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Dealing with earthquakes and other non-linear motions

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GAMIT/GLOBK/TRACK Short Course for GPS Data Analysis
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Material from T. A. Herring, R. W. King, M. A. Floyd (MIT) and S. C. McClusky (now ANU)

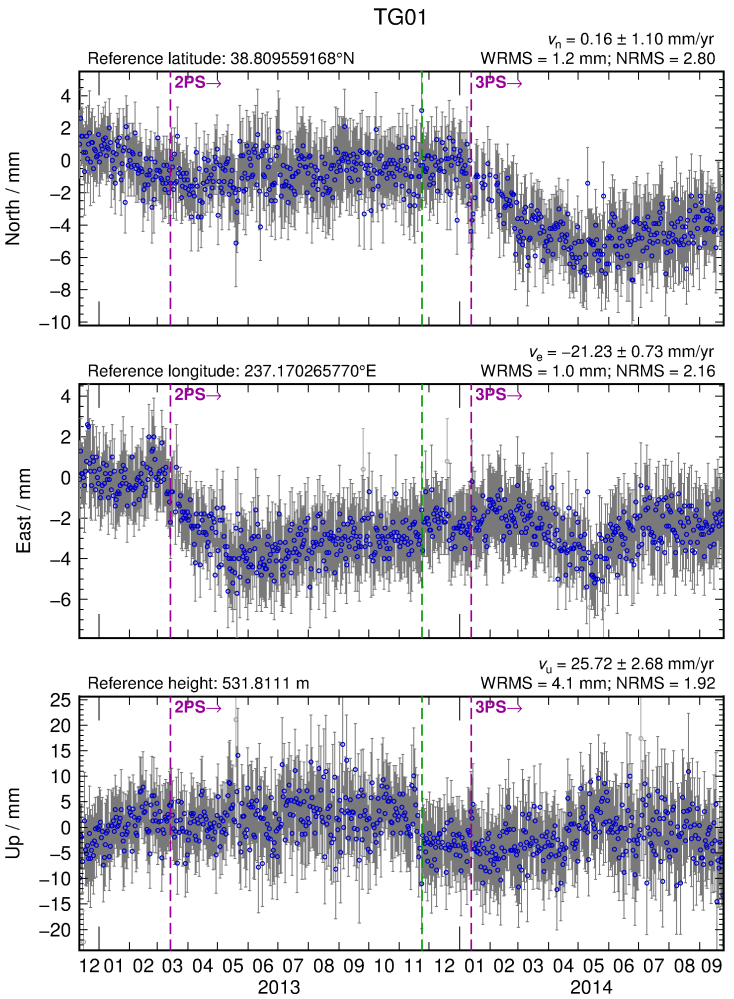
Outline

- Previous lecture showed common time series models
  - Linear rate
  - Seasonal terms
  - Temporally correlated noise
- Irregular perturbations to such models include
  - Discontinuities due to equipment or environment changes
  - Discontinuities due to earthquakes
  - Non-linear motions due to earthquakes
  - Non-linear motions due to transient events (e.g. volcanic inflation episodes)
- Recommended implementation

Changes to equipment

- Antenna is main concern, although receiver may also affect continuity of calculated position
  - Even antennas of the same model type may not be manufactured within acceptable geodetic tolerance
- stinf_to_rename useful for creating automatic list

Changes in multipath environment

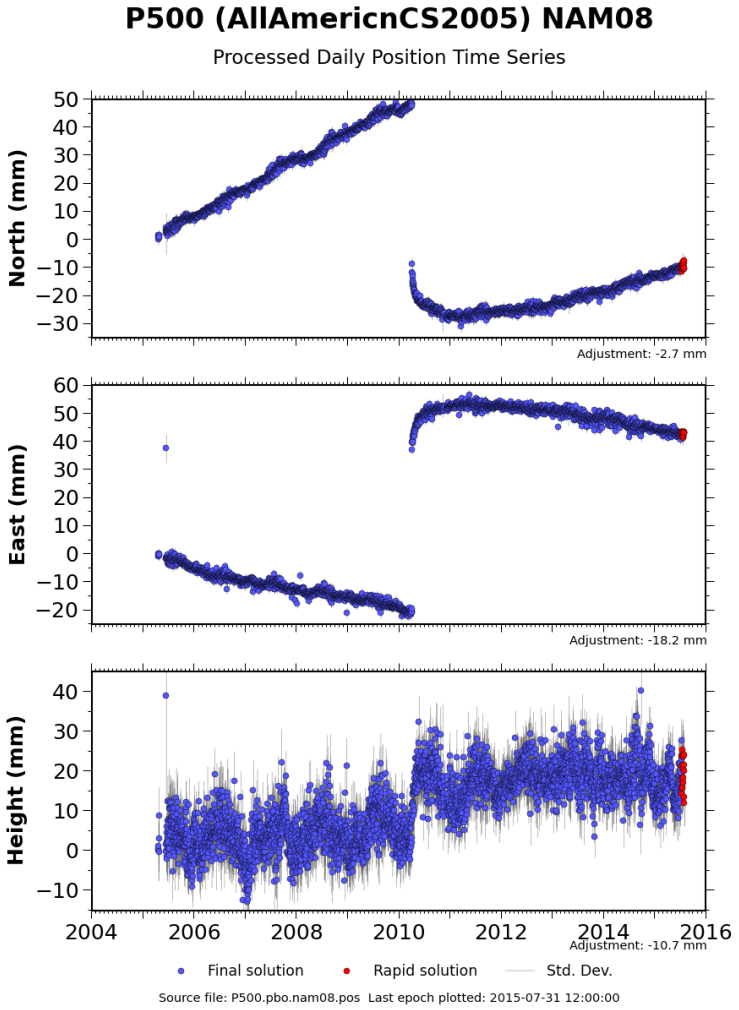


Rename scheme

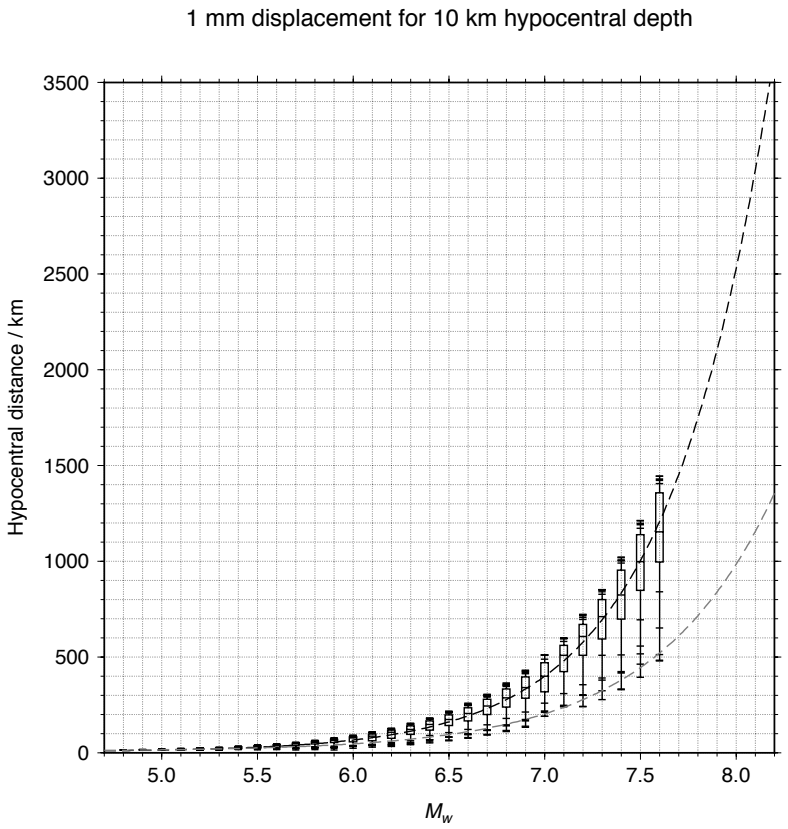
- Rename scheme uses first character of suffix
  - XXXX_GPS → XXXX_2PS → XXXX_3PS → … etc.
- Beyond "9PS", convert to 10th letter of alphabet ("JPS") and beyond
  - … → XXXX_9PS → XXXX_JPS → XXXX_KPS → … etc.
  - But remember "XPS" is a special case for excluding sites from globk runs
- For manual renames (e.g. due to manual inspection rather than known events), use 8 available letters in alphabet before "J"
  - XXXX_APS, XXXX_BPS, etc.
  - But remember "GPS" is a special case (the default)

Earthquakes

- Earthquakes occur at known times
- May exhibit more than just a discontinuity
- Take care when earthquake occurs in the middle of processing day
  - Some data will fall before and some after ground displacement
  - Time series point on day of earthquake may appear between pre-earthquake and post-earthquake position



Radius of influence



- eq_def line in eq-file contains earthquake ID (two characters), location, etc.
  - ID is used to substitute last two characters of 8-character site name, e.g. XXXX_GPS → XXXX_GSN
- sh_makeeqdef will search archives (ANSS ComCat or ISC) to generate eq_def records

Non-linear motions

Logarithmic decay

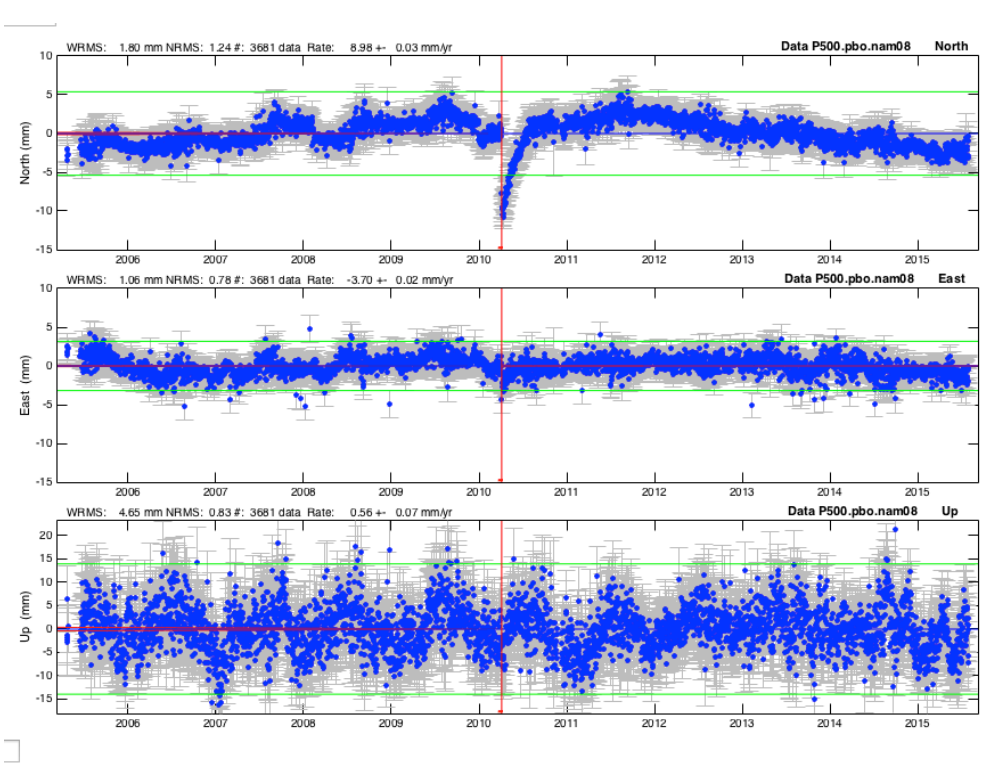
- Derives from afterslip on fault plane controlled by rate-and-state friction (e.g. Marone et al., 1991)
- Velocity perturbation reduces with $^{1}/_{t}$

Exponential decay

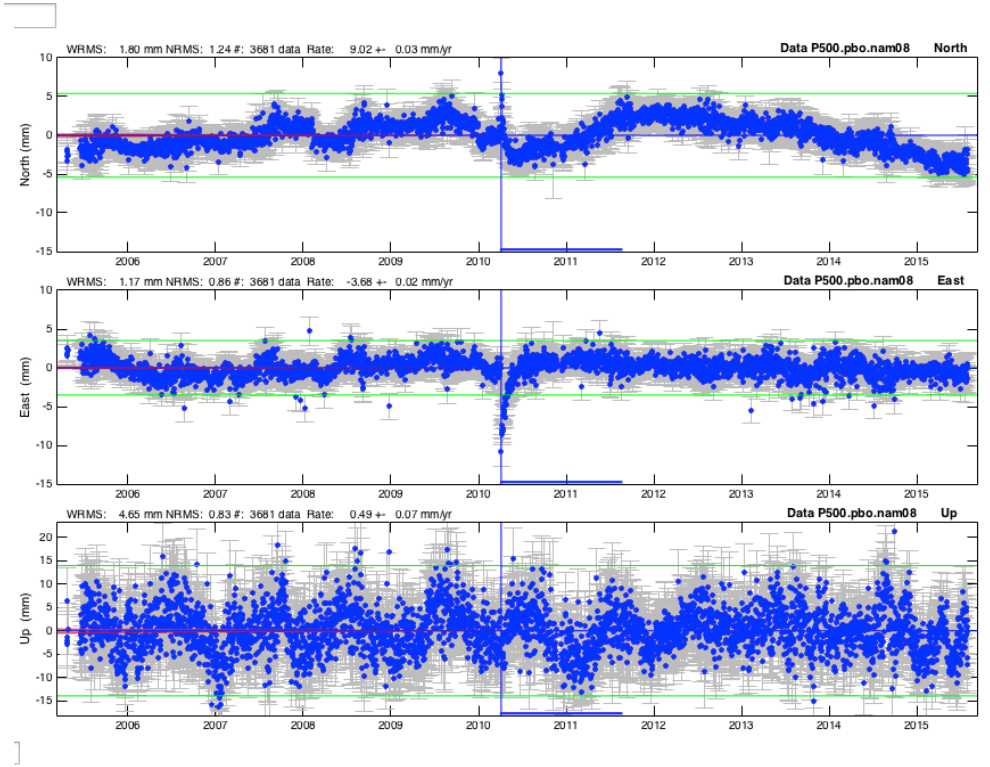
- Derives from assumption of viscoelastic relaxation in stressed medium, e.g. after an earthquake

Non-linear motions

Logarithmic decay



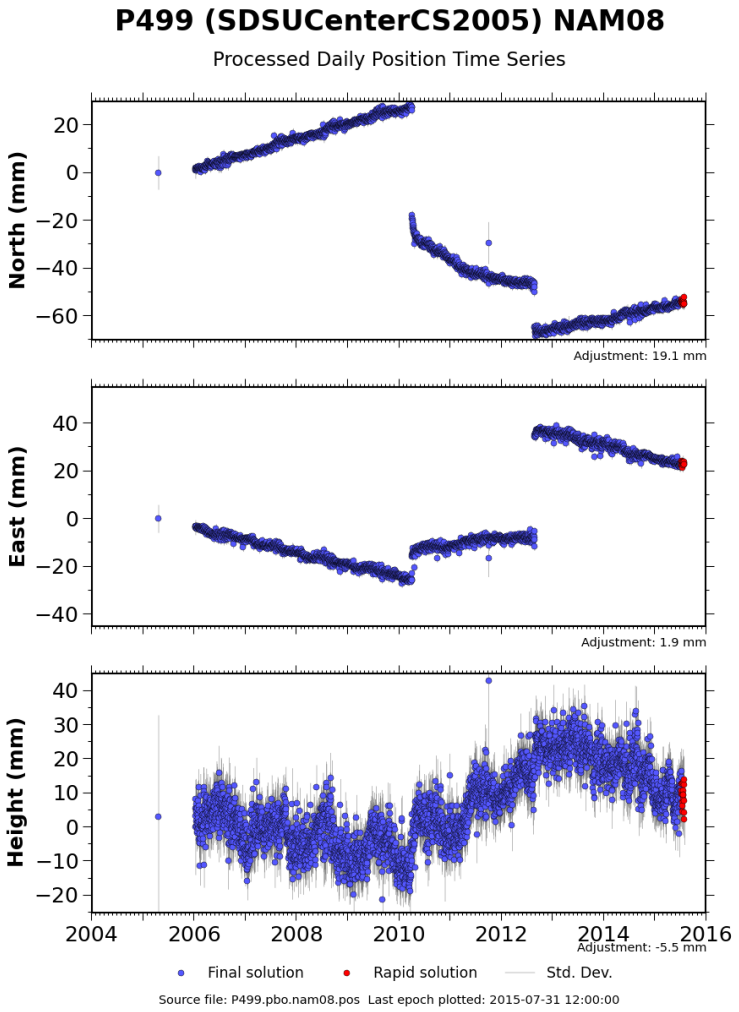
Exponential decay



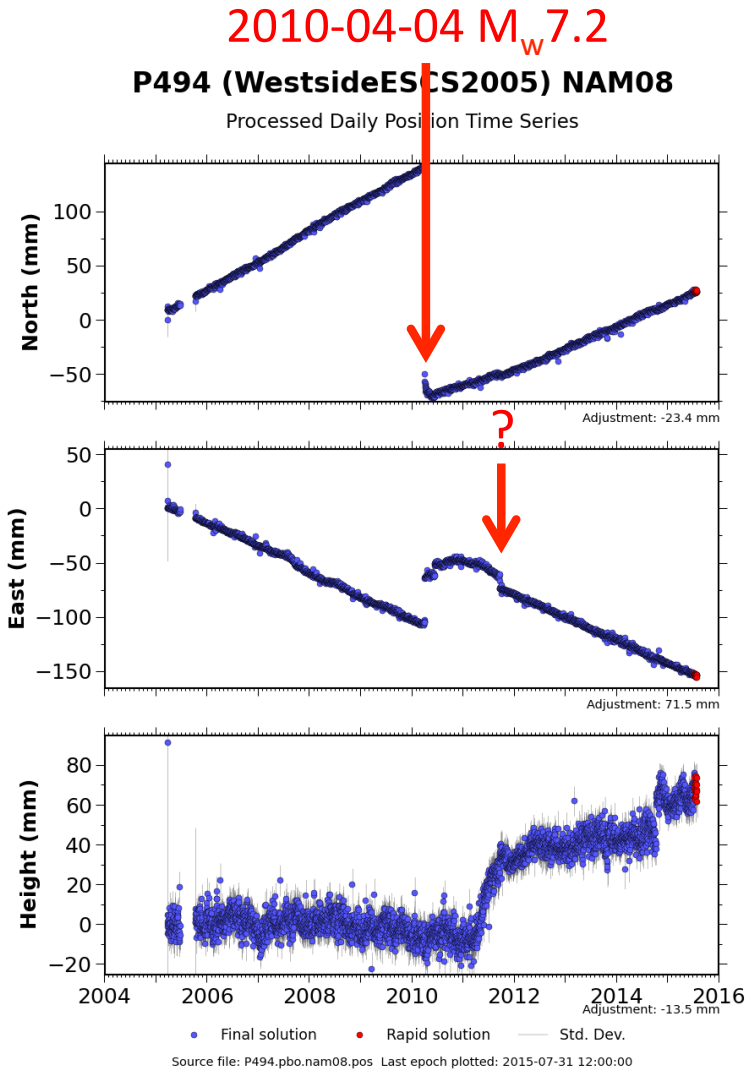
Logarithmic looks good in East; Exponential looks good in North; Height doesn't care

Many earthquakes…

- Complications arise in a tectonically active area with multiple events
- Sites may be renamed several times and therefore have various two-character suffixes
- Non-linear motions may be included in apr-file with "`EXTENDED`" records (see globk help)



Undocumented effects

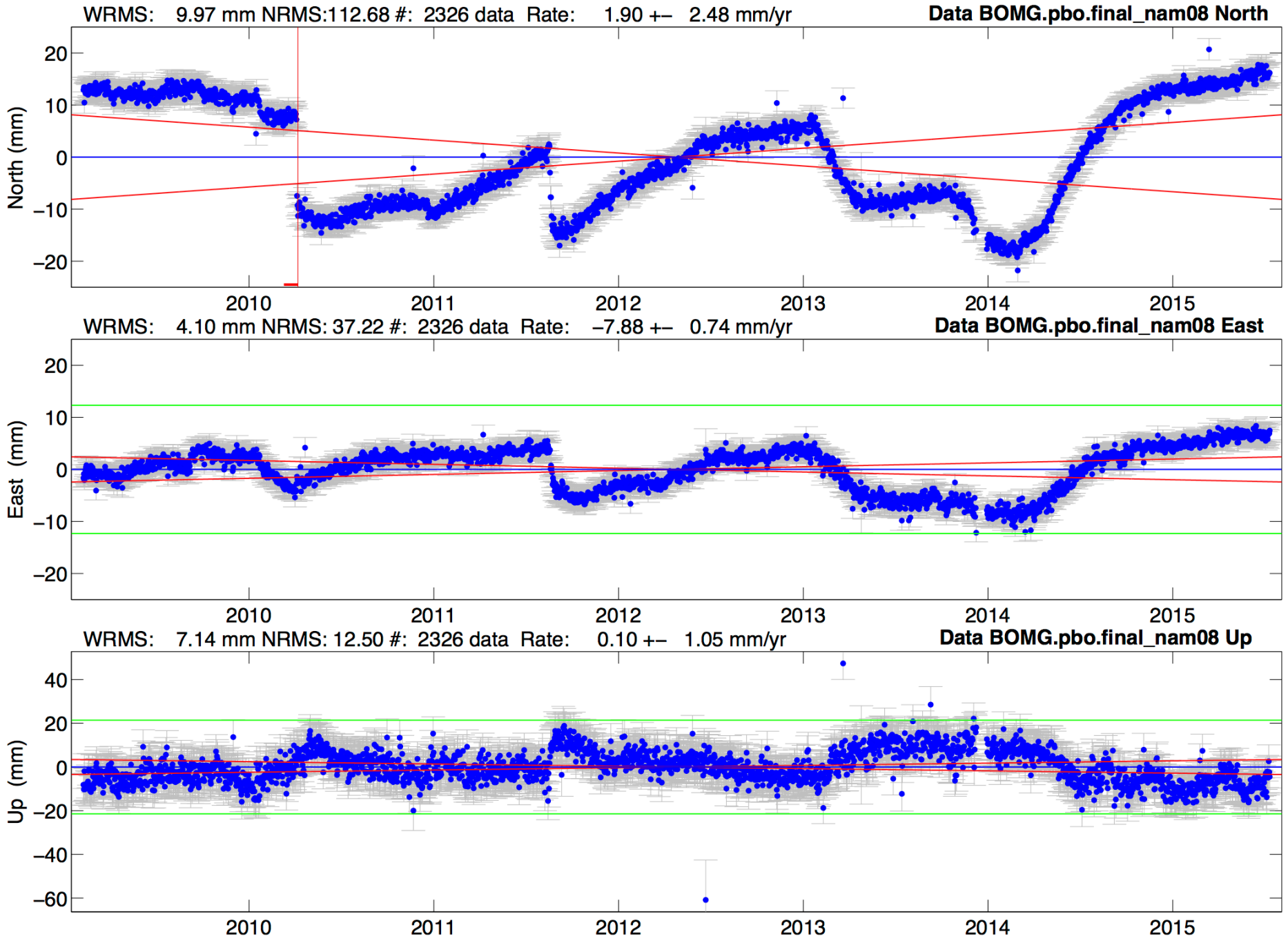


- Time series inspection is *very* important to catch undocumented effects
- Insert manually-determined discontinuities using letter for first character of suffix
- ? Jump is due to washer removal from top of the antenna.

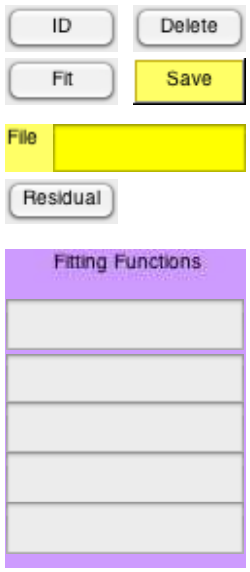
Other phenomena

- Several examples of other phenomena some of which are likely to be motions of the monuments (often not tectonic), propagation medium effects, or failed equipment.
- With continuous data these types of effects can often be diagnosed from the data.
- For artifact effects, multipath and SNR measures are often useful for diagnostics.

Bombay Beach Creep?

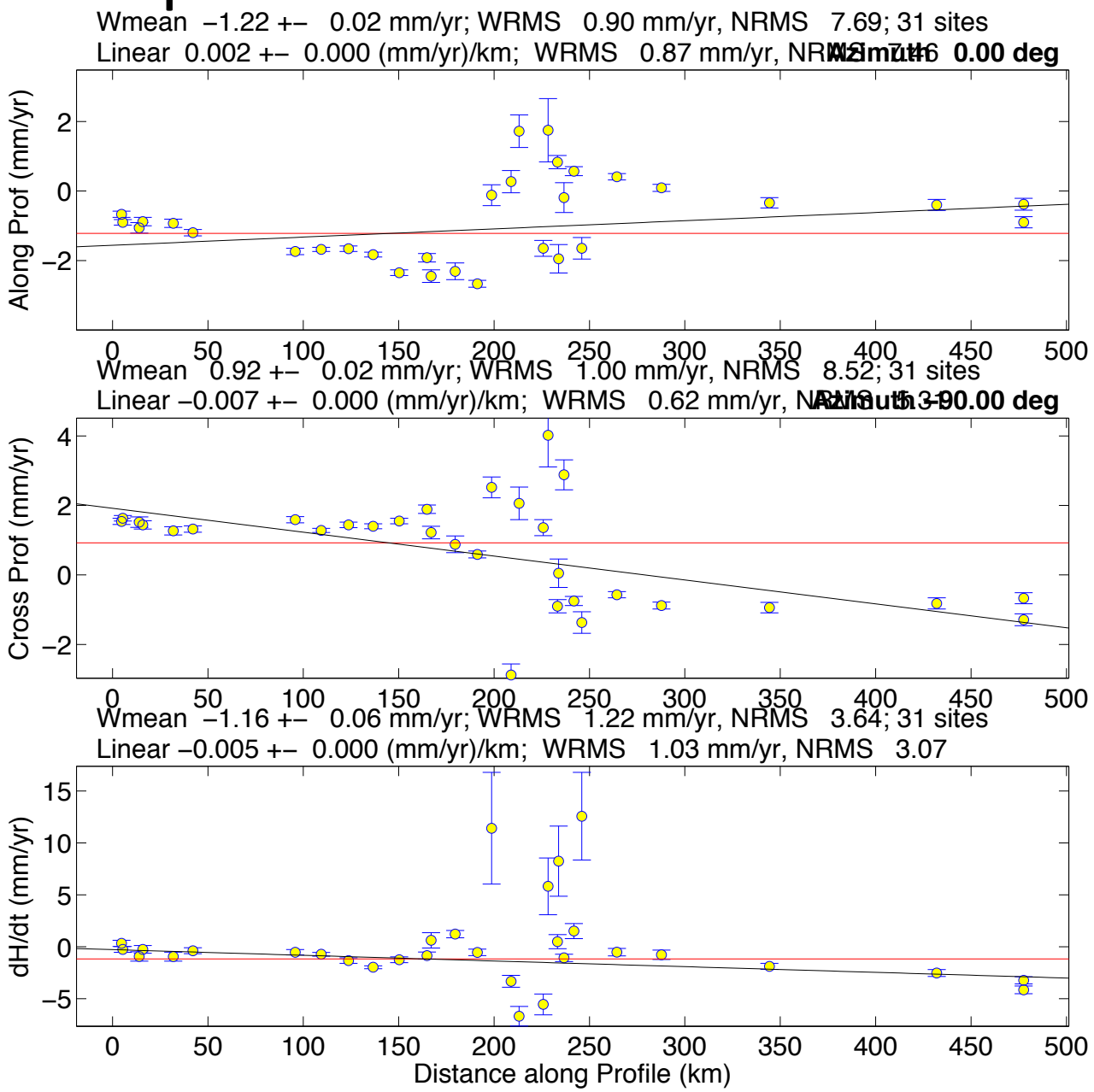


Episodic events: Yellowstone



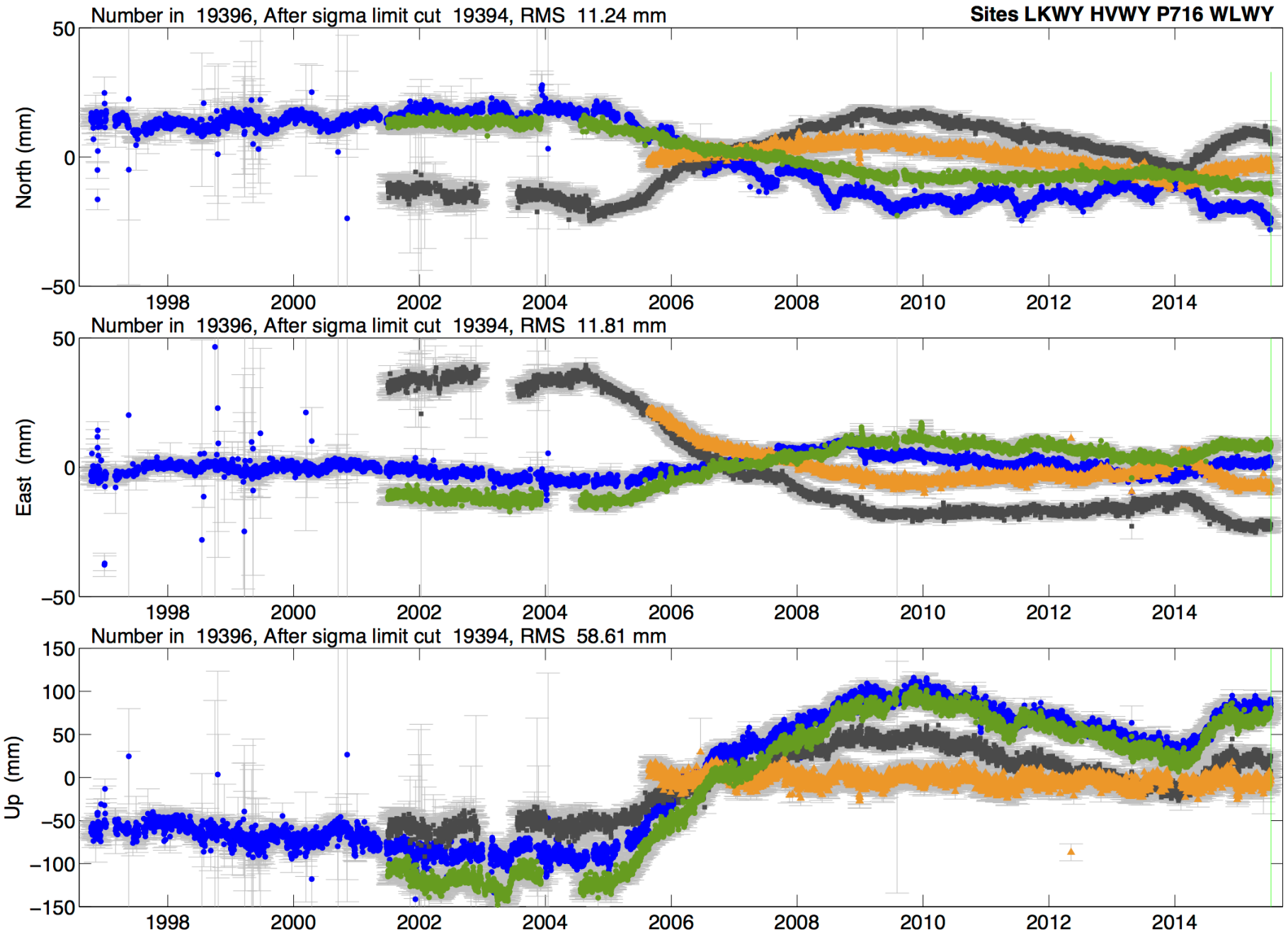
List of noisy sites

```
Site: OFW2_GPS
Site: P711_GPS
Site: P801_GPS
Site: NRWY_GPS
Site: HVWY_GPS
Site: P714_GPS
Site: LKWY_GPS
Site: MAWY_GPS
Site: WLWY_GPS
Dist  245.99 km
OffT  -25.10 km
AP  -1.65+-  0.31
CT  -1.37+-  0.31
Ht  12.57+-  4.22
```

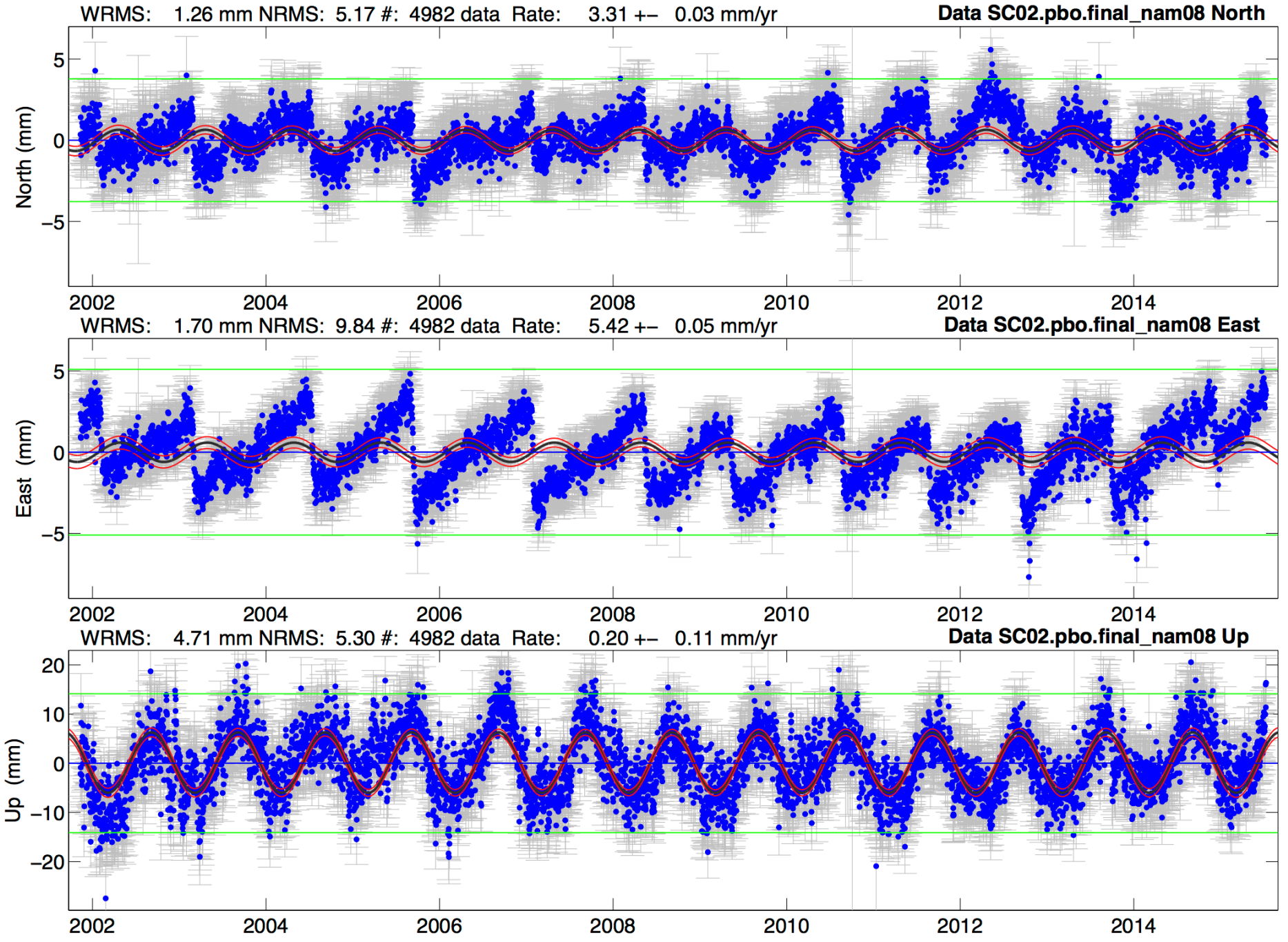


Profile of velocity estimates across region. Large error bars (FOGMEX) show systematic sites

Selected Yellowstone time series



Episodic Tremor and Slip (ETS): Cascadia



Other examples

- The following examples are from the UNACVO GAGE Data technical news: http://plus.google.com/u/0/communities/112834235701900858710
- Reports here on various anomalies that have been detected and investigated. Useful place to look for site issues.
- GAGE ACC quarterly reports also contain information on anomalies

Local collapse

- Site EOCG

http://plus.google.com/u/0/communities/112834235701900858710

Figure 2. Station EOCG at the Santa Barbara Emergency Operations Center. Seismic vault is located in the foreground. Photo courtesy of Dan Determan, USGS. Photo was taken sometime between July and December 2014.

Figure 3. Subsidence at EOCG. Note the seismic vault has clearly subsided, and the yellow posts have been recently installed. Photo courtesy of Dan Determan, USGS. Photo taken on January 6, 2015.

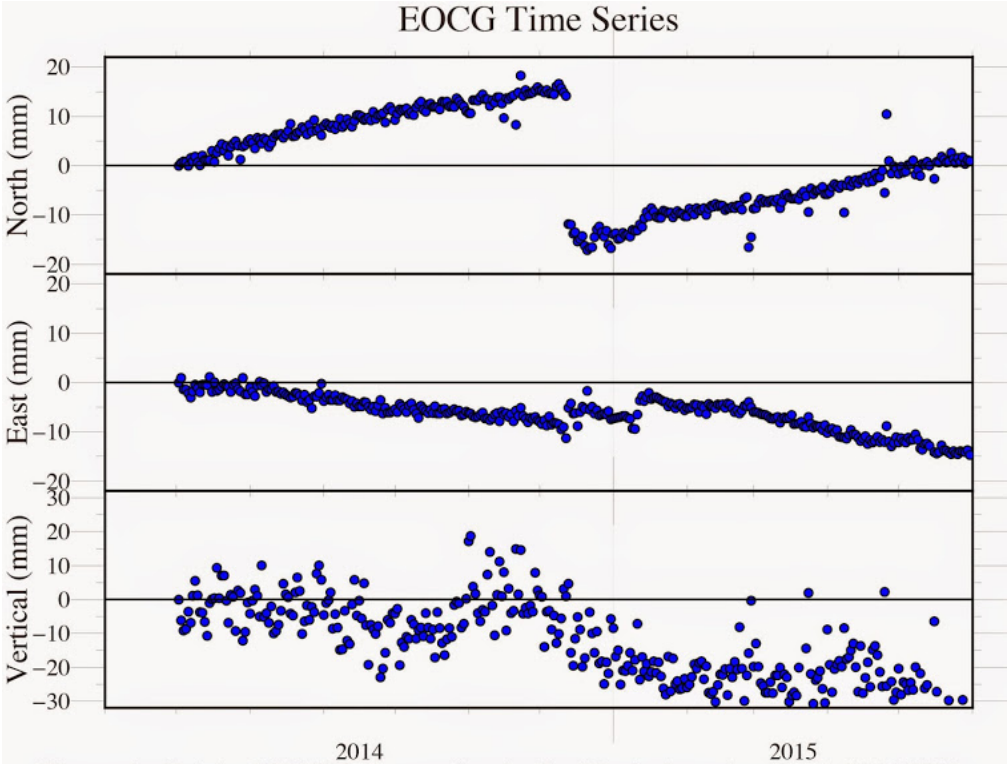


Figure 1. Original EOCG time series, in the North America-fixed (NAM08) reference frame.

Landslide prone site

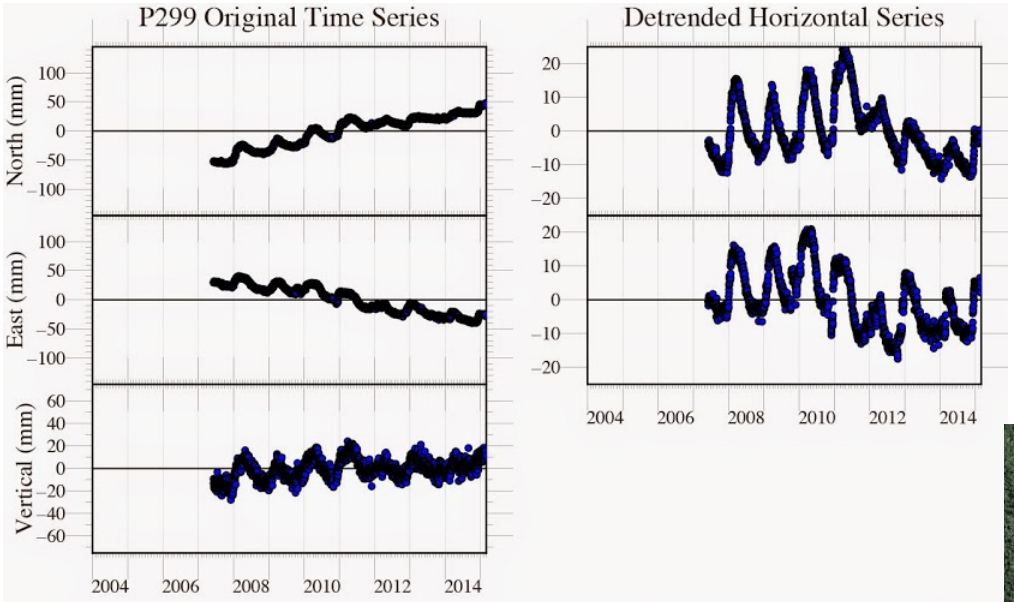


Figure 1. P299 time series. Original plot in NAM08 reference frame on right; slope has been removed on left for the horizontal components only. The strong seasonal signals are caused by the site's proximity to a small landslide in the Diablo Range, California. The ground motions have decreased in magnitude since 2011, when drought conditions developed from a decline in annual precipitation. The presence of water appears to control ground stability near the slide.

Location of earlier landslide showing strong seasonal

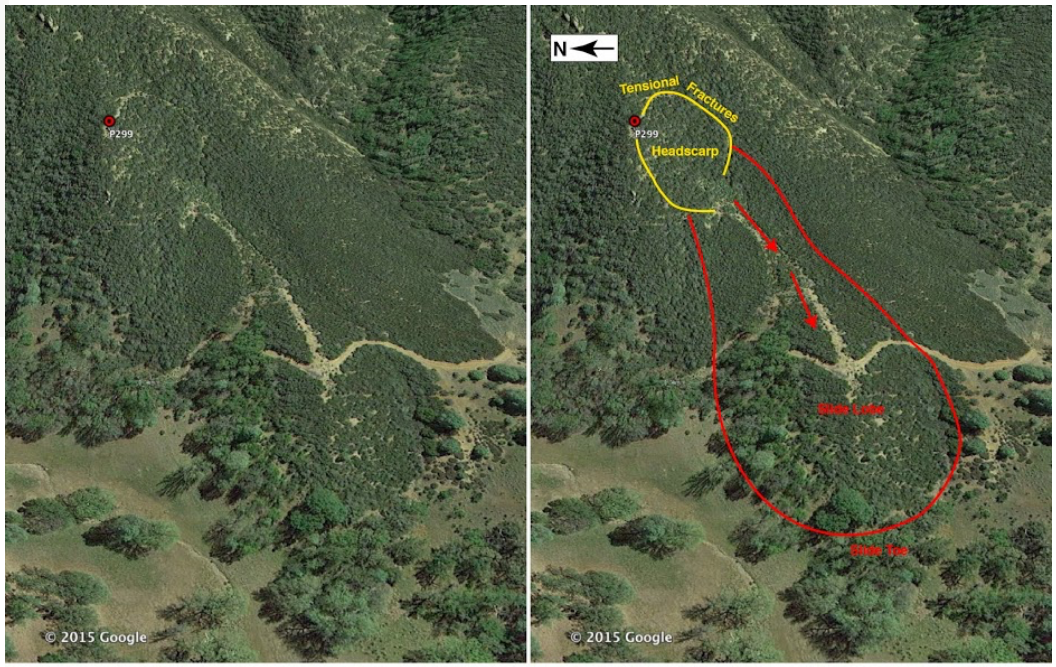


Figure 3. GoogleEarth view of P299 and landslide. The slide originates in the small bowl to the south of P299 and flow downhill into a lobe at the base. Original image (left) has been annotated to show extent of slide (right).

Ground water P271

Figure 1. Photo of station P271 taken in April 2013.

Site P271 is strongly affected by ground water withdrawal

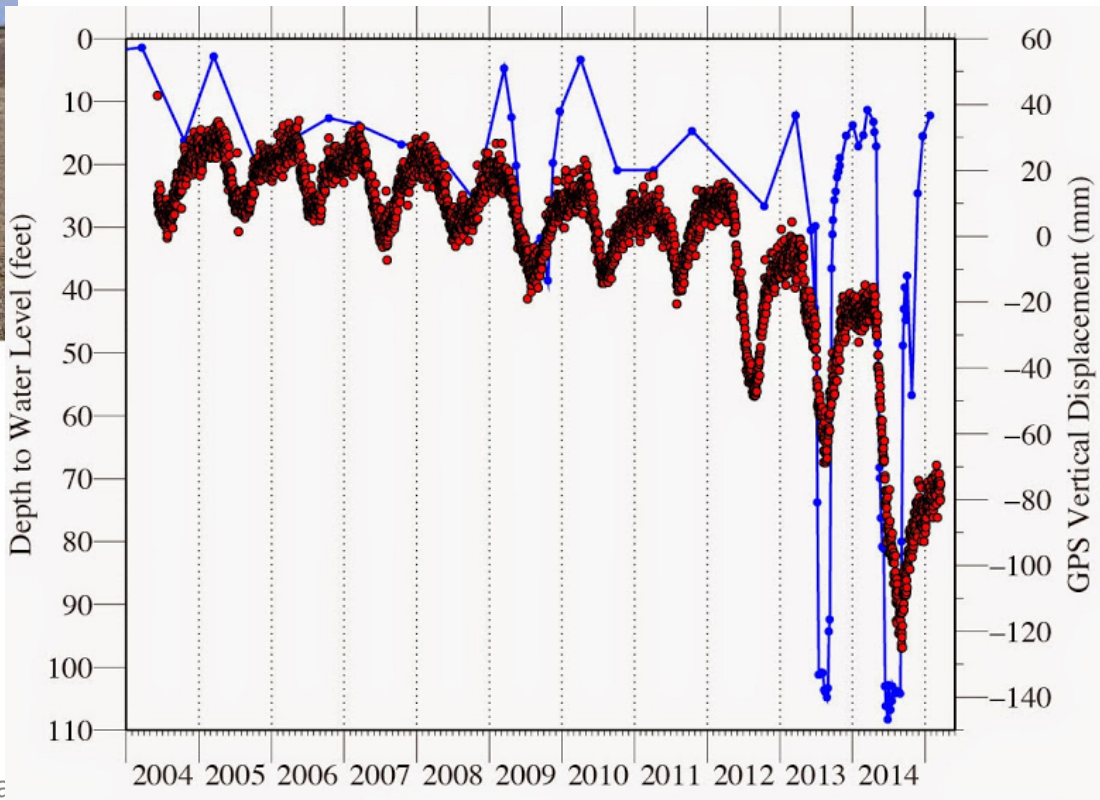
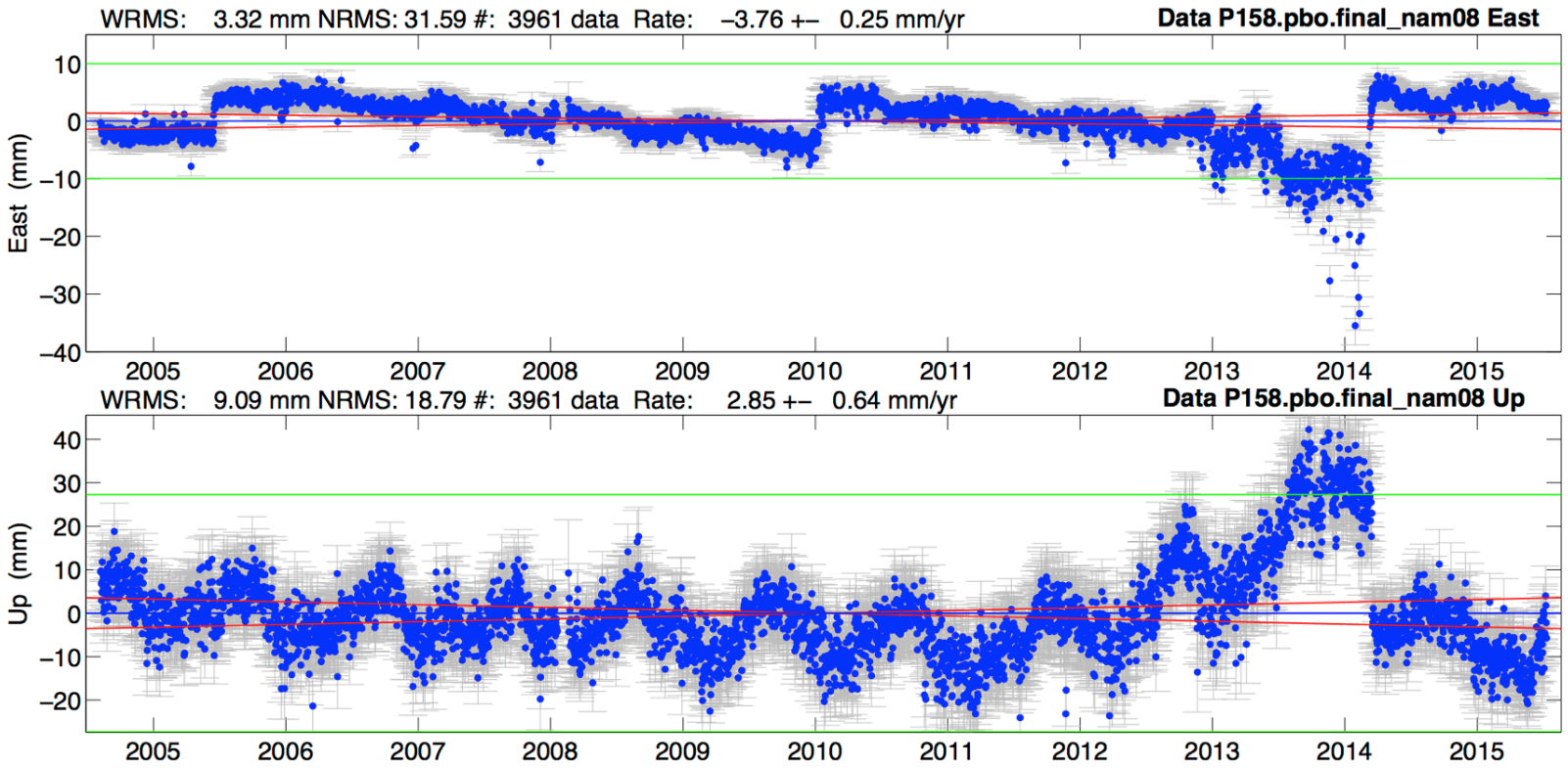


Figure 3. P271 vertical motion (red) vs. groundwater levels at a well ~5 km away (blue).

There are also horizontal periodic signals as well

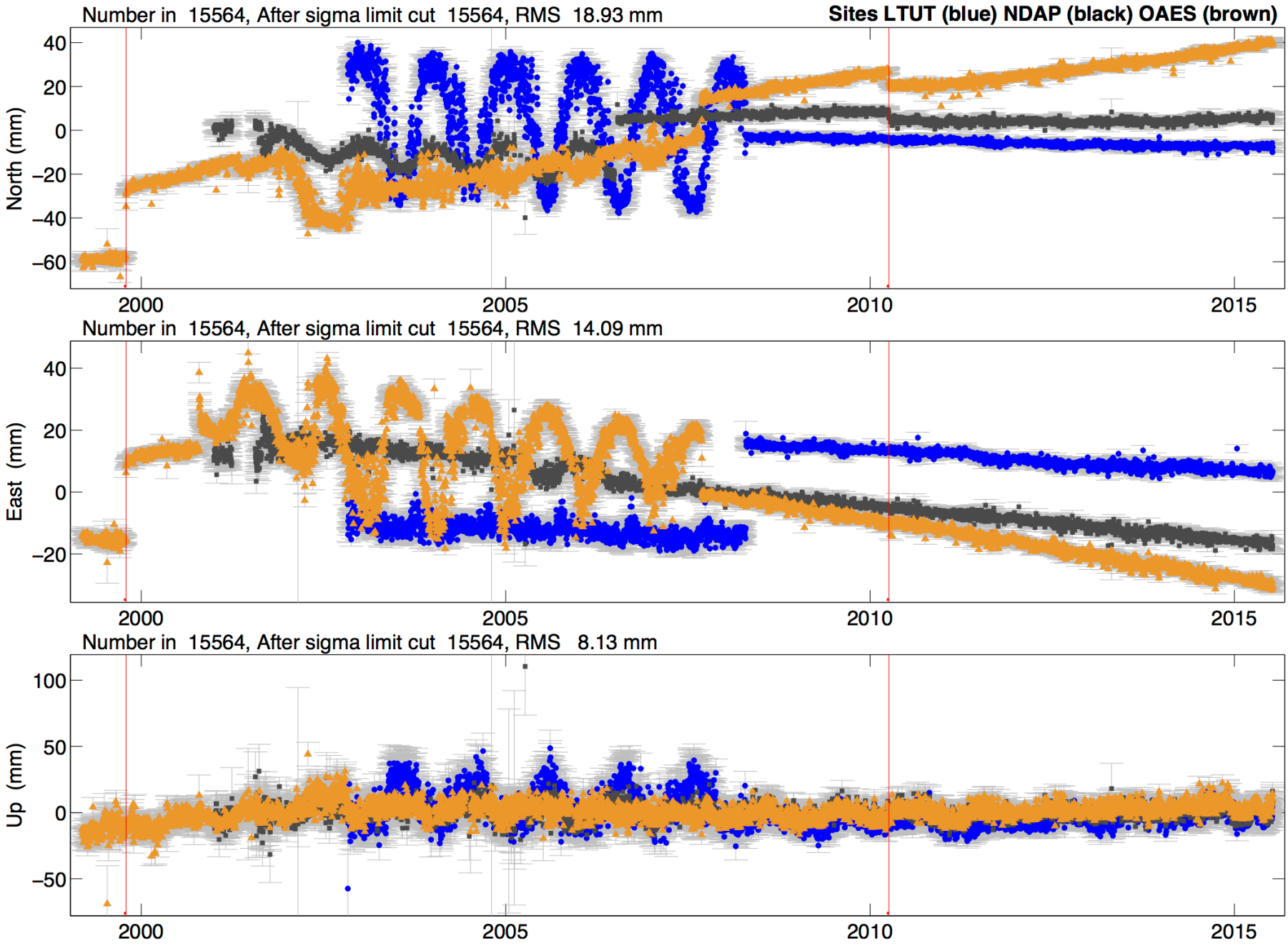
Vegetation Growth P158



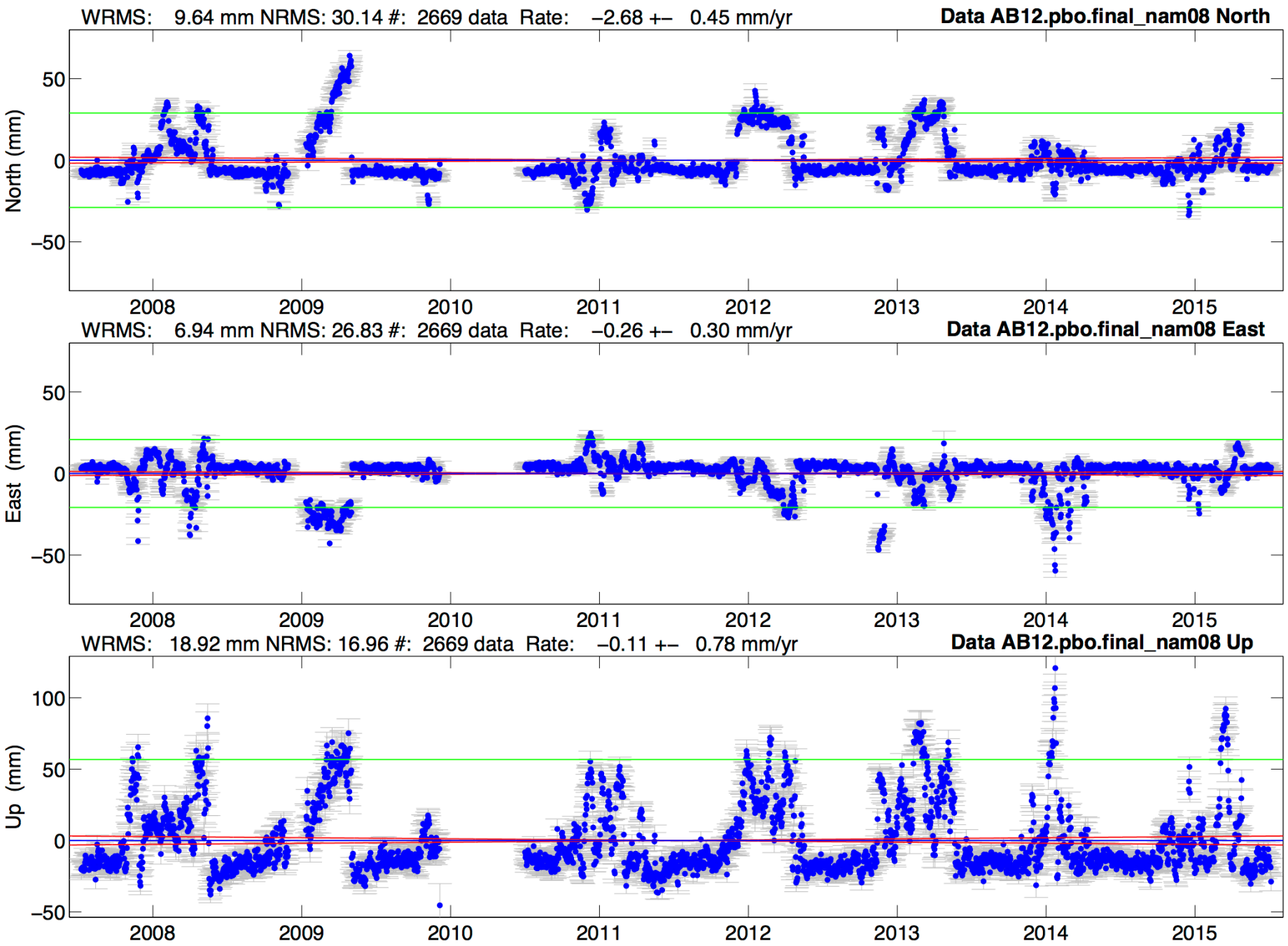
North (not shown) is less affected.

Figure 4. P158 at installation (left), ~10 years later (middle), ~10 years+2 hours later (right). The small tree north of the station grew into a larger tree and was removed on March 3, 2014.

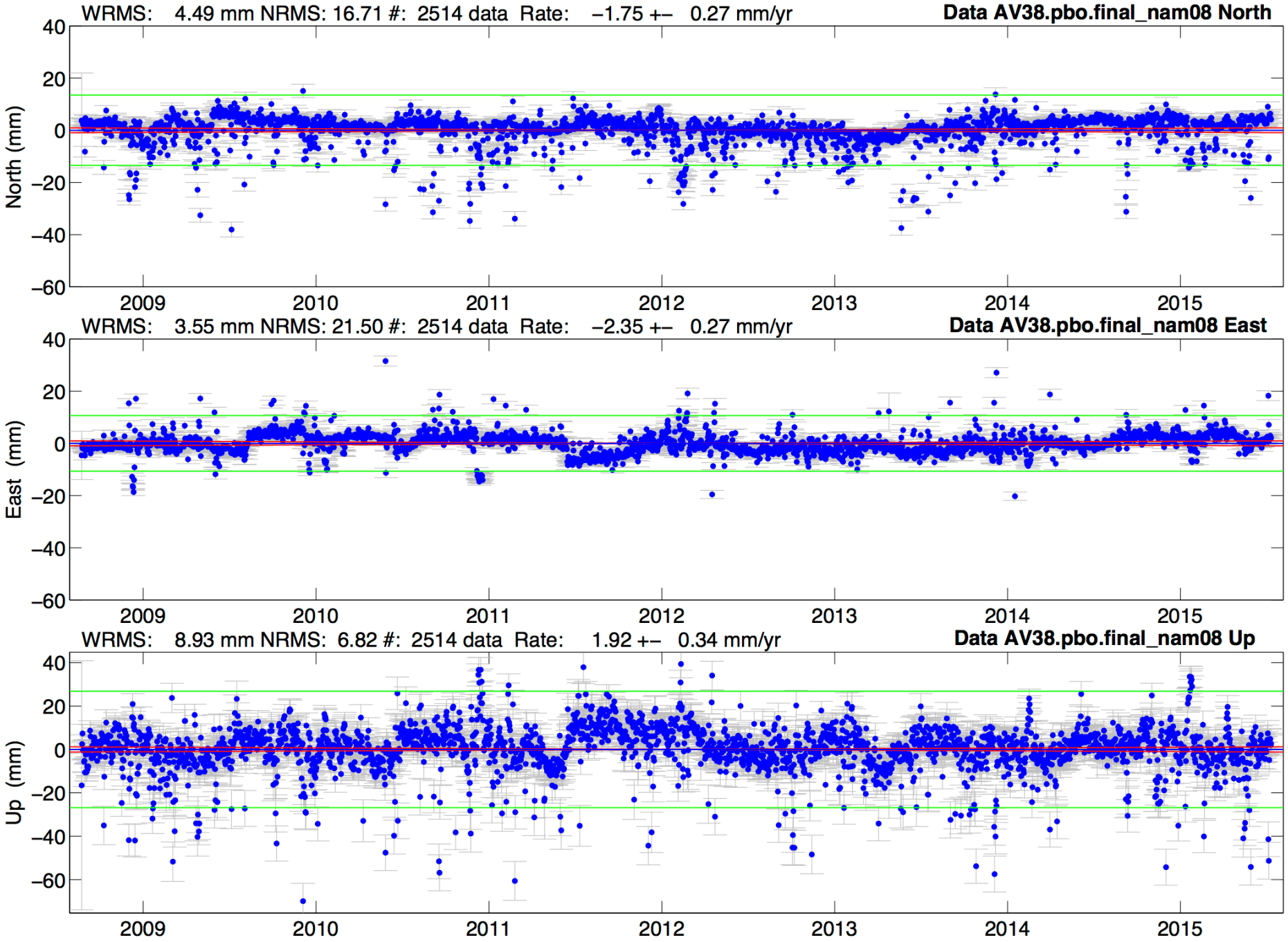
Bad antennas



Snow on antenna



Skewed position residuals: Atmosphere delays?



Recommendations

- Know your goals
  - Only fit “nuisance” terms
  - It is usually best not to try to fit signals that you are interested in, e.g. seasonal terms if you are studying these.
- Depending on your goal (e.g. linear tectonic velocities), sometimes you just have to abandon data as it is likely to do more harm than good (rename to xxxx_XPS or xxxx_XCL). Adding large process noise in GLOBK is one approach but be careful not to make too large. GLOBK sig_neu command can be used for small duration “bad” events.