
  – Data processing capability has been developed & demonstrated
  – Does not compete with GPS for **point** precision
  – But initial results are consistent in the ECSZ-YM region
  – Research into combined GPS/InSAR looks promising (reduced tropospheric noise, improved reference frame)

• **Scientific Interpretation**
  – Strain rate at YM is too high to be explained by far-field ECSZ
    • East of YM: $22.3 \pm 2.1$ ns/yr observed versus $8.6 \pm 0.7$ ns/yr model
    • $> 0.7$ mm/yr right lateral shear local to YM area (< 30 km)
  – Indicates YM within boundary of currently active ECSZ
  – Geological work in progress by Caltech may shed light on this