UNAVCO

STABILITY OF GNSS MONUMENTATION:
ANALYSIS OF CO-LOCATED MONUMENTS IN THE PLATE BOUNDARY OBSERVATORY

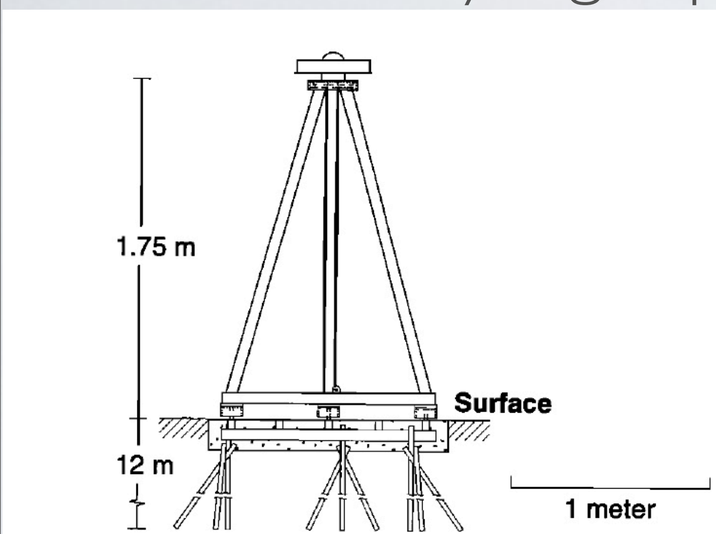
Frederick Blume, Henry Berglund, Karl Feaux, Ken Austin,
Tim Dittman, Chris Walls, Glen Mattioli
UNAVCO

Tom Herring
MIT

2014 IGS Workshop

IGS MONUMENTATION HISTORY

- 1991 Call for Participation: "A core network, comprising 20 to 30 globally distributed, very high quality sites" from existing permanent networks.



SIO3 - La Jolla, CA

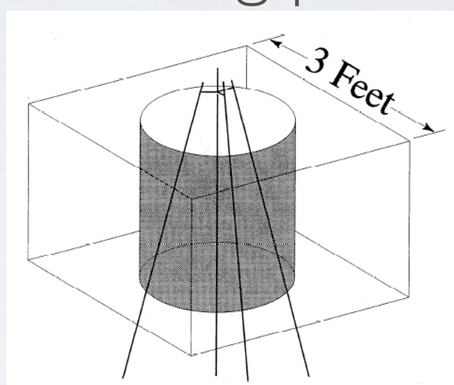
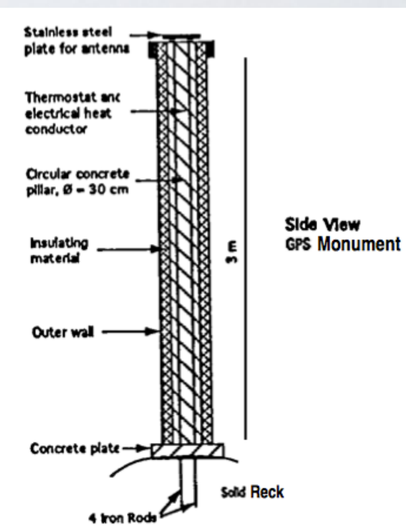


Figure 2. Permanent GPS sites. The heavy lines show the monument, constructed of stainless steel rod. Each of the four legs extends 6 to 8 m into the ground. A pipe (shaded) encloses the monument. The pipe is in a hole of one cubic yard, and concrete fills the space between the pipe and the sides of the hole.

Hayward, CA



Kiruna, Sweden

- 1993 IGS Workshop: "The stations should have good enough monumentation to be used in geodynamic applications."

IGS MONUMENTATION HISTORY

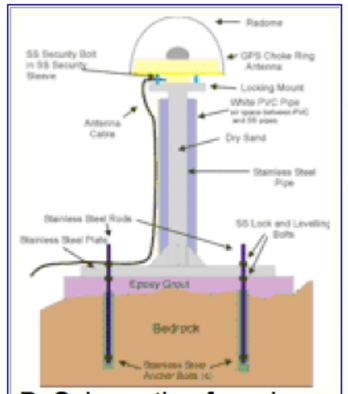
New GPS monument design for permanent GPS installations in the Western Canada Deformation Array

M. Schmidt, H. Dragert, W. Hill, N. Courtier

Contents of this page:

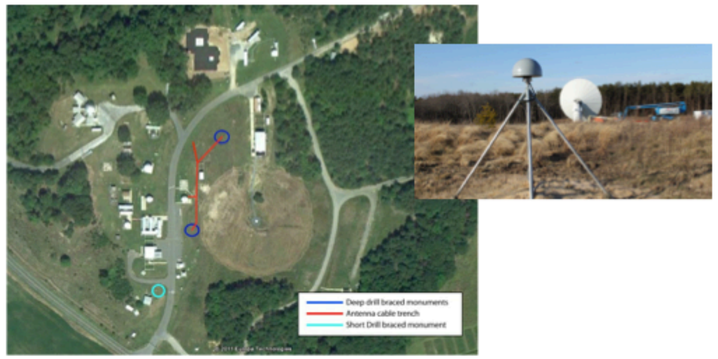
2000 IGS Workshop: NRCan

This paper was presented at the IGS Network Workshop 2000, 12 - 14 July, 2000, Soria Moria, Oslo, Norway



B. Schematic of newly designed stainless steel antenna pier.

NASA Goddard Geodetic Astronomical Observatory



(Left) GODN GNSS north site shown with NGVLBI antenna in background.

Aerial view of GGAO showing new monument locations:
GODN, GODS, and short drilled-braced monument (IGN Doris and GNSS co-lo. GODE GODZ original Flynn monuments. lso located on site are the next generation VLBI with 10m dish and moblas7 ngsSRL and other SLR telescopes.

See: NASA SGP website.

2012 IGS Workshop: UNAVCO

(Left) GODS GNSS south site with deep drilled-braced monument.

BRFT

Thank You

for mounting your antennas away from reflecting surfaces!

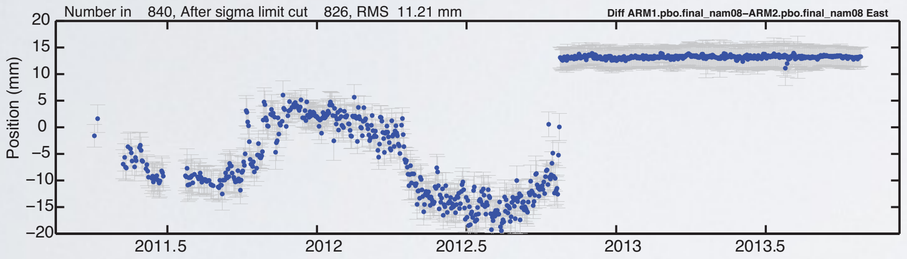
2006 IGS Workshop- Jim Ray

PREVIOUS STUDIES

Earlier Multi-Monument Sites in North America

SCIGN DDBM Pair

ARM1, ARM2 located in Bakersfield, CA (2001)
Deep-Drilled Braced Monuments (DDBM) separated by ~34m



Yucca Mountain

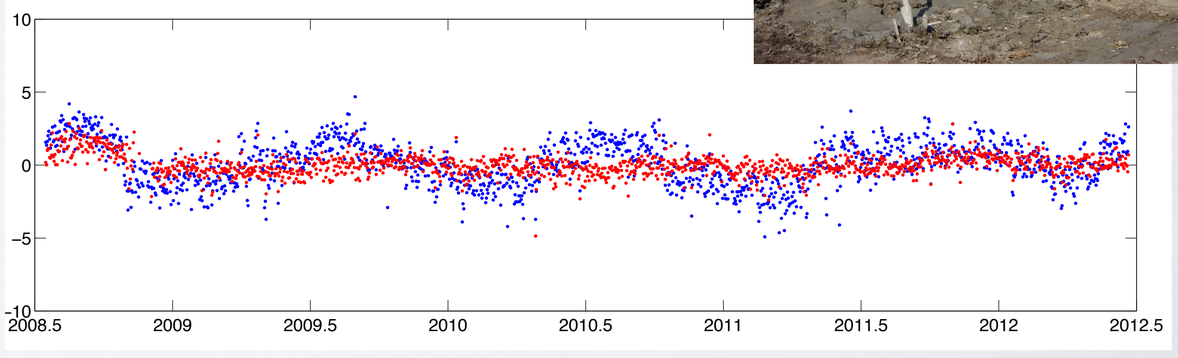
Hill et al. 2009
Drilled-braced monuments in bedrock)REPO, REP2, REP3, REP4 - Varied baseline lengths (~10, 100, and 1000 m)
Mixed anchoring depth

New Madrid Seismic Zone

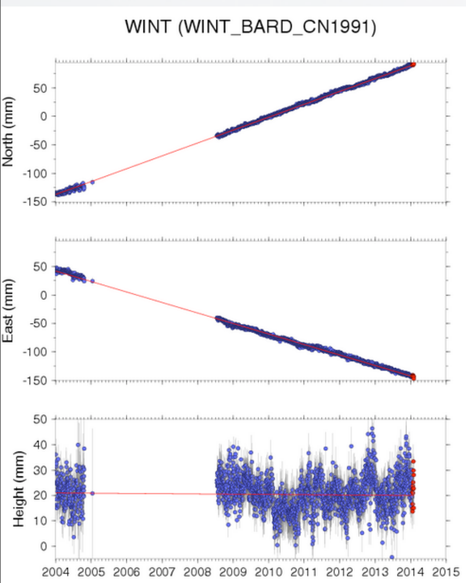
Matioli and Jansma, 2007
Two new deep-drilled braced GPS monuments (HCEX and PTGX) were installed in the New Madrid Seismic Zone. These sites are co-located with existing driven I-beam monuments (HCES and PTGV) in unconsolidated sediment.

East Bay, Hayward Fault

WIN2 (deep-drilled braced), installed 2008
PBO Nucleus upgrade of 1991 USGS shallow driven rod enclosure at Winton



WINTON AVE (HAYWARD FAULT): 1991-2014



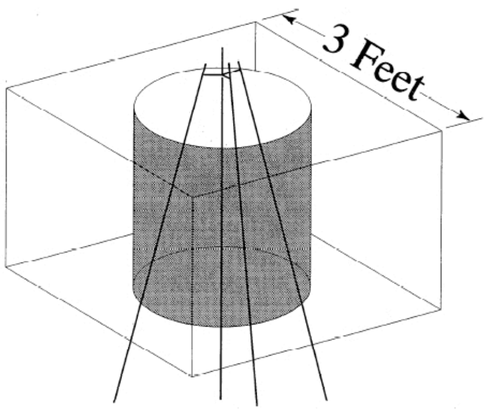
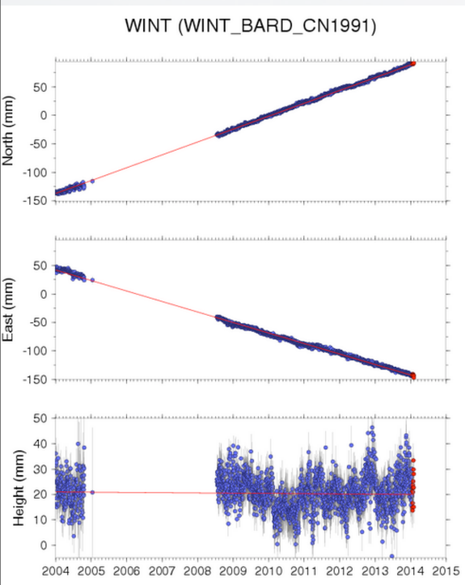
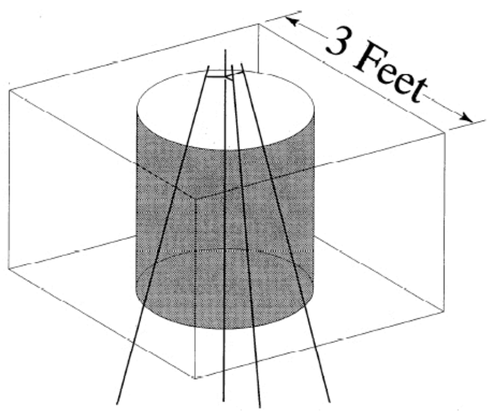


Figure 2. Permanent GPS sites. The heavy lines show the monument, constructed of stainless steel rod. Each of the four legs extends 6 to 8 m into the ground. A pipe (shaded) encloses the monument. The pipe is in a hole of one cubic yard, and concrete fills the space between the pipe and the sides of the hole.

WIN2: 2008-2014





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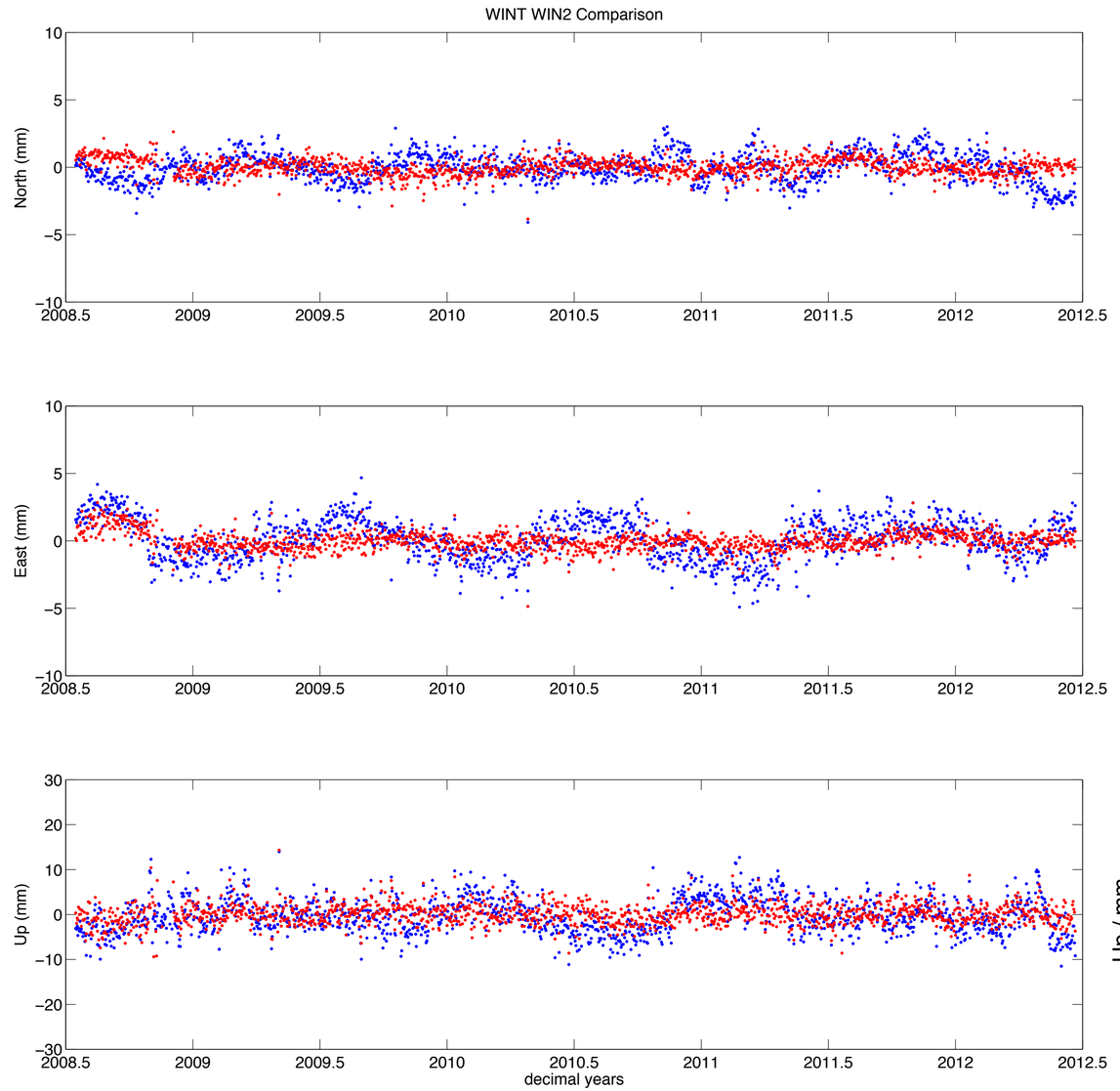
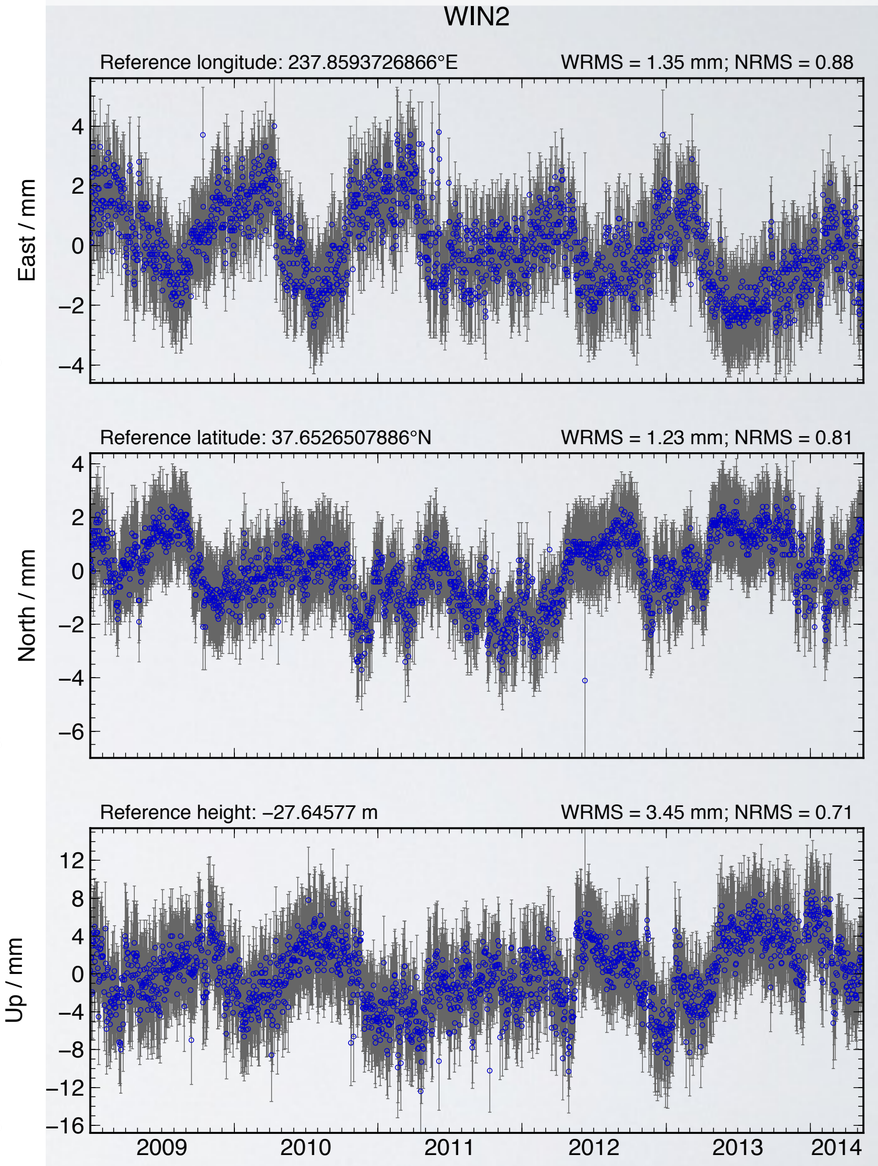




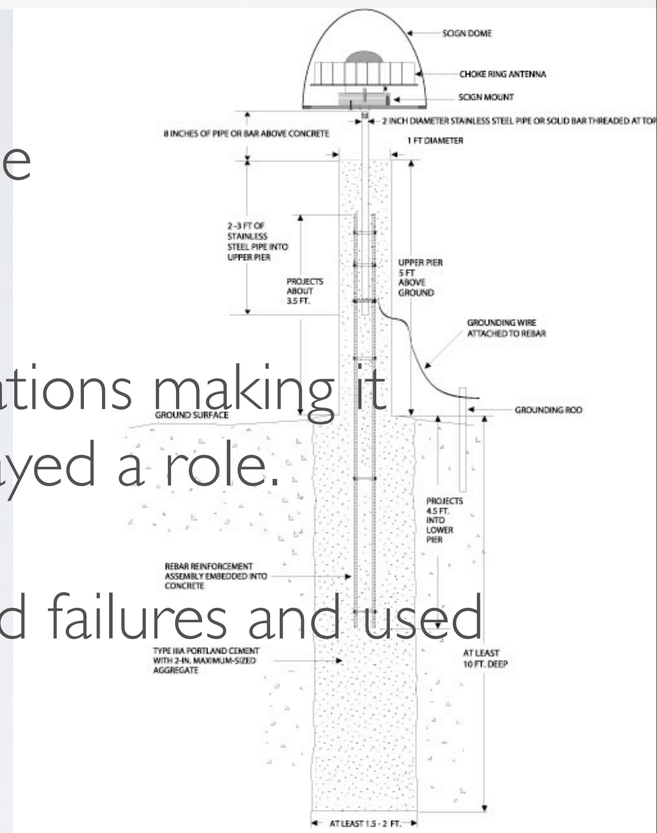
PBO MULTI-MONUMENTATION 2013

- DDBM's are very expensive, high-impact and labor-intensive
  - >50% of PBO are DDBM; were installed wherever logistically possible
  - Pillars are much cheaper at soil sites, but are they stable?

- Previous multi-monument sites were either pairs or had varying separations making it difficult to discern which monument was stable or if baseline length played a role.

- Many previous monument studies have had multiple antenna swaps and failures and used inconsistent equipment reducing their value for stability studies.

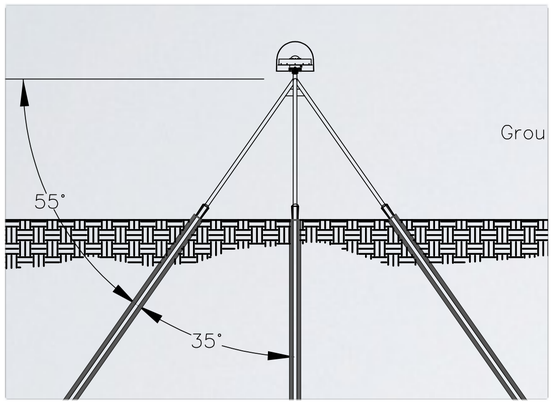
  - Receivers at PBO multi-monuments are all the same type (NETR9)
  - Antennas are all DM choke rings
    - New installations used TRM59800.00 GNSS while existing DDBMs were left with original TRM29659.00 GPS models to preserve time-series integrity.



PBO MULTI-MONUMENTATION 2013

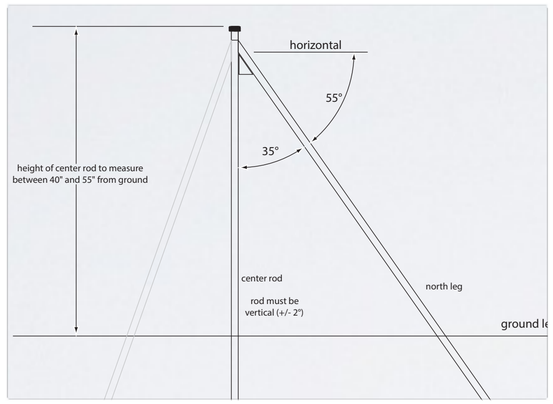
Five different monument types will be evaluated

Deep-Drilled Braced Monument



Cost: $7500-15000
Labor: 3-4 people
Time: 2-4 days
Impact: High
Depth: 35’

Shallow-(Drilled and Driven) Braced Monument



Cost: $800
Labor: 2-3 people
Time: 1-3 days
Impact: Med
Depth: 5’

Short Mast Style Monument

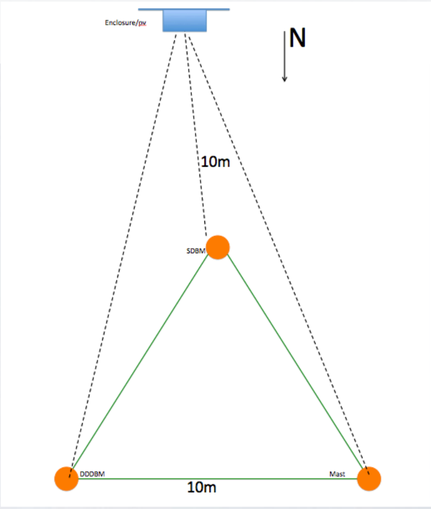
Cost: $150
Labor: 1-2 people
Time: 1 days
Impact: Low
Depth: 2’

Pillar Style Monument

Cost: $500-2000
Labor: 2-3 people
Time: 1-3 days
Impact: Med-High
Depth: 11’

MULTI-MONUMENT LOCATIONS

	4-Char Code	Monument Type	Installation
The Rock, GA	P804	DDBM	Oct 2012
Granite	P805	SDBM	Oct 2012
	P806	Mast	Oct 2012
Wilbur, WA	P453	DDBM	Oct 2005
Basalt	P813	Mast	Aug 2013
	P814	SDBM	Aug 2013
Forks, WA	P401	DDBM	Apr 2005
Clay Substrate	P815	Pillar	Aug 2013
	P816	Driven SBM	Aug 2013
Delano, CA	P565	DDBM	Nov 2005
Clay/Silt/Sand	P809	Pillar	Feb 2013
	P810	Driven SBM	Feb 2013
California City, CA	P591	DDBM	June 2005
Sand	P811	Pillar	Feb 2013
	P812	Driven SDBM	Feb 2013



- 5 localities were chosen
  - 2 in California
  - 2 in Washington
  - 1 in Georgia
- 3 monument types at each
- Existing DDBM were utilized at 4 installations
  - Delano, CA - California City, CA - Wilbur, WA - Forks, WA
- Site selection criteria:
  - Low multi-path
  - Clear sky view
  - Multiple geological conditions

- Site Geometry
  - Triangular with 10m spacing

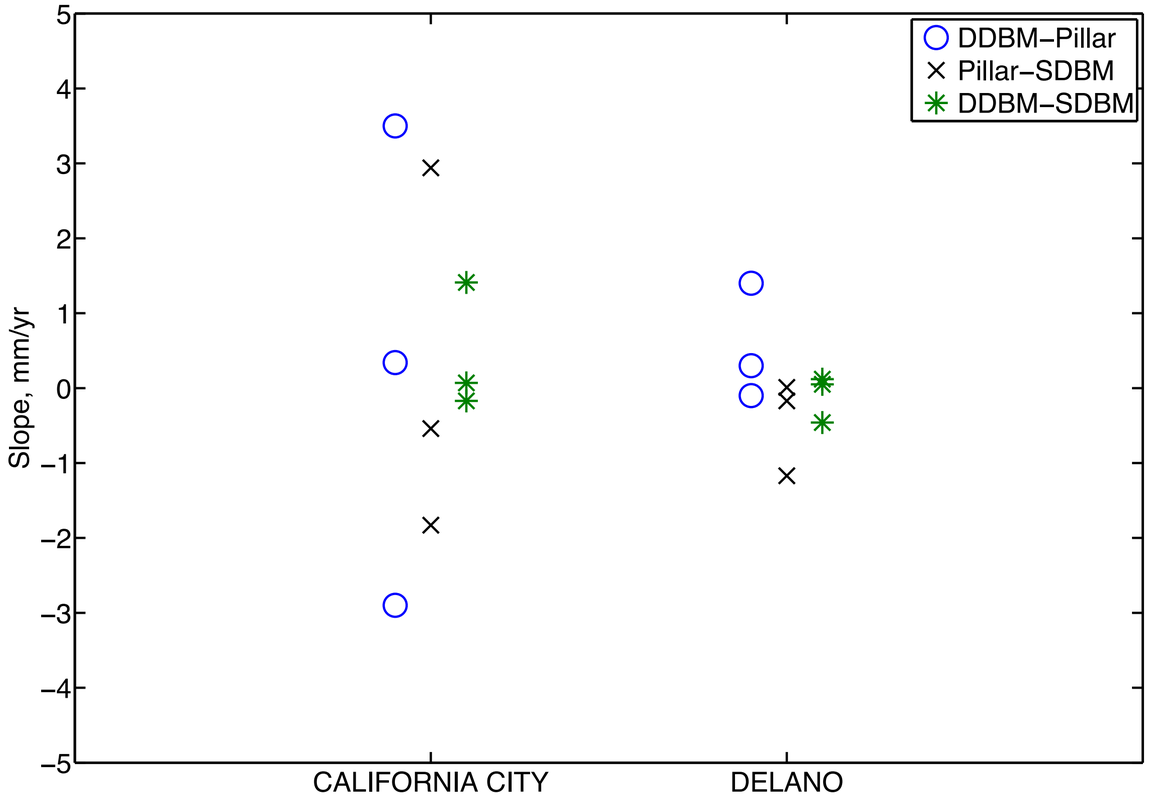
ANALYSIS STRATEGIES

- All the sites are processed by the PBO analysis centers (GAMIT + GISPY)
- Uncombined solutions are available as well (NMT and CWU).
- Routine processing uses the standard LC combination.
- L1+L2 Atmosphere-independent solutions. (Herring)
  - Difference reveals multi-path effects

- Current LC results show sub-millimeter RMS.
- Already seeing lower RMS between DDBM/SDBM vs. DDBM/PILLAR.
- Also seeing smaller slope estimates between DDBM/SDBM vs. DDBM/PILLAR.
- Kinematic processing has revealed periodic RF interference at Delano Airport.

BASELINE SLOPE ESTIMATES

Delano, CA	Baseline	Component	Slope (mm/yr)	WRMS (mm)
Clay/Silt/Sand	P565-P809	North	1.40 ± 0.1	0.20
	DDBM-PILLAR	East	-0.10 ± 0.1	0.20
		Up	0.30 ± 0.3	0.96
	P809-P810	North	-1.17 ± 0.1	0.22
	PILLAR-DSBM	East	0.01 ± 0.1	0.23
		Up	-0.17 ± 0.3	0.69
	P565-P810	North	0.12 ± 0.1	0.19
	DDBM-DSBM	East	0.05 ± 0.1	0.19
		Up	-0.46 ± 0.3	0.96
California City, CA	Baseline	Component	Slope (mm/yr)	WRMS (mm)
Sand	P591-P811	North	-2.90 ± 0.1	0.27
	DDBM-PILLAR	East	0.34 ± 0.12	0.34
		Up	3.50 ± 0.28	0.78
	P811-P812	North	2.94 ± 0.1	0.28
	PILLAR-DSBM	East	-0.54 ± 0.1	0.14
		Up	-1.83 ± 0.3	0.80
	P591-P812	North	-0.17 ± 0.1	0.21
	DDBM-DSBM	East	0.07 ± 0.1	0.26
		Up	1.41 ± 0.2	0.73



DELANO, CA

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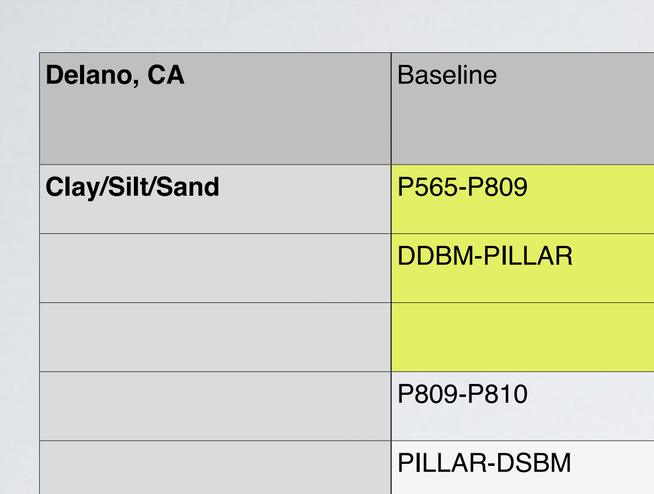
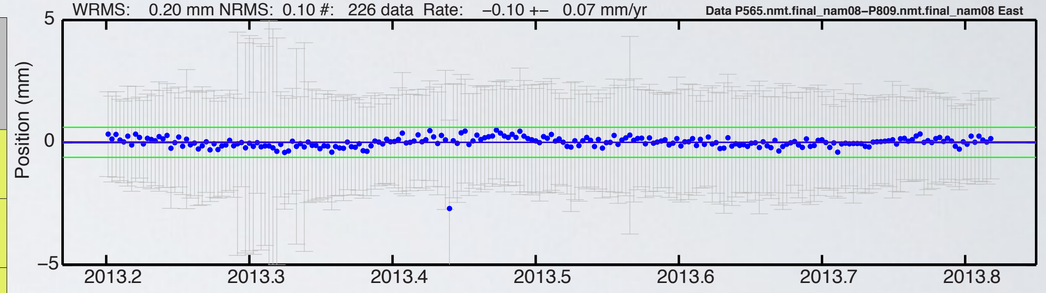
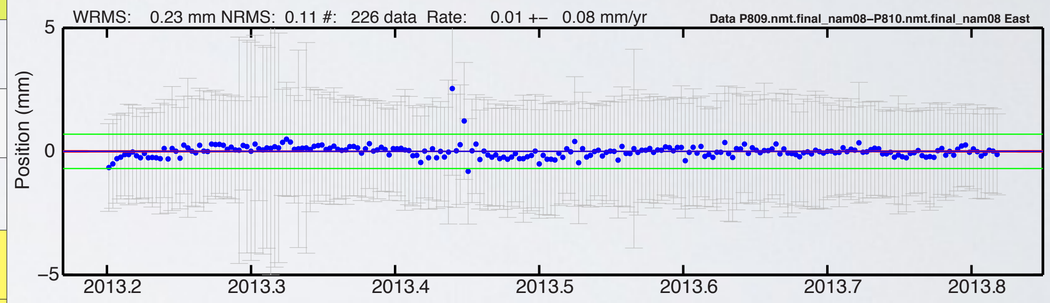
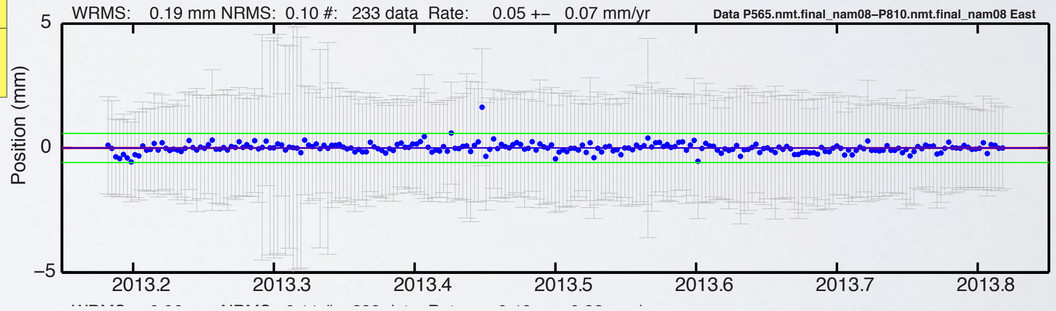




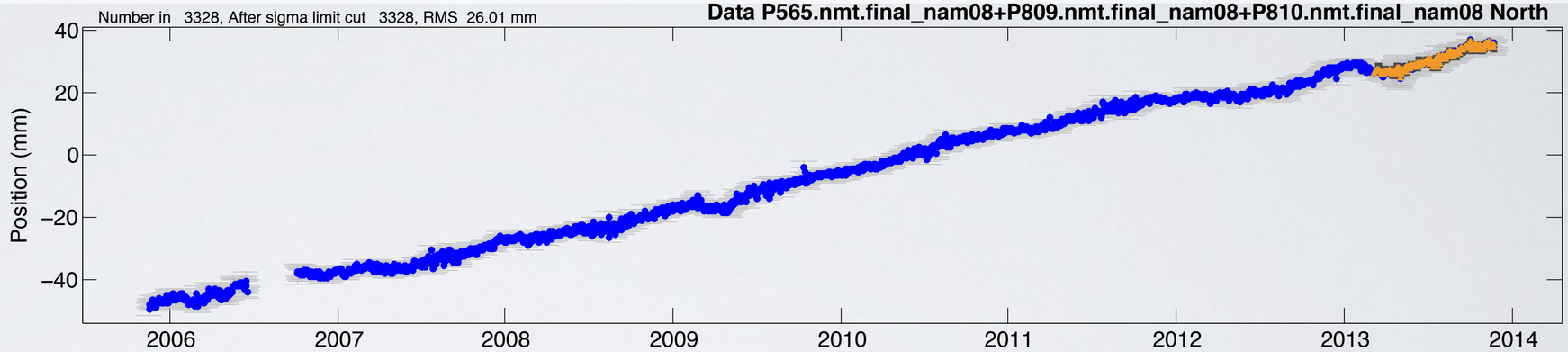


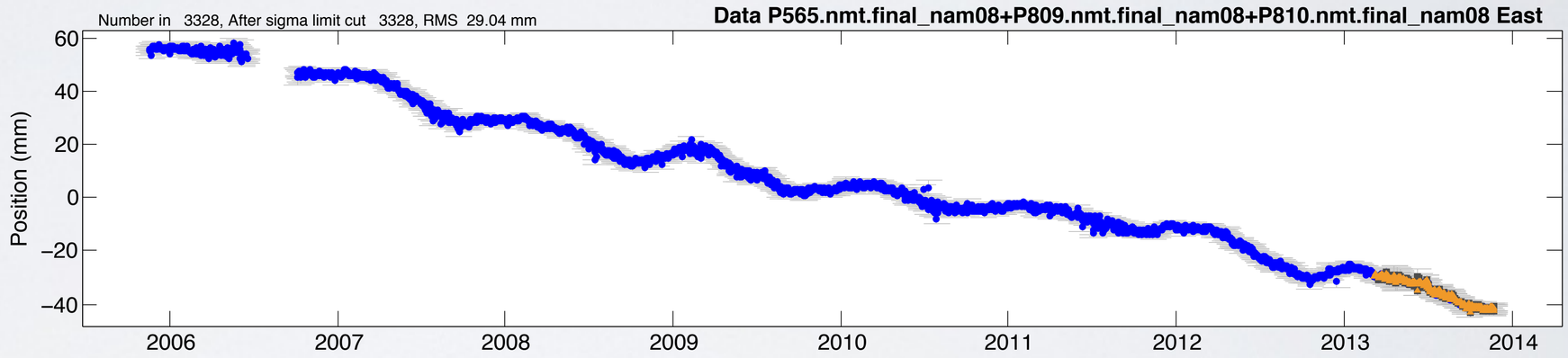


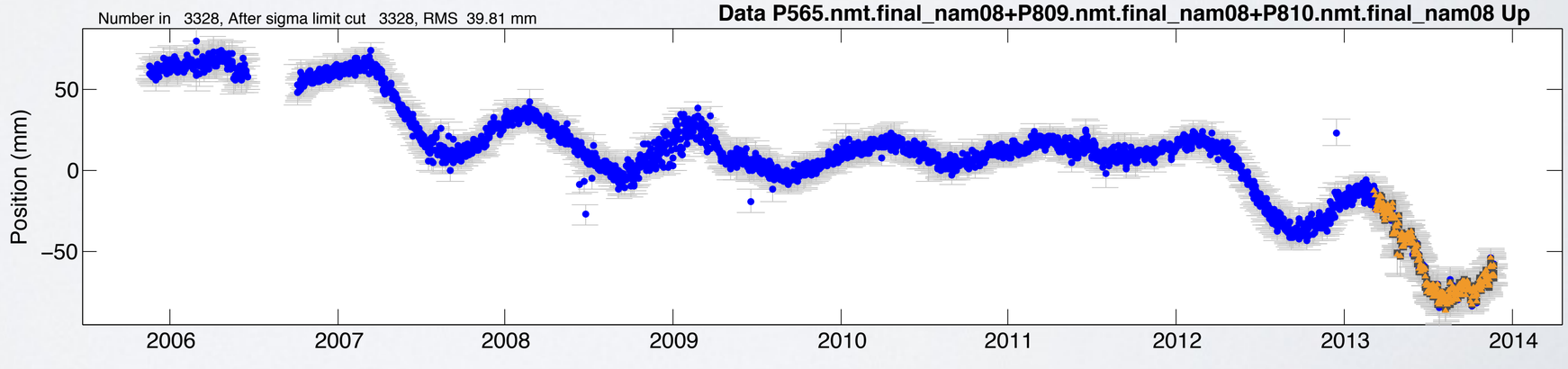
UNAVCO

DELANO, CA

Unconsolidated sand/silt/clay soil



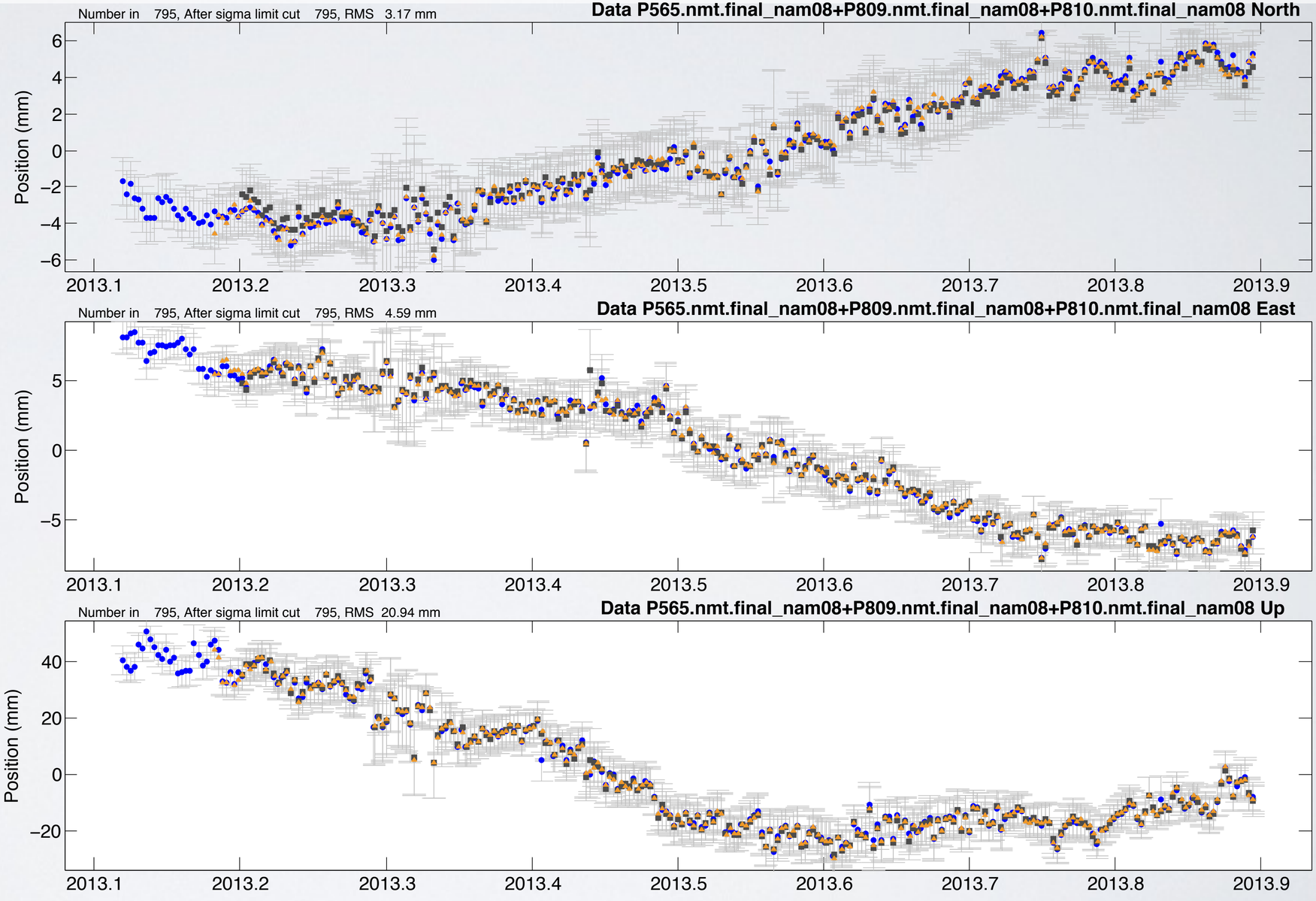




UNAVCO

DELANO, CA

Unconsolidated sand/silt/clay soil



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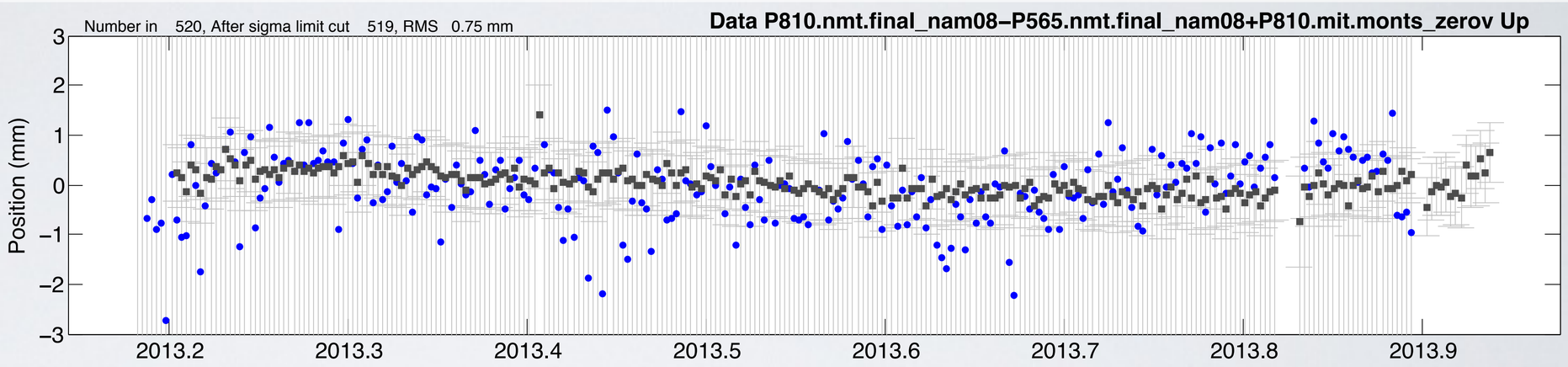
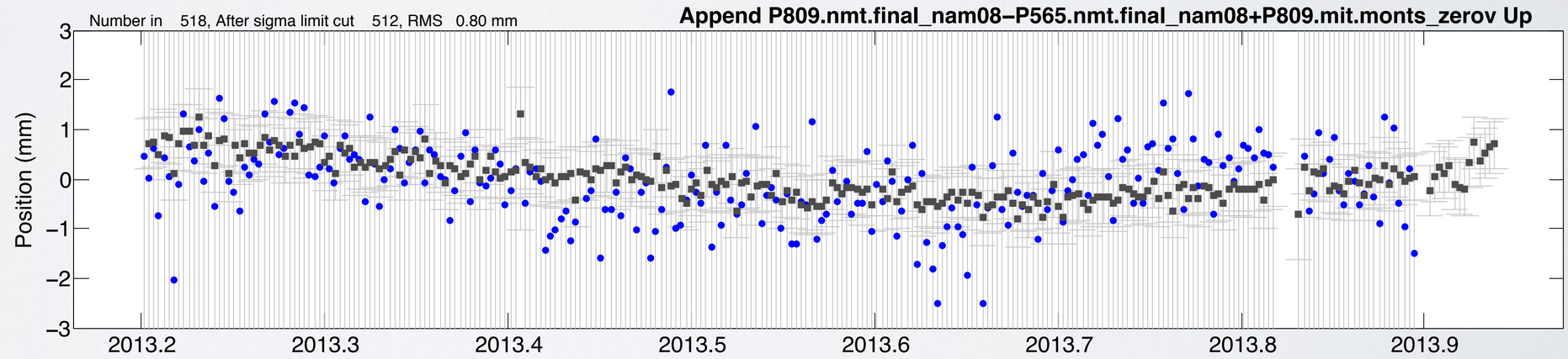


DDBM - SDBM (Vertical, LC (blue), L1 +L2 (Green)

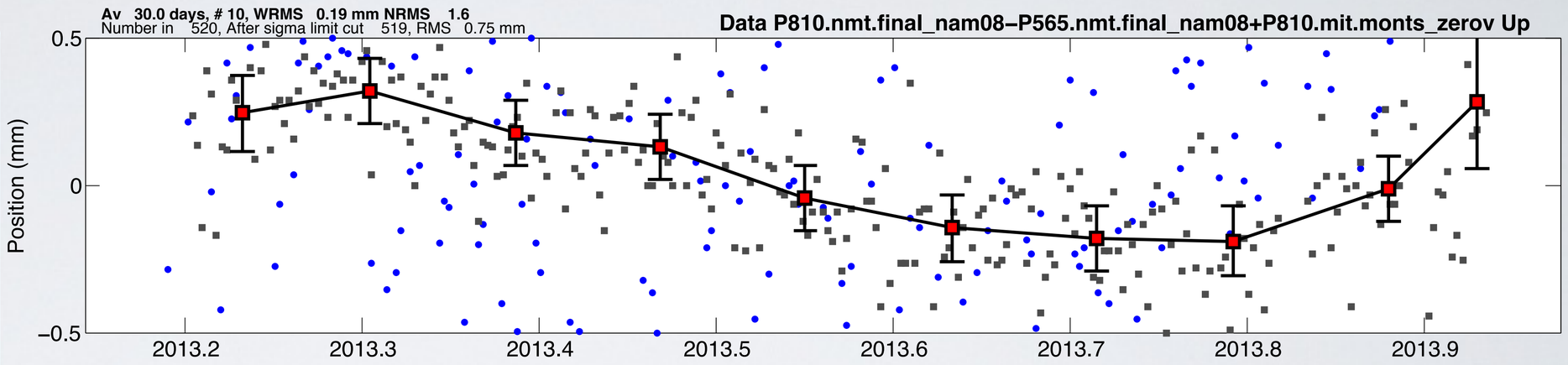


DDBM - Pillar (Vertical, LC (blue), L1 +L2 (Green)

UNAVCO

DELANO, CA

Unconsolidated sand/silt/clay soil



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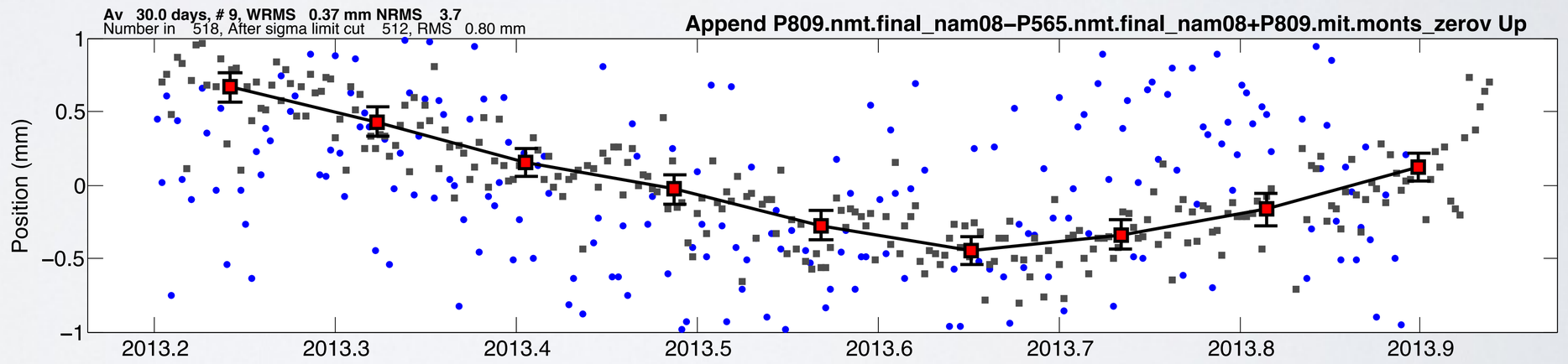

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DELANO, CA

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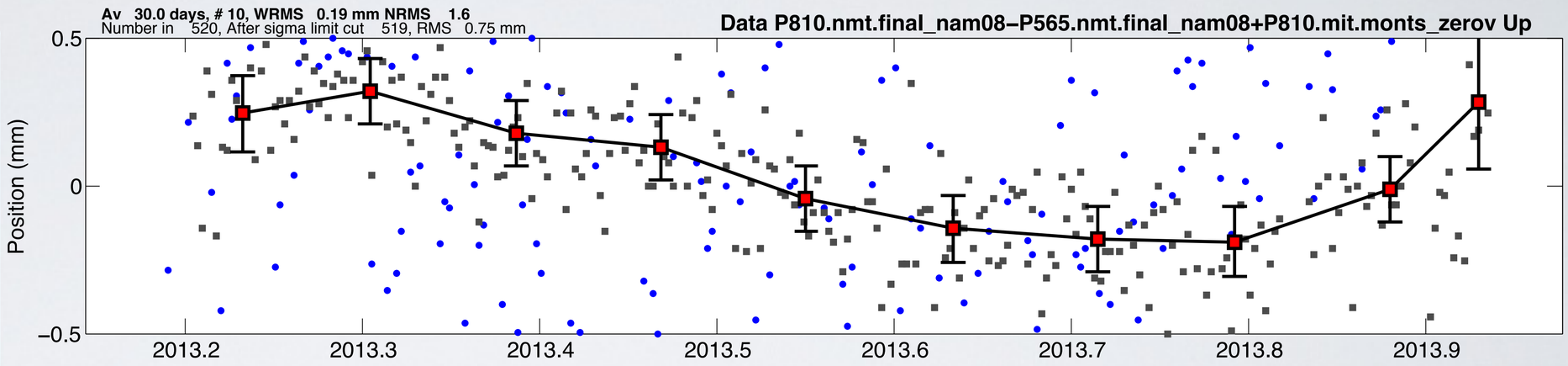
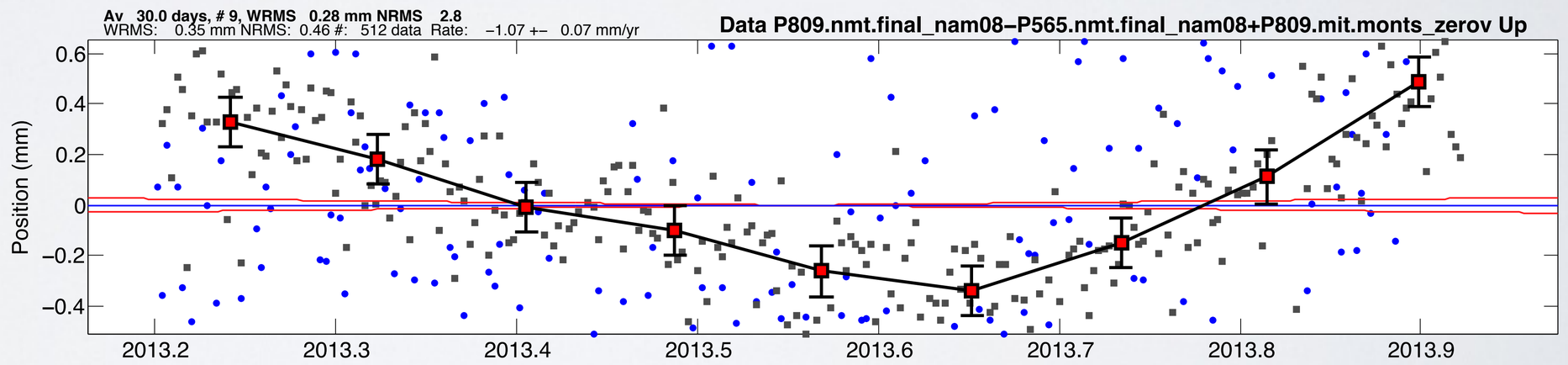


DDBM - SDBM (Vertical, LC (blue), L1 +L2 (Green)



DDBM - Pillar (Vertical, LC (blue), L1 +L2 (Green)

CALIFORNIA CITY, CA

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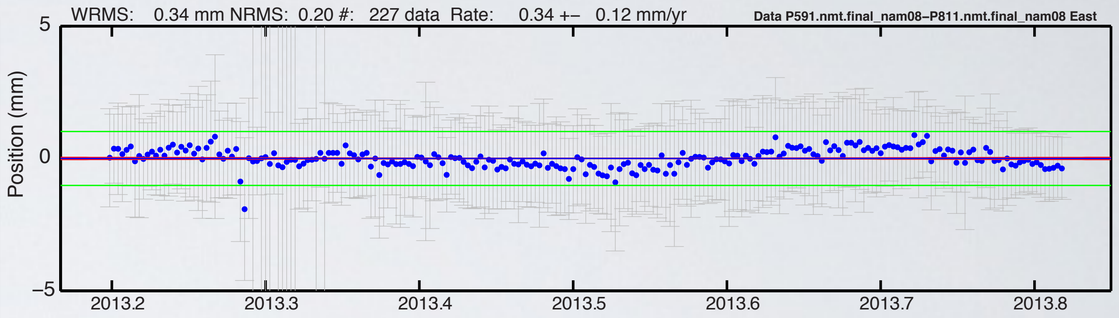
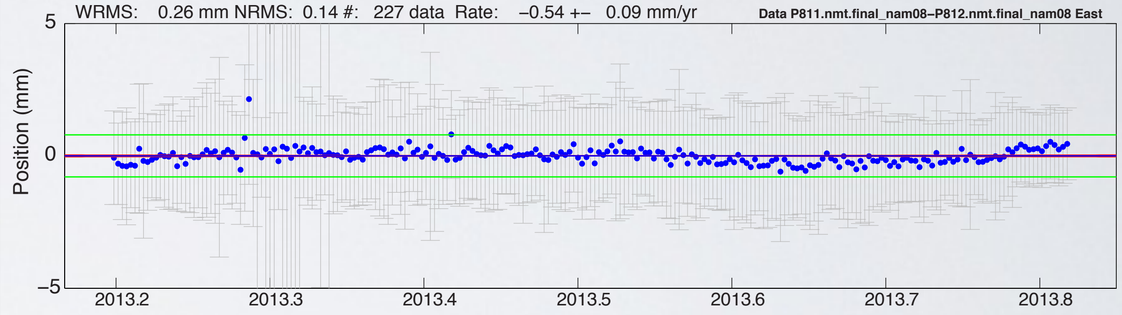
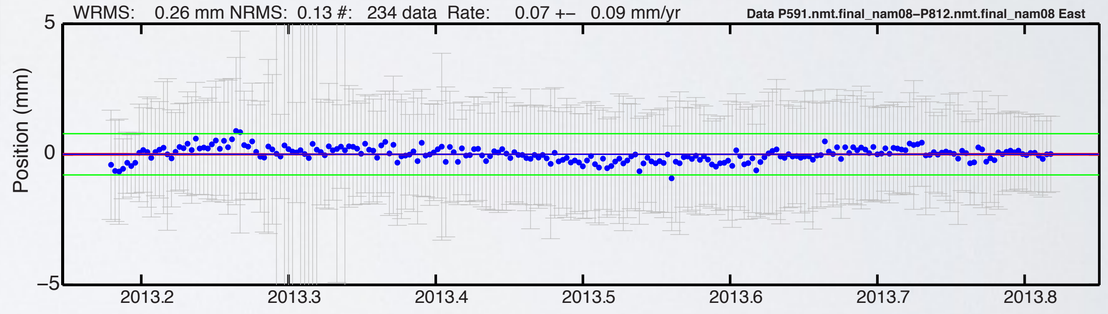
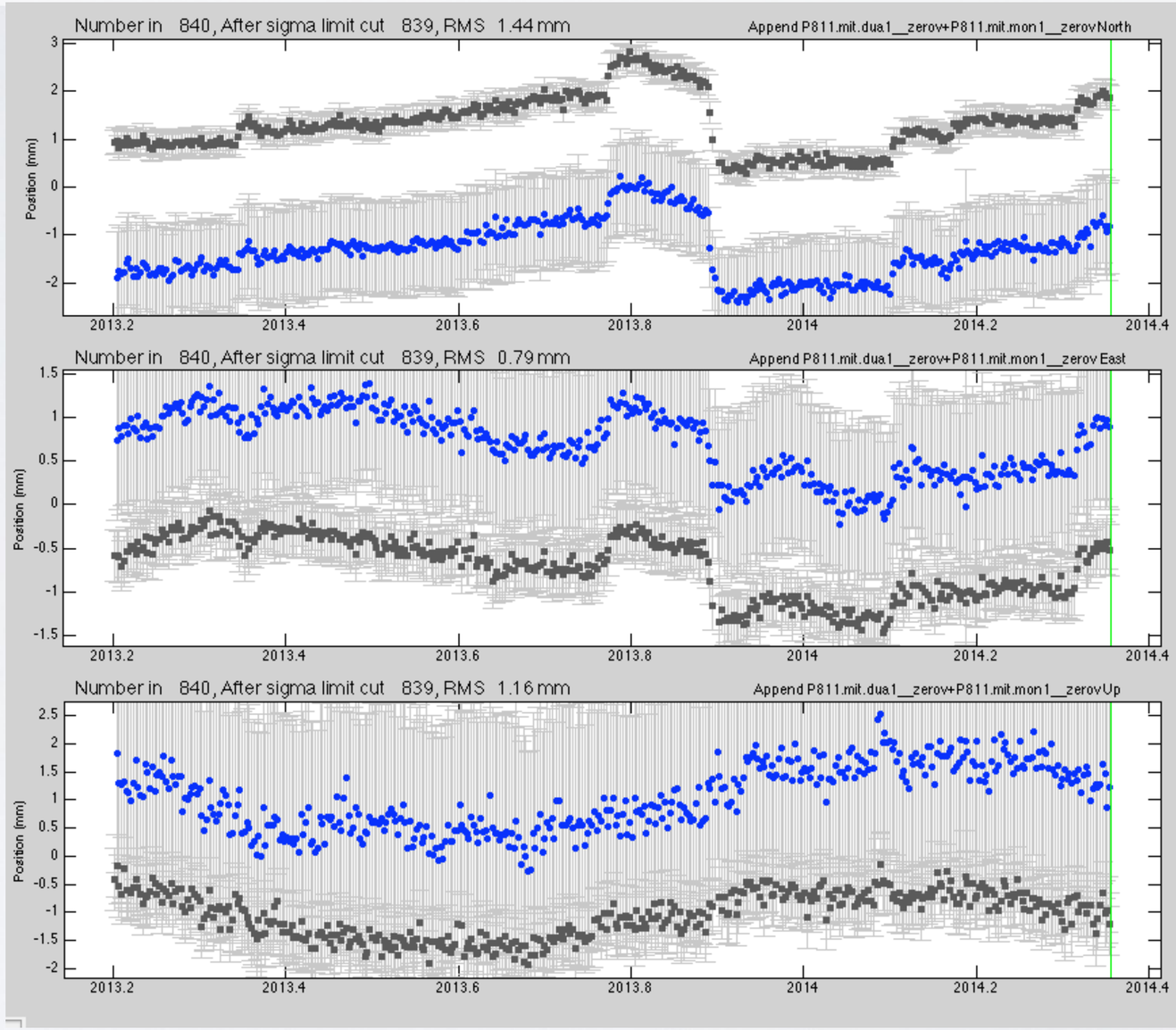






CALIFORNIA CITY, CA

18” diameter hole about 15ft deep



DDBM - Pillar (LC (blue), L1 +L2 (green) - Offsets due to antenna calibration errors?

UNAVCO

CALIFORNIA CITY, CA

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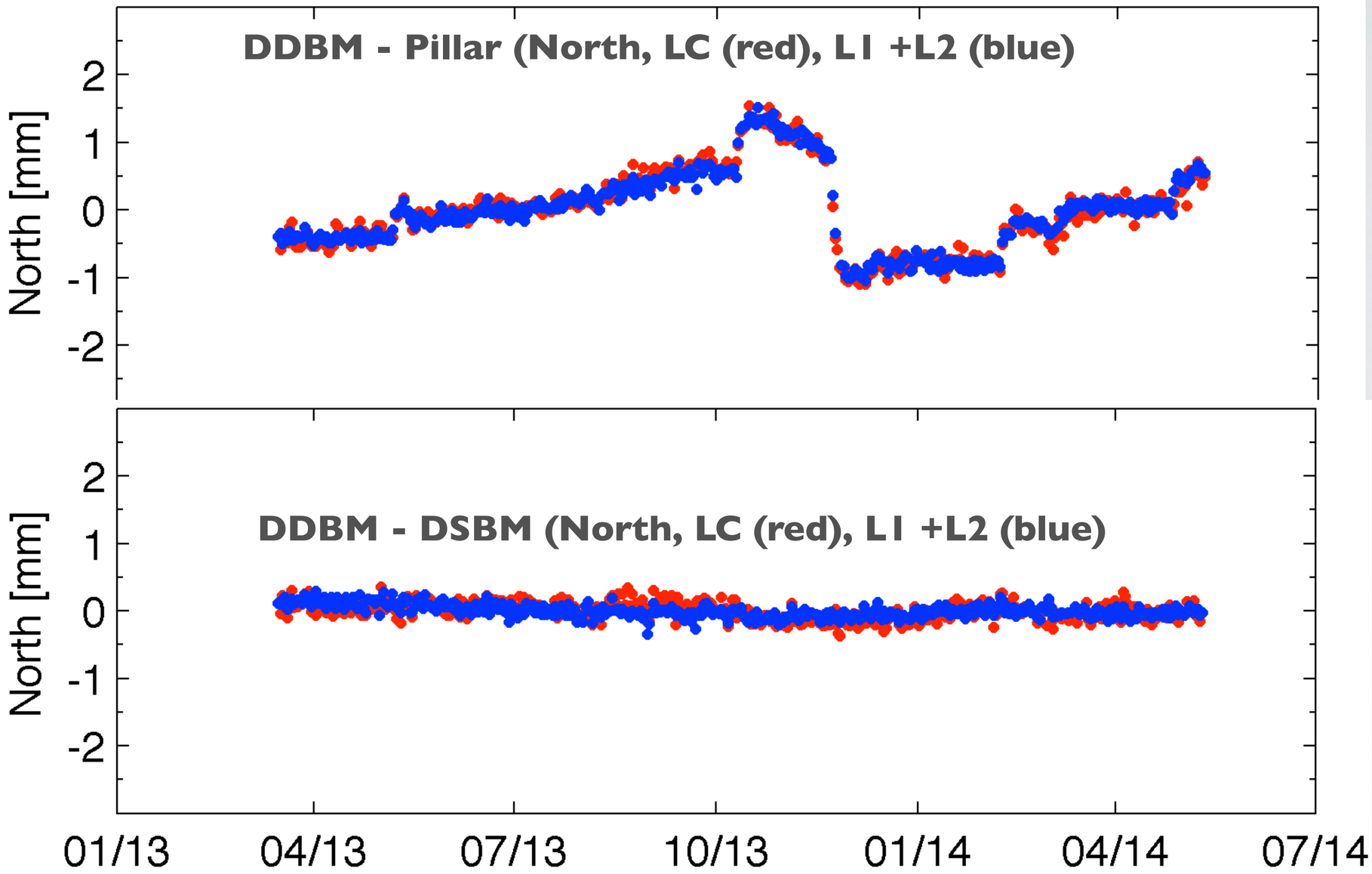

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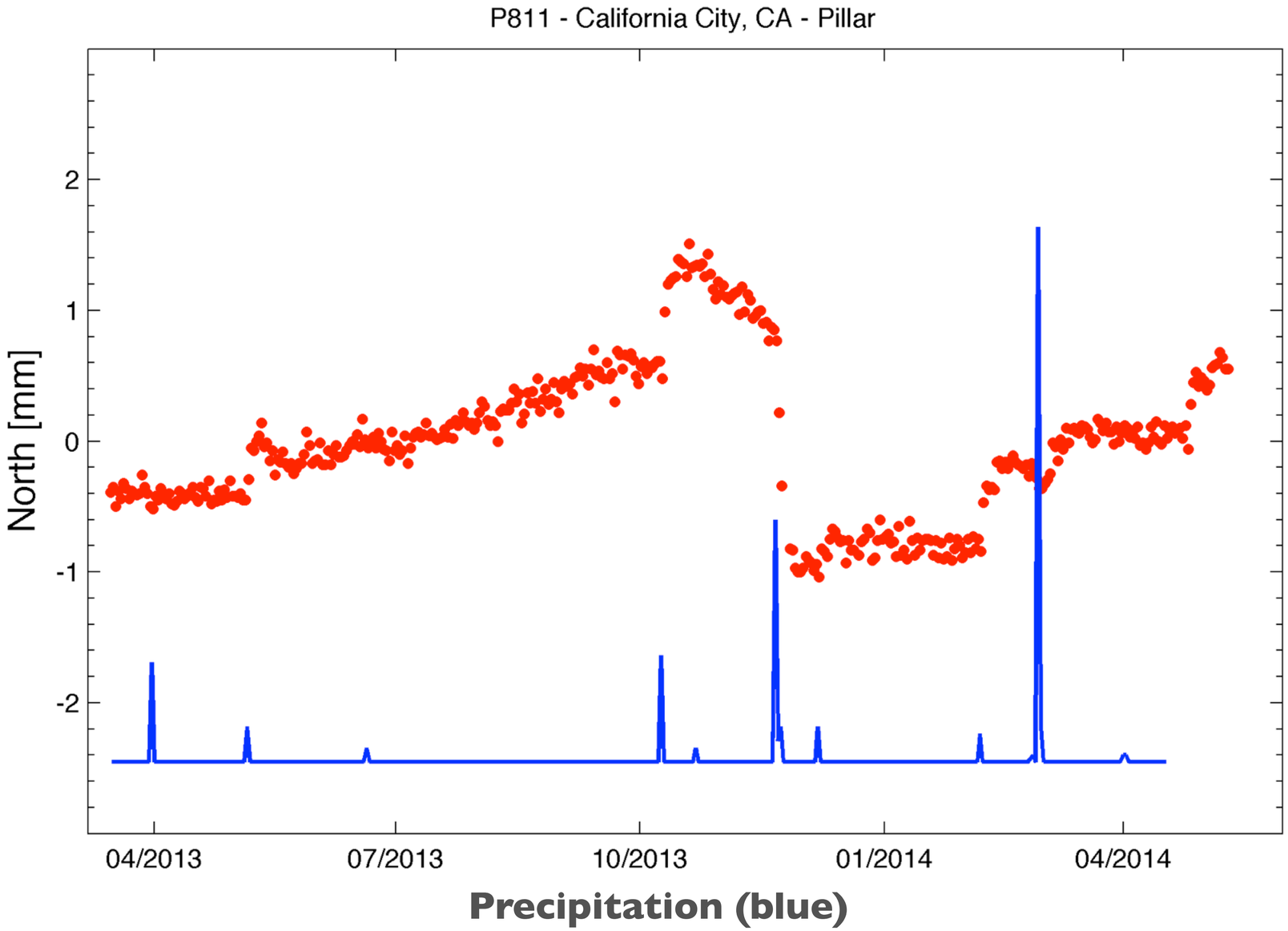
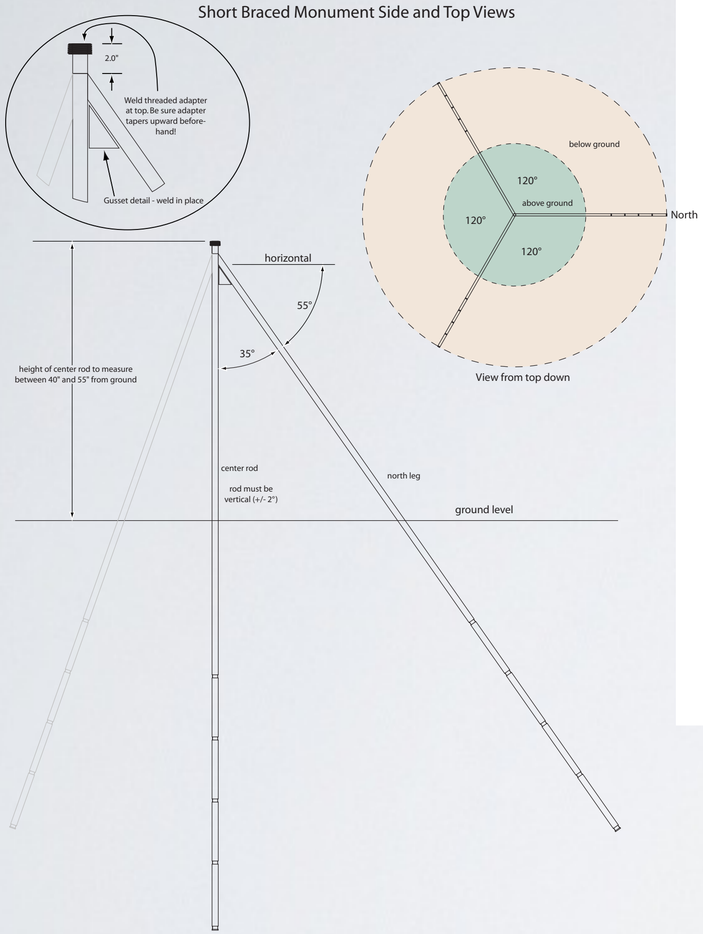
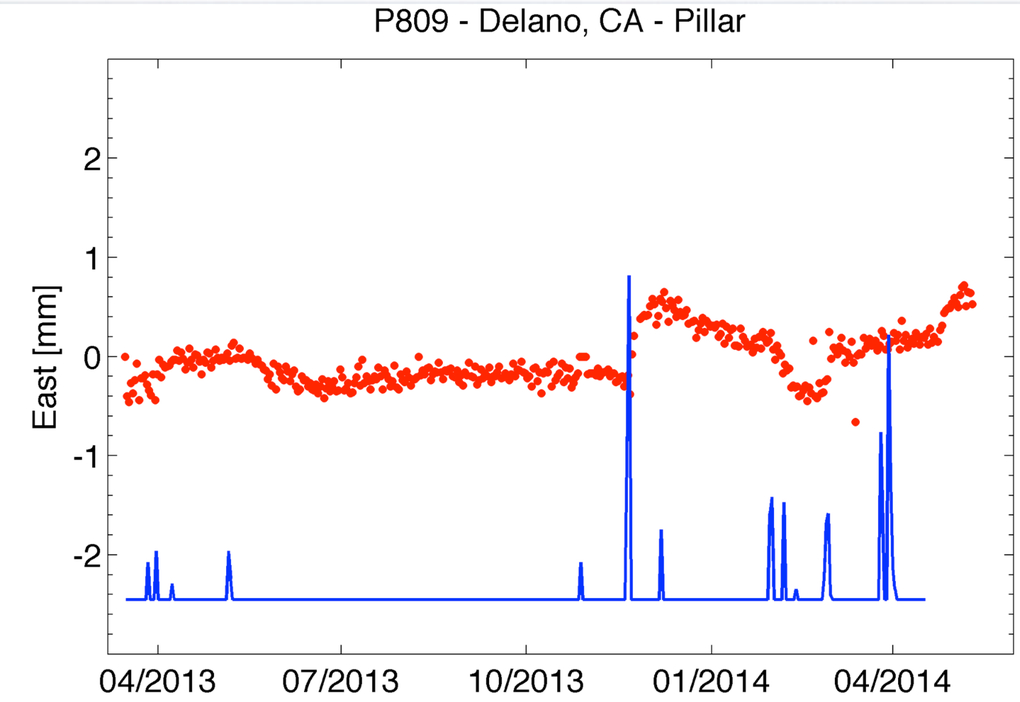


CALIFORNIA CITY, CA

Rods Driven to only 1.8m!

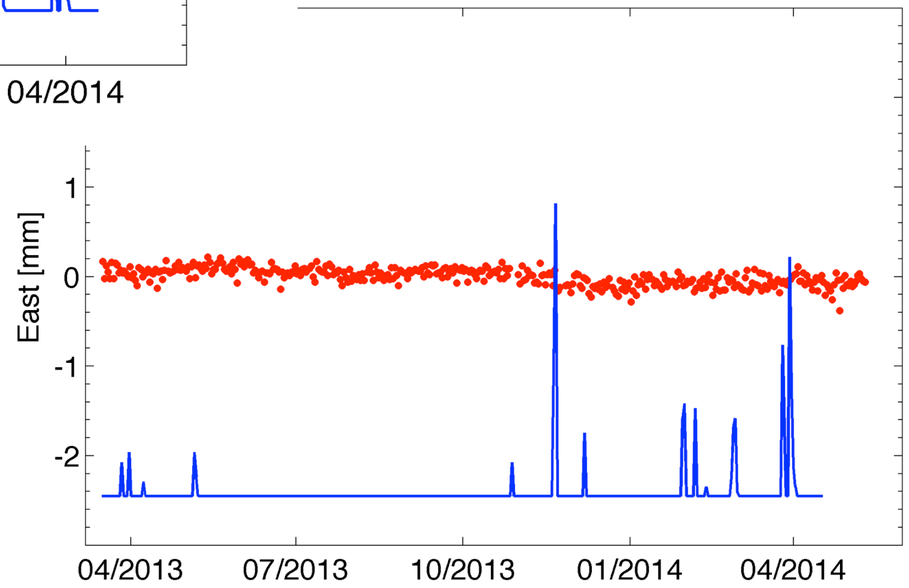
DELANO, CA





Unconsolidated sand/silt/clay soil

P810 - Delano, CA - SDBM

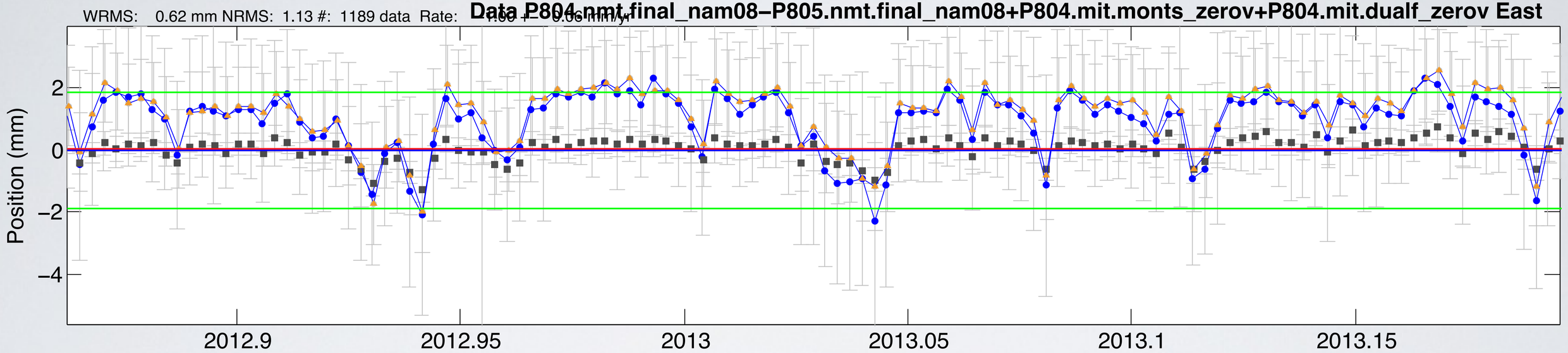


Lateral bracing more impotant than depth!

UNAVCO

THE ROCK, GEORGIA

THE ROCK, GEORGIA

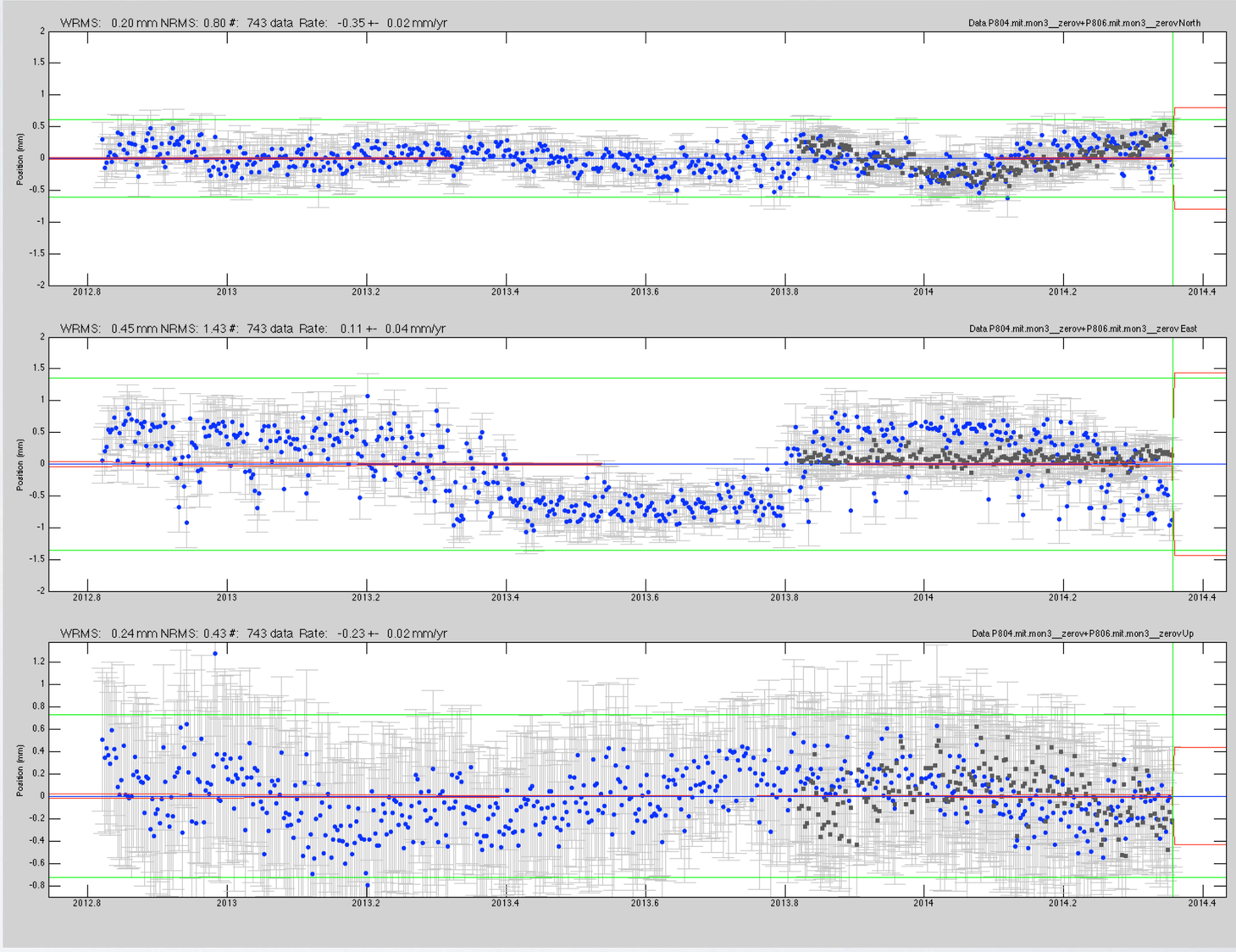


DDBM - SDBM (East)

LC GAMIT Network (blue)
LC No Atmosphere (yellow)
L1 +L2 (Green)

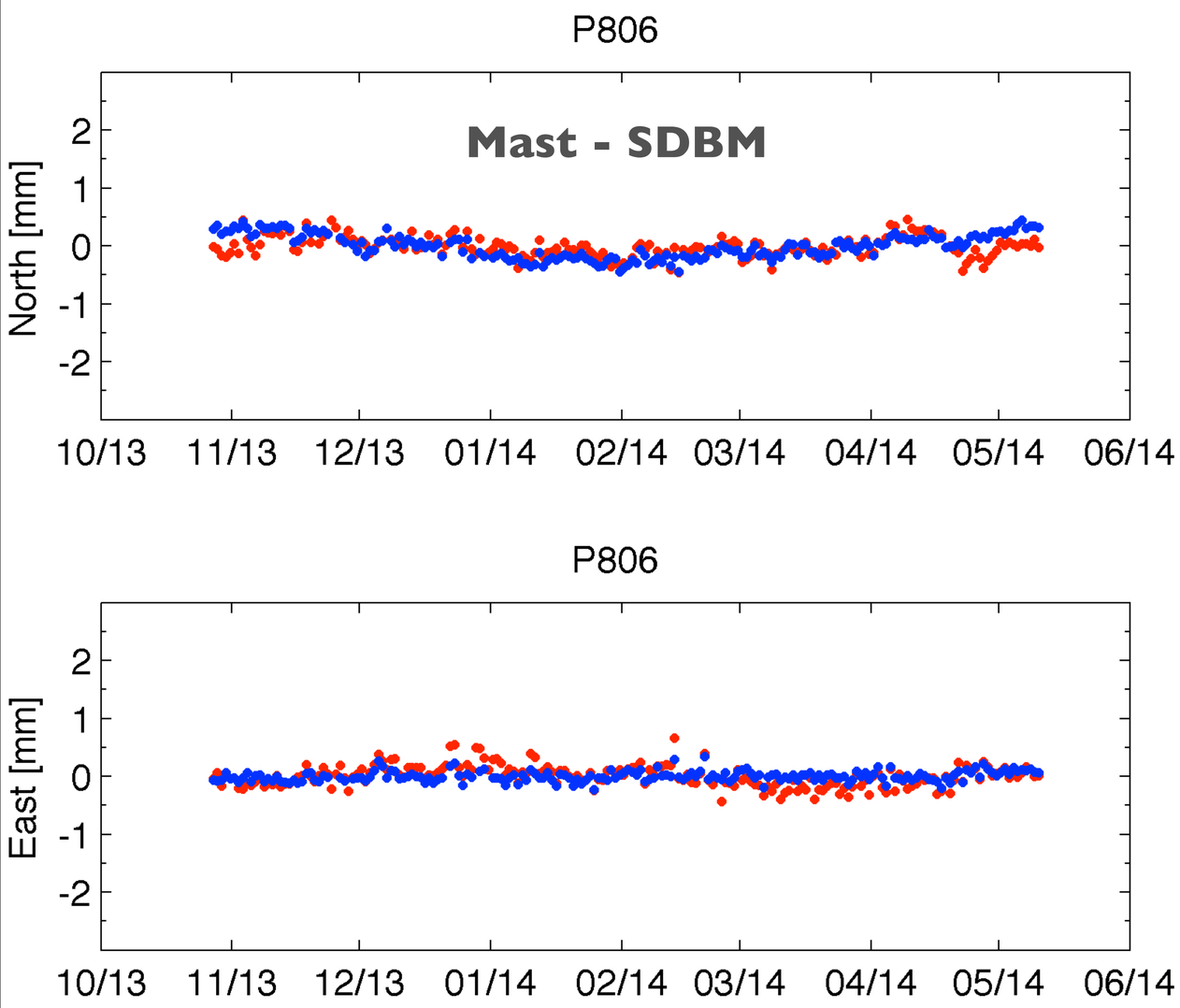
sub-mm stability in Granite

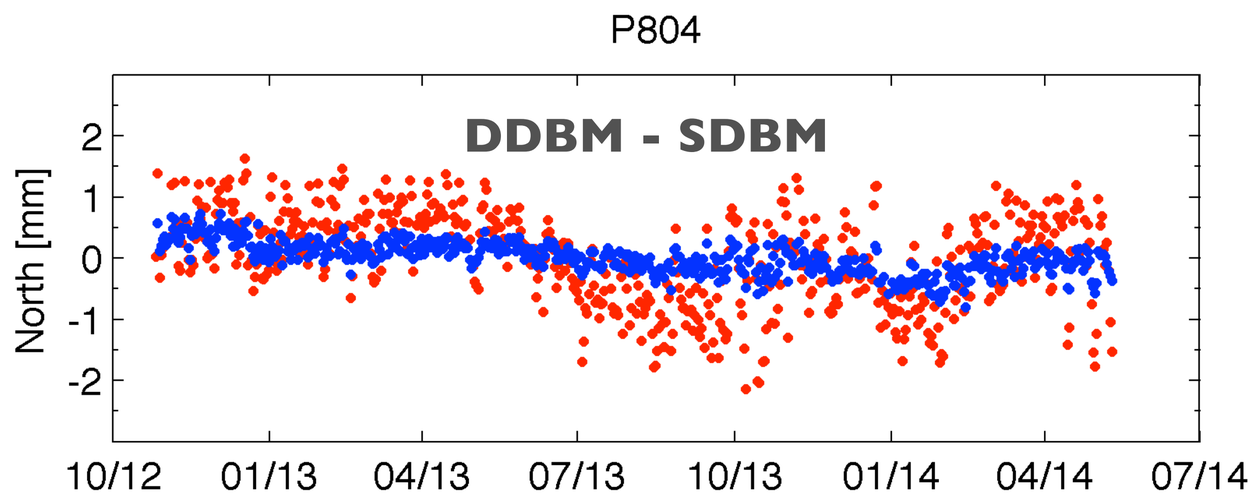
THE ROCK, GEORGIA

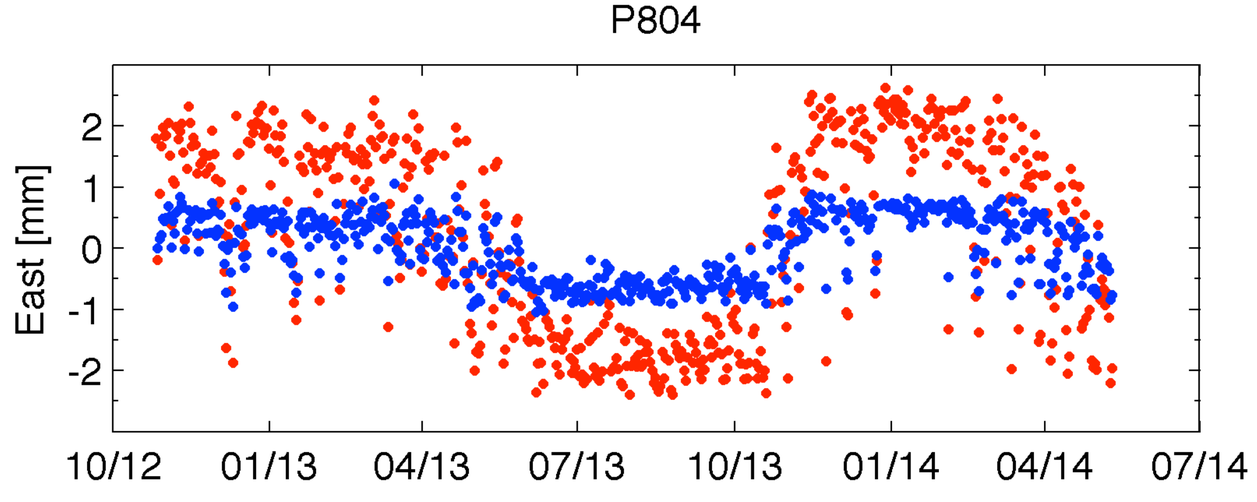


Shallow Mast (Green) vs. DDBM (Blue) - SDBM Fixed

THE ROCK, GEORGIA



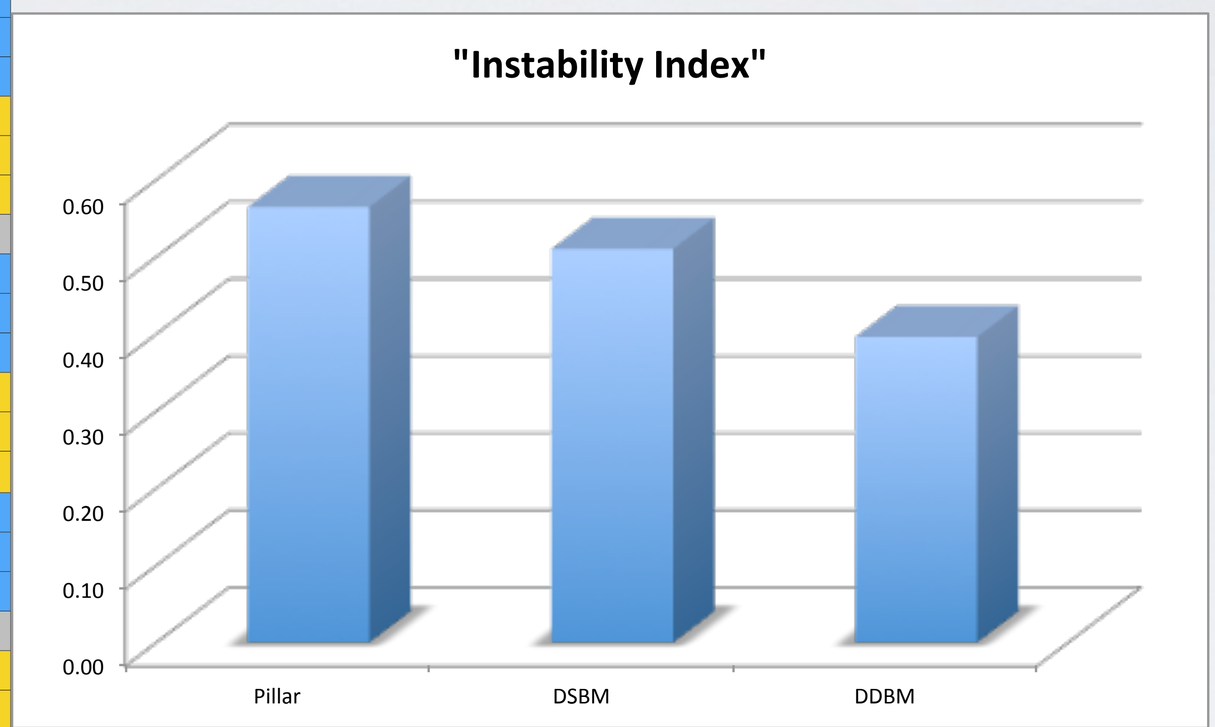




L1+L2 (blue) - LC (red) - Multipath affects DDBM! Need to model reflections and study antenna height

L1+L2 PROCESSING RESULTS- SEDIMENTS

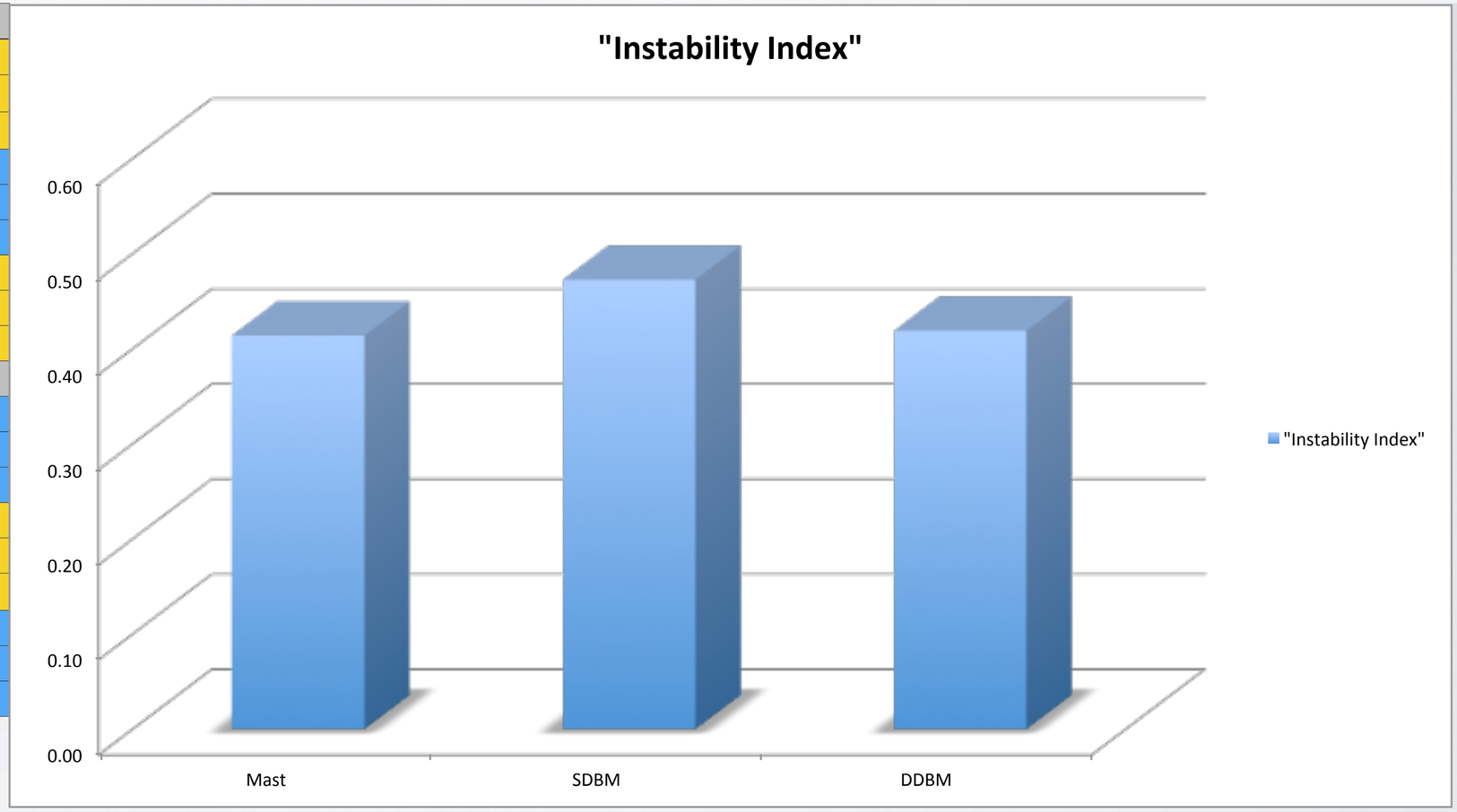
Forks, WA	Baseline	Component	Slope (mm/yr)	Months
Clay/Silt/Sand	P401-P815	North	-0.68 ± 0.06	8
	DDBM-Pillar	East	0.15± 0.06	8
		Up	-0.96 ± 0.12	8
	P401-P816	North	-.9 ± 0.19	8
	DDBM-DSBM	East	-0.65±0.18	8
		Up	-1.22±0.36	8
	P804-P806	North	1.58±0.19	8
	DSBM-Pillar	East	-0.5±0.18	8
		Up	-0.27±0.36	8
Delano, CA	Baseline	Component	Slope (mm/yr)	Months
Clay/Silt/Sand	P565-P809	North	-0.69±0.03	14
	DDBM-PILLAR	East	0.4±0.04	14
		Up	0.19±0.08	14
	P809-P810	North	-0.5±0.04	14
	PILLAR-DSBM	East	0.57±0.05	14
		Up	-0.06±0.09	14
	P565-P810	North	0.19±0.04	14
	DDBM-DSBM	East	0.17±0.04	14
		Up	-0.13±0.09	14
California City, CA	Baseline	Component	Slope (mm/yr)	Months
Sand	P591-P811	North	-0.05±0.04	14
	DDBM-PILLAR	East	0.34 ± 0.12	14
		Up	3.50 ± 0.28	14
	P811-P812	North	0.16±0.04	14
	PILLAR-DSBM	East	-0.76±0.05	14
		Up	0.2±0.09	14
	P591-P812	North	-0.05±0.04	14
	DDBM-DSBM	East	0.73±0.04	14
		Up	-0.4±0.08	14



Horizontal Motions greatest for pillars
Brace your monuments in sediments!

L1+L2 PROCESSING RESULTS- BEDROCK

Wilbur, WA	Baseline	Component	Slope (mm/yr)	Months
Basalt	P453-P814	North	0.32±0.13	7
	DDBM-SDBM	East	0.5±0.13	7
		Up	-1.06±0.25	7
	P813-P814	North	-0.54±0.14	8
	Mast-SDBM	East	0.09±0.03	8
		Up	0.13±0.26	8
	P813-P453	North	0..86±0.12	8
	Mast-DDBM	East	-0.41±0.12	8
		Up	1.19±0.23	8
The Rock, GA	Baseline	Component	Slope (mm/yr)	Months
Granite	P805-P804	North	0.38±0.02	18
	SDBM-DDBM	East	0.4±0.04	18
		Up	0.19±0.08	18
	P806-P804	North	0.23±0.08	6
	Mast-DDBM	East	0.56±0.1	6
		Up	-0.02—0.19	6
	P806-P805	North	-0.15±0.08	6
	Mast-SDBM	East	-0.47±0.1	6
		Up	-0.25±0.19	6



Cheap shallow mast outperforms DDBM

L1+L2 PROCESSING RESULTS- BEDROCK

Wilbur, WA	Baseline	Component	Slope (mm/yr)	Months
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	DDBM-SDBM	East	0.5±0.13	7
		Up	-1.06±0.25	7
	P813-P814	North	-0.54±0.14	8
	Mast-SDBM	East	0.09±0.03	8
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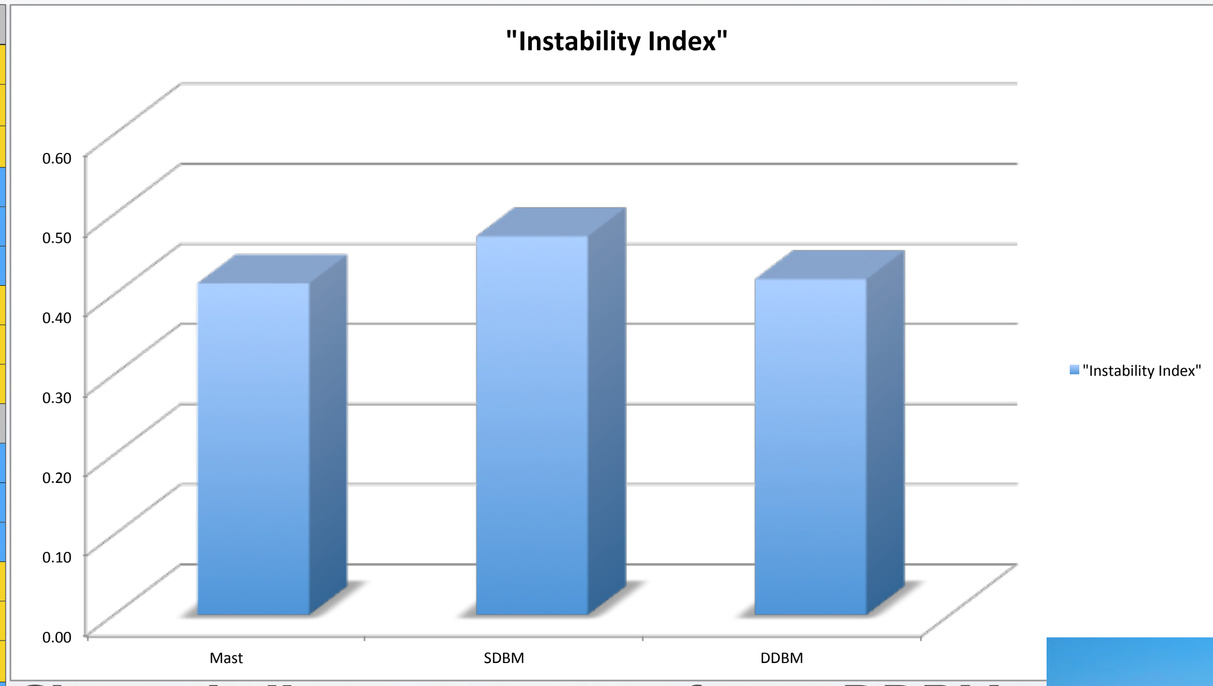
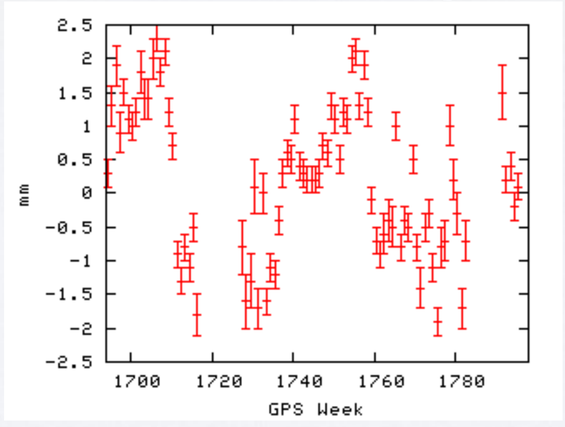


Cheap shallow mast outperforms DDBM



IGS Station ABPO - Ambohimpanompo, Madagascar, 2007 - 2014

CONCLUSIONS AND FUTURE WORK

Based on a few months of data at new installations:

- **GNSS monuments are as stable as the ground they are put in.**
- **Pillars do not perform as well in unconsolidated sediments; SDBM are better than Pillars and almost as good as DDBM**
  - **If you don't have bedrock - drill as deep as you can afford**
  - **Horizontal footprint is more important than vertical footprint**

- **Monumentation selection may not have a significant impact at sites with competent bedrock.**
  - **If you have good bedrock, use a mast and save $$$ for other stations.**

Wilbur, WA: P453/P813/P814

Ongoing continued QC and detailed analysis over a few years will provide further clarity.

- **Data are available to the public at UNAVCO Archive.**
- **Detailed analysis needed to separate antenna eccentricities and multipath from monument instability.**
  - **Independent study of antenna height would be useful.**
- **Additional monument farms should be installed to improve sample size and assess a wide variety of geological regimes.**

Forks, WA: P401/P815/P816