Reference Frame Realization
Lecture 05

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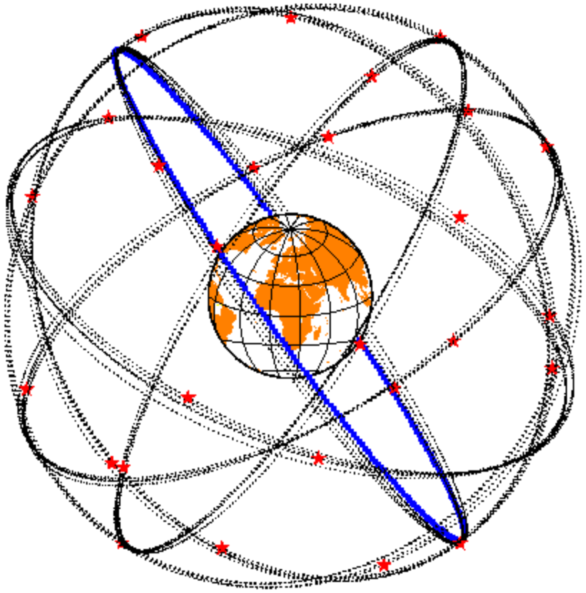
Reference Frames



Global

Center of Mass ~ 30 mm

ITRF ~ 2 mm, < 1 mm/yr

Continental

< 1 mm/yr horiz., 2 mm/yr vert.

Local -- may be self-defined

Reference frames in Geodetic Analyses

- Output from GAMIT
  - Loosely constrained solutions
  - Relative position well determined, "Absolute position" weakly defined
  - Need a procedure to expressed coordinates in a well defined reference frame
- Two aspects
  - Theoretical (e.g., rigid block, mantle-fixed, no-net-rotation of plates)
  - Realization through a set of coordinates and velocities
    - "finite constraints" : a priori sigmas on site coordinates
    - "generalized constraints" : minimize coordinate residuals while adjusting translation, rotation, and scale parameters
- Three considerations in data processing and analysis
  - Consistent with GPS orbits and EOP (NNR)
    - not an issue if network small or if orbits and EOP estimated
  - Physically meaningful frame in which to visualize site motions
  - Robust realization for velocities and/or time series

Basics of reference frame realization

GLOBK frame realization methods

- In GLOBK analyses, normally all stations and orbit initial conditions are loosely constrained, the reference frame is defined in a module called glorg (global origin). The methods used are similar to other programs but there are some subtle differences. Specifically, the frame transformation is implement with a Kalman filter constraint equation, not by direct application of the rotations, translations and scale.
- Details are discussed in Dong, Herring and King, J. Geodesy, 1998.

Specific implementation

- Glorg computes a set of condition equations using weighted least squares. The weights are settable to be dependent on site uncertainty (iteratively) and with weight between horizontal and vertical site positions and rates.
- The condition equations are then applied through a Kalman filter formulation to the loose solution covariance matrix and solution vector. The KF formulation allows zero variance for the condition (LSQ approach would need a small but finite variance). The condition can also be given finite variance (avoids zero eigenvalues).
- If the original loose solution is free to translate, rotate and scale, the application of the condition solution generate the same answer explicit application of transformation (SDET option).
  - For VLBI, translation is rank deficient and rotation is explicitly estimated (scale needs to be explicitly estimated if included in the constraints)
  - For GPS, translation is not rank deficient and so condition modifies solution if translation not explicitly estimated. It is not clear whether translation should be estimated explicitly.

Formulation

- Condition application, T are estimates of transformation parameters, W is weight matrix, and superscript – and + denote values before and after the conditions are applied. R is the variance of the condition and can be set to zero. (MIT weekly IGS sinex submission, sets 1 m^2 on translation so not forced to zero)

$$\bar{T} = (A^T W A)^{-1} A^T W \Delta X_s \equiv H \Delta X_s$$

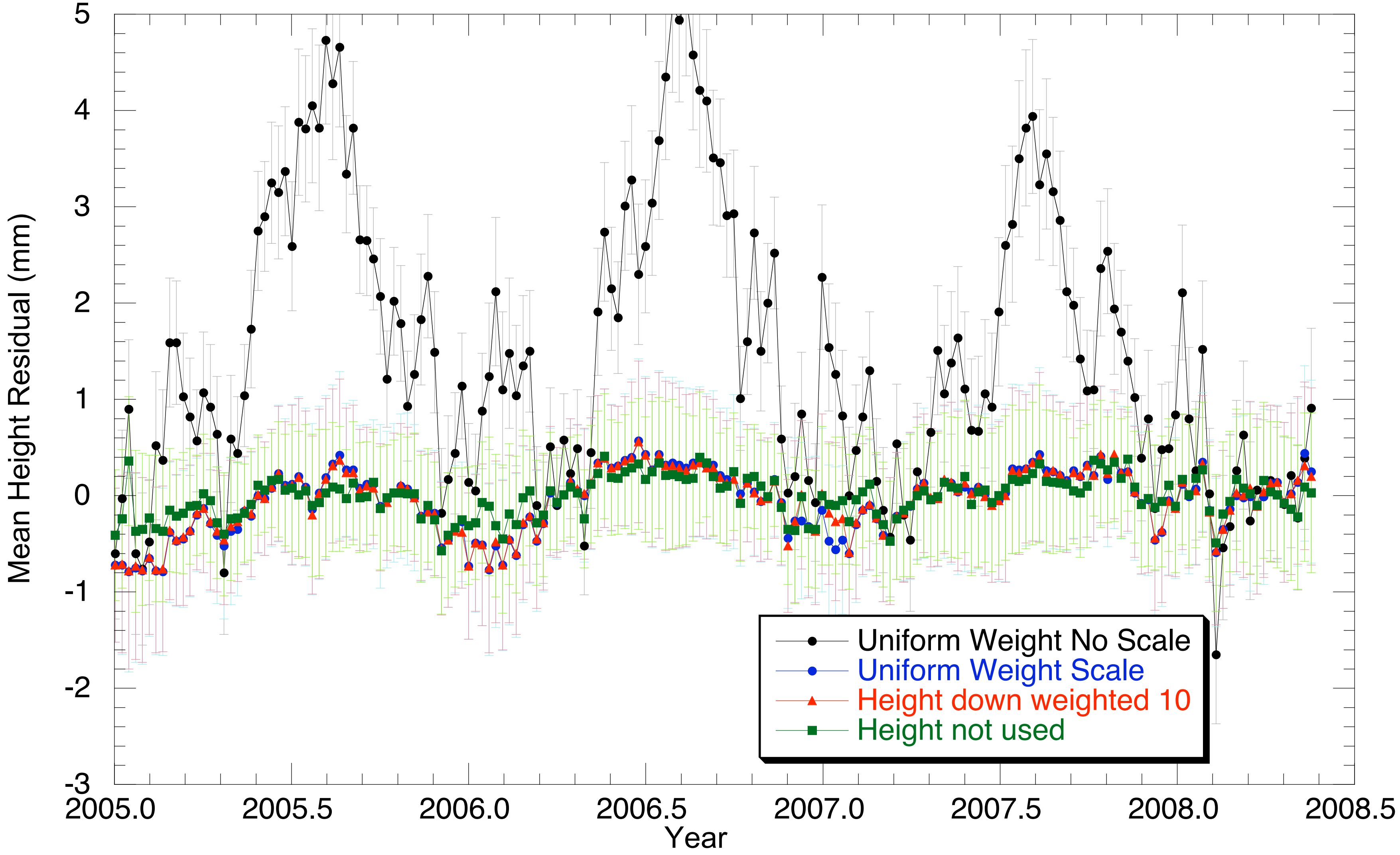
$$\Delta X^+ = P^- H^T [H P^- H^T + R]^{-1} (\Delta X^- - A\bar{T}) \equiv K \delta X^-$$

$$P^+ = [I - KH] P^-$$

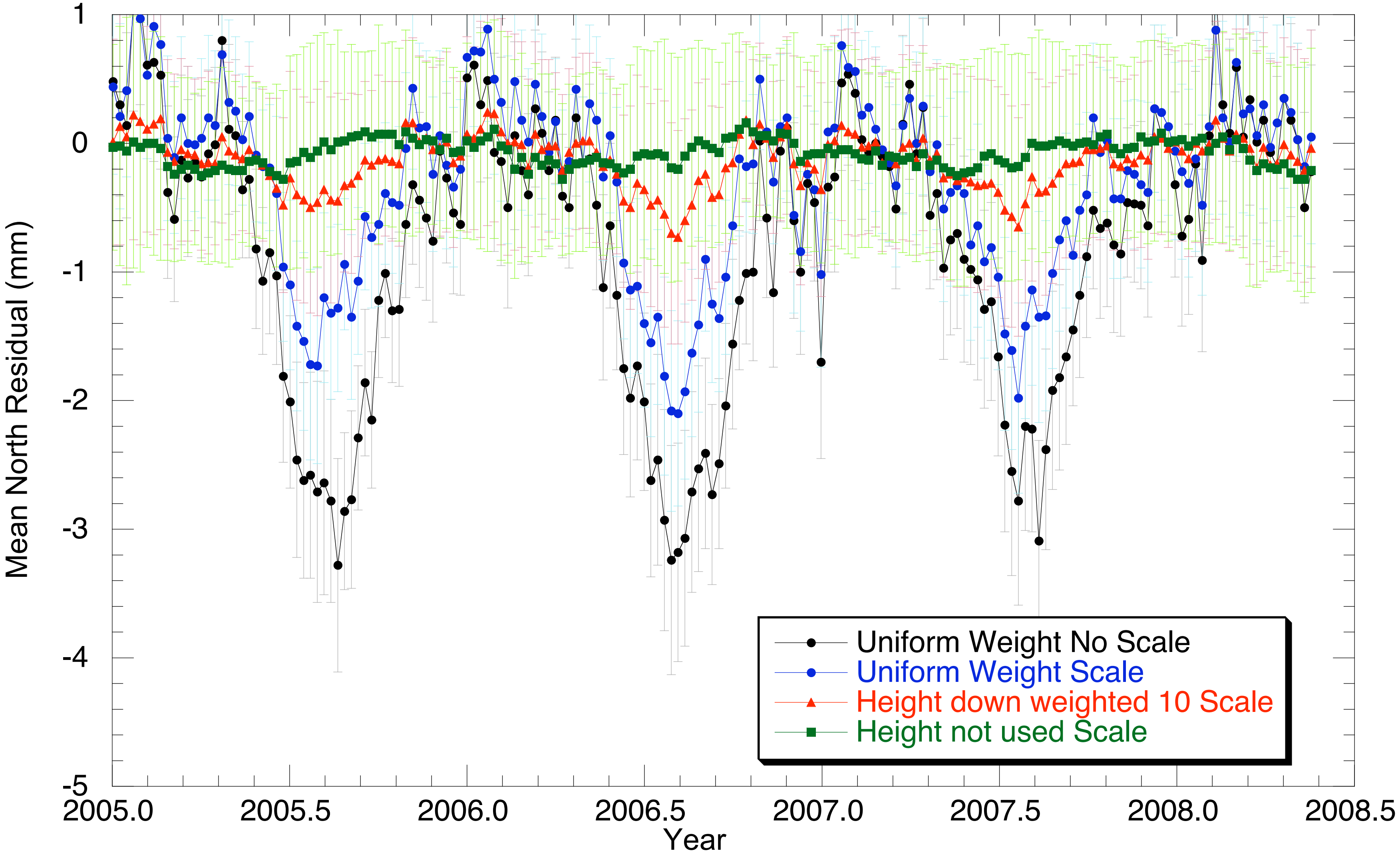
Coordinate Weight effect

- Next set of slides show the effects of height weight on the means of site position residuals after transformation:
  - when uniform weight (i.e., height is weighted same as horizontal) is used with no scale estimated (mean height residual is scale)
  - when scale estimated with
    - Uniform height weight
    - Heights down weighted by 10 (consistent with sigmas, default)
    - Height so down weighted so much that effectively not used.

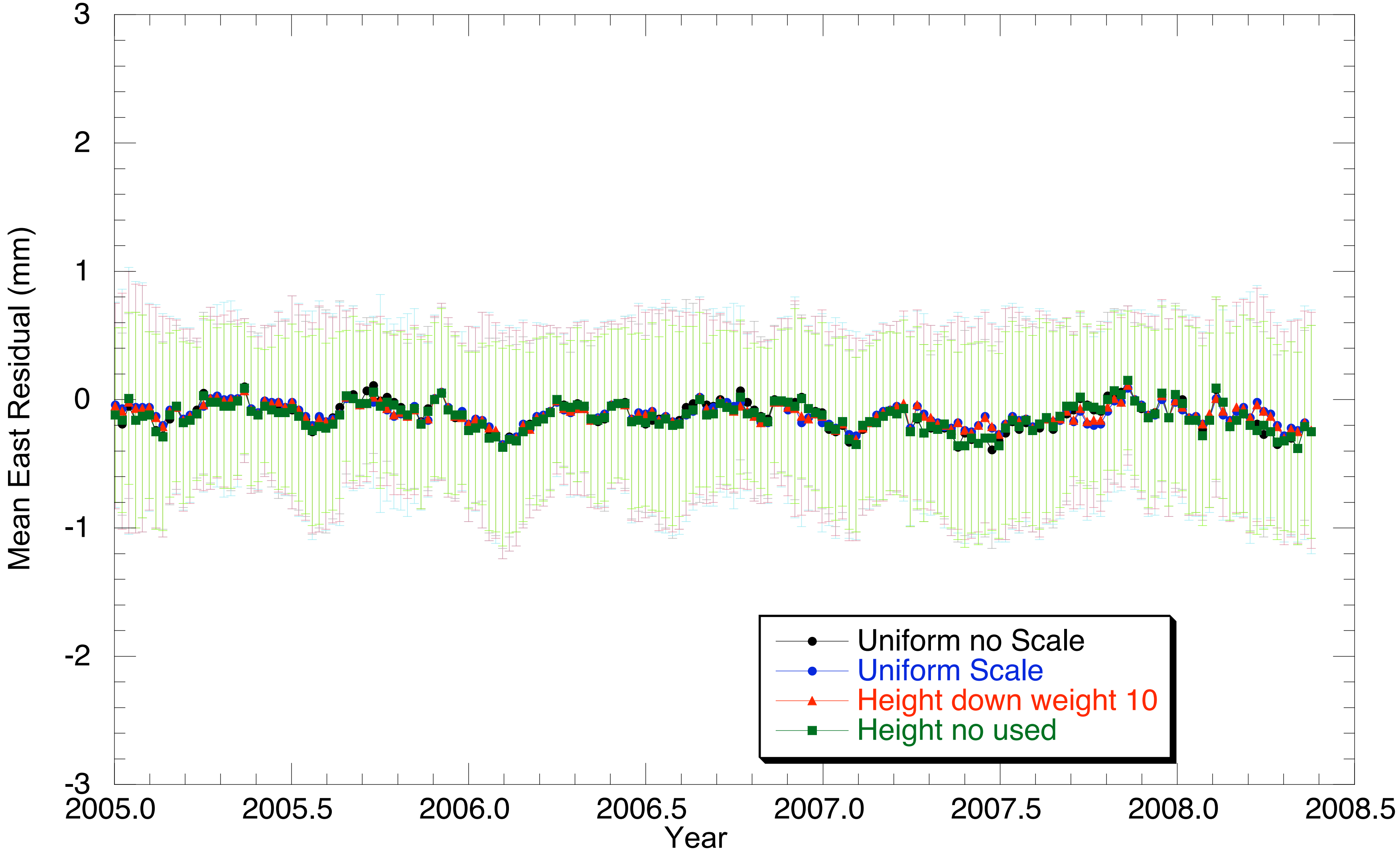
Mean Heights



Mean North Residual

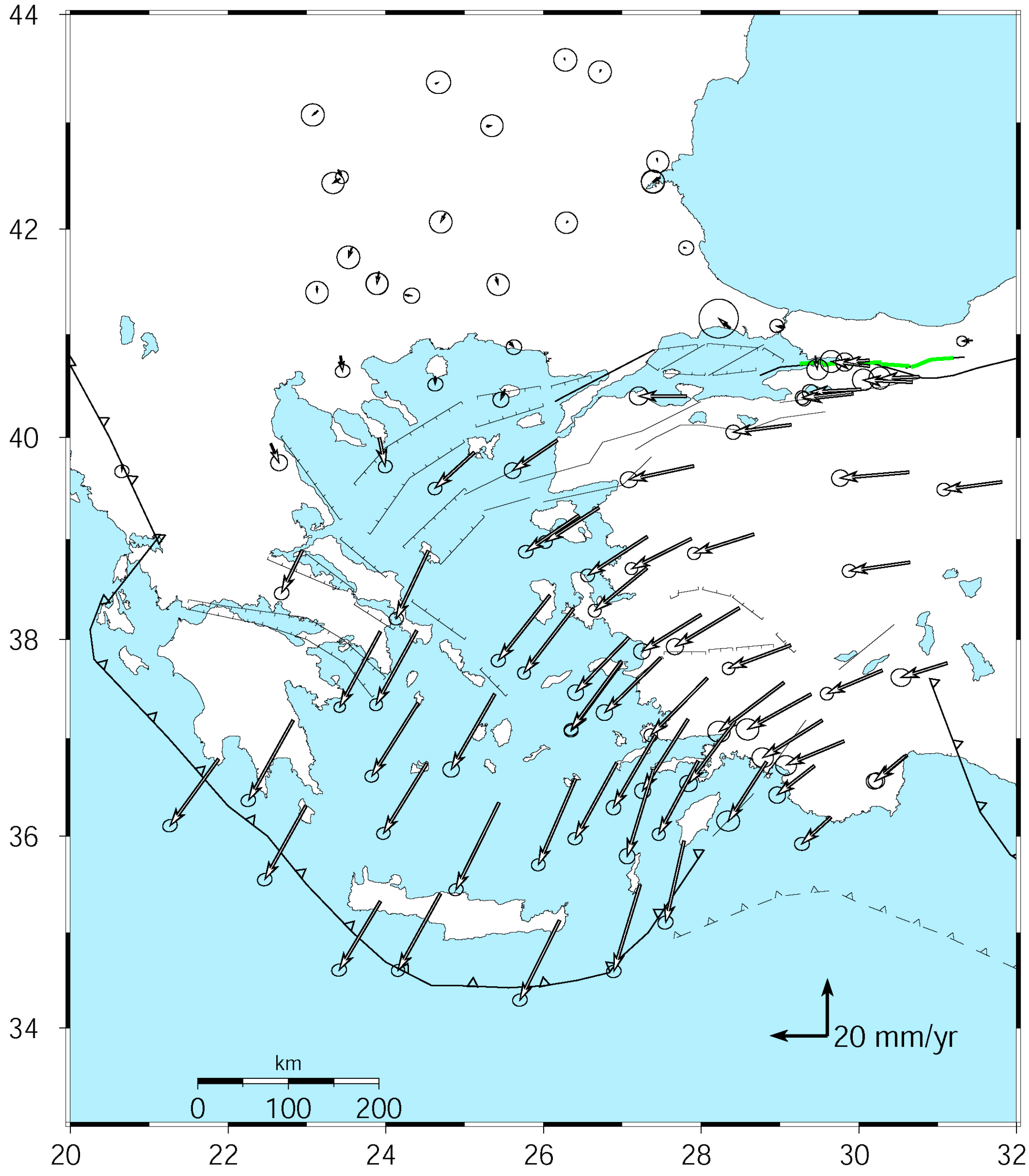


East mean residual



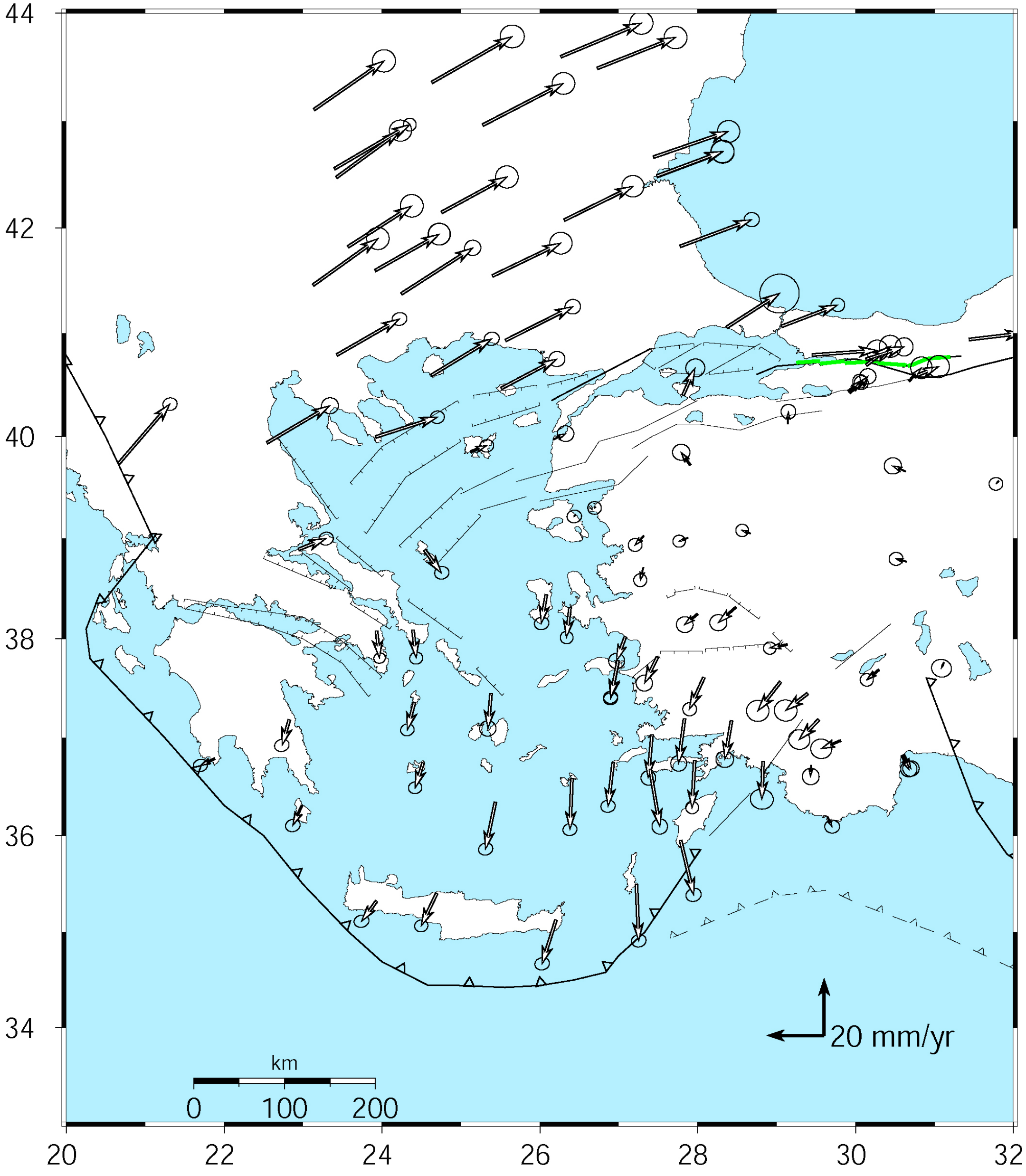
Local Frame Realization

- When dealing with a local region (100-3000 km in size), there are a number of choices of approach:
  - Sometime motion relative to a stable plate (e.g., Eurasia) is needed
  - Often since local strains are important, a local reference frame provides a more useful way of viewing results.
  - In the GLORG, translation/rotation method only the rotational part of the strain tensor is effected by how the reference frame is realized. (This is not the case when tight constraints are applied).



Velocities of Anatolia and the Aegean in a Eurasian frame

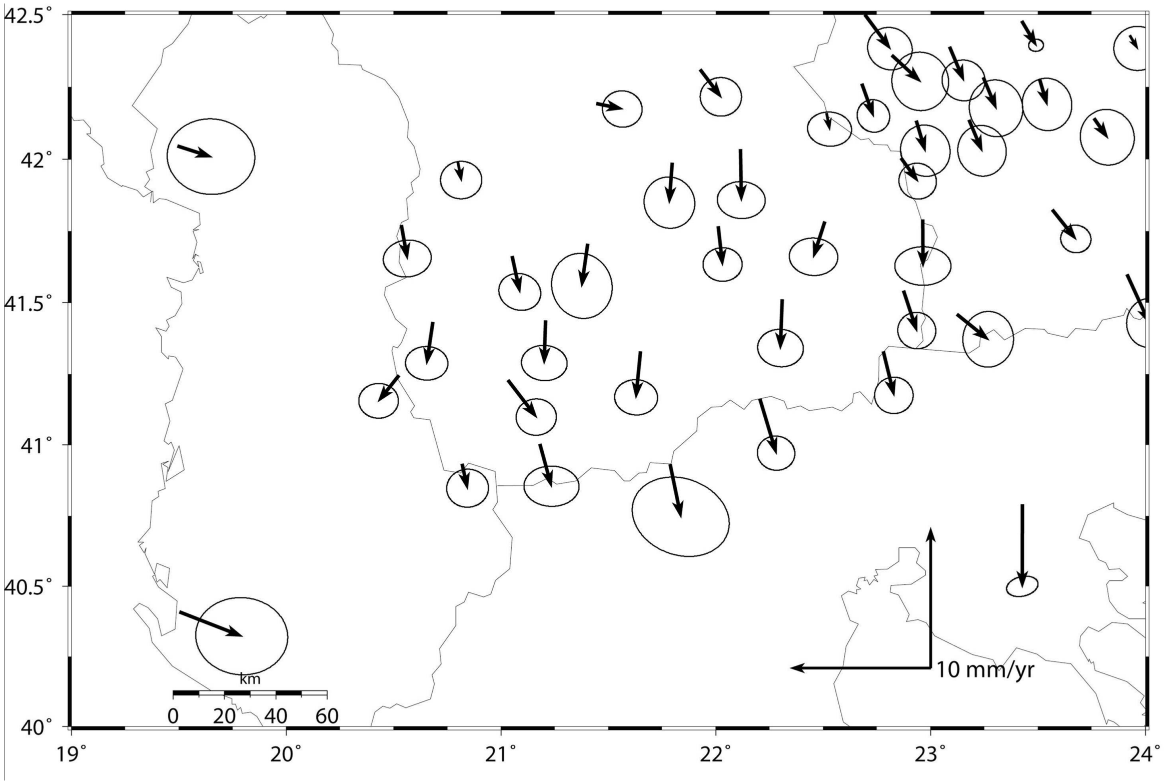
- Realized by minimizing the velocities of 12 sites over the whole of Eurasia
- McClusky et al. [2000]



Velocities in an Anatolian frame

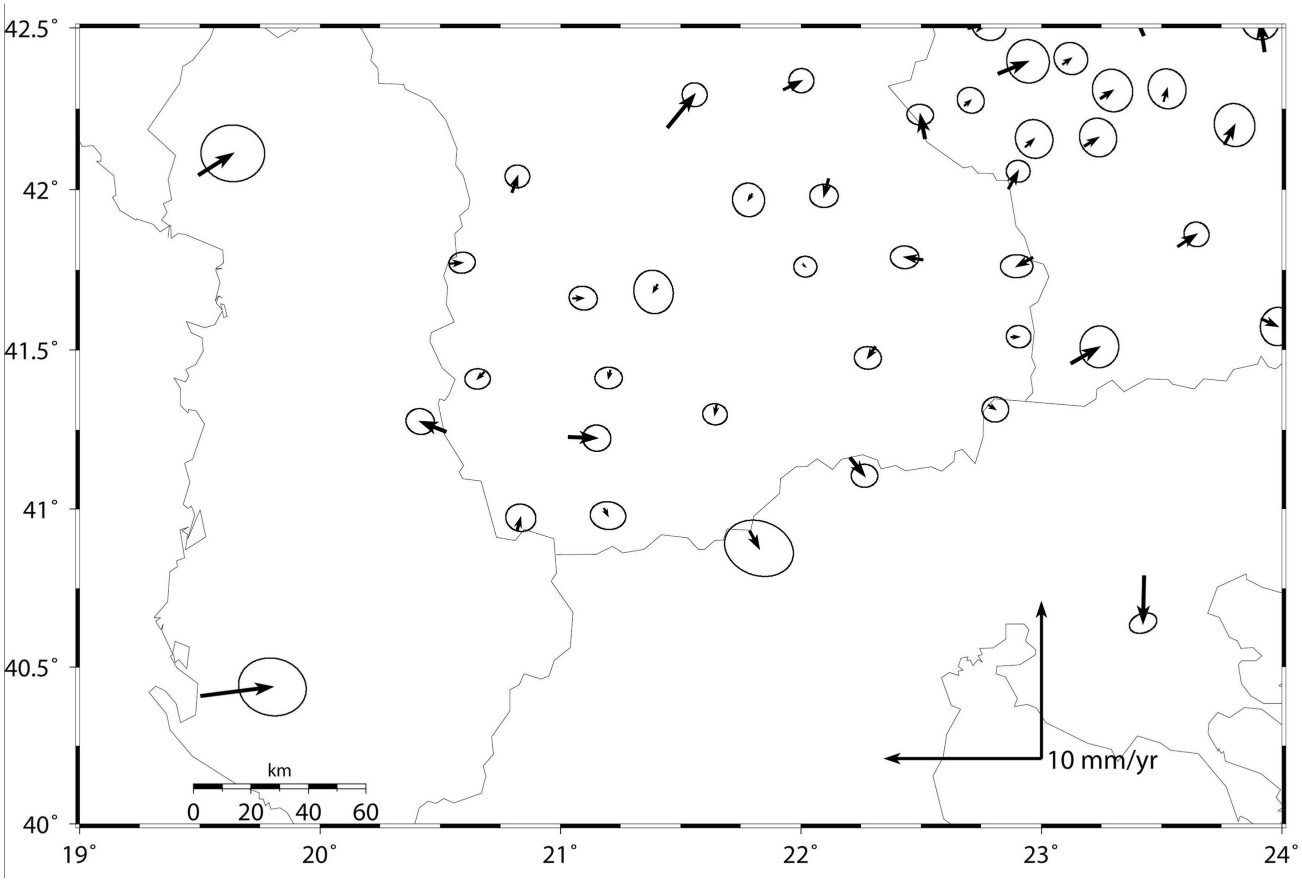
- Better visualization of Anatolian and Aegean deformation
- Here stations in Western/Central are used to align the reference frame (apriori velocity set to zero).
- *McClusky et al.* [2000

Another example: southern Balkans



- Pan-Eurasian realization (as in last example)
- Note uniformity in error ellipses, dominated by frame uncertainty

Local Frame Realization



- Frame realization using 8 stations in central Macedonia
- Note smaller error ellipses within stabilization region and larger ellipses at edges

Defining Reference Frames in GLOBK

- Three approaches to reference frame definition in GLOBK
  - Finite constraints (in globk, same as GAMIT)
  - Generalized constraints in 3-D (in glorg)
  - Generalized constraints for horizontal blocks (‘plate’ feature of glorg)
- Reference frame for time series
  - More sensitive than velocity solution to changes in sites
  - Initially use same reference sites as velocity solution
  - Final time series should use (almost) all sites for stabilization

Frame definition with finite constraints

- Applied in globk (glorg not called): We do not recommend this approach since it is sensitive to over-constraints that can distort velocities and positions
- Example:

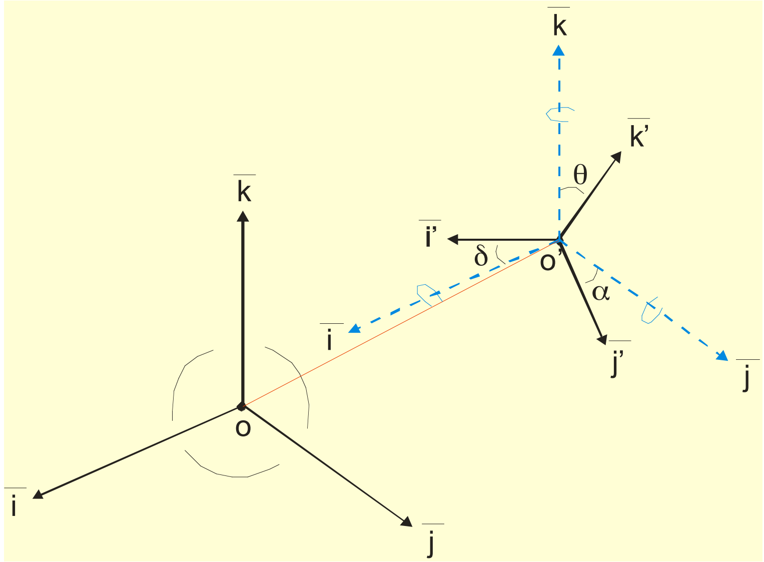
```
apr_file itrf08.apr
apr_neu all 10 10 10 1 1 1
apr_neu algo  .005  005  .010  .001 .001 .003
apr_neu pie1  .002  005  .010  .001 .001 .003
apr_neu drao  .005  005  .010  .002 .002 .005
  …
```

- Most useful when only one or two reference sites or very local area.
- Disadvantage for large networks is that bad a priori coordinates or bad data from a reference site can distort the network

Frame definition with generalized constraints

- Applied in glorg: minimize residuals of reference sites while estimating translation, rotation, and/or scale (3 -7 parameters)

```
apr_file itrf05.apr
pos_org xtran ytran ztran xrot yrot zrot
stab_site algo pie1 drao …
cnd_hgtv  10  10  0.8  3.
```

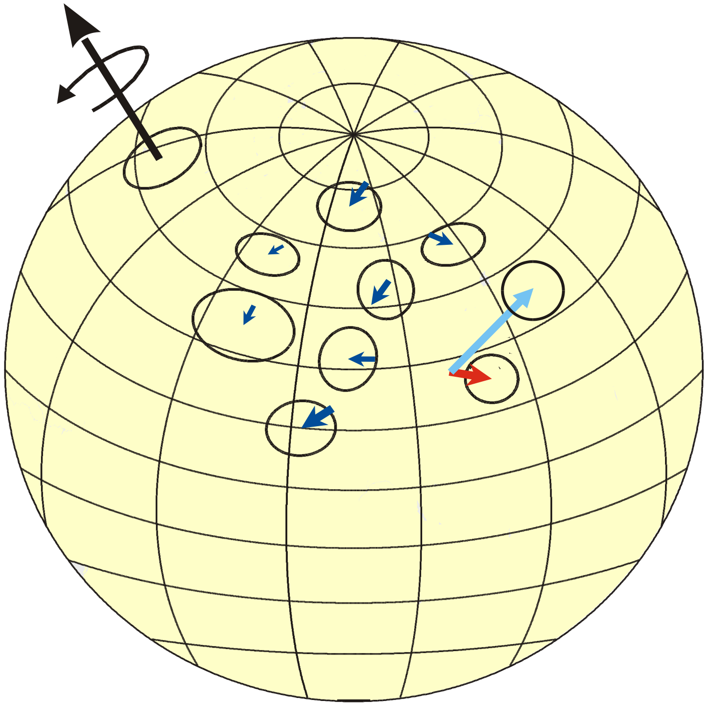


- All reference coordinates free to adjust (anomalies more apparent); outliers are iteratively removed by glorg
- Network can translate and rotate but not distort
- Works best with strong redundancy (number and [if rotation] geometry of coordinates exceeds number of parameters estimated)
- Can downweight heights if suspect or to minimuze loading effects

Referencing to a horizontal block (‘plate’)

Applied in glorg: first stabilize in the usual way with respect to a reference set of coordinates and velocities (e.g. ITRF-NNR), then define one or more ‘rigid’ blocks

```
apr_file itrf05.apr
pos_org xtran ytran ztran xrot yrot zrot
stab_site algo pie1 nlib drao gold sni1 mkea chat
cnd_hgtv  10  10  0.8  3.
plate noam algo pie1 nlib
assign_p noam drao fair
plate pcfc  sni1 mkea chat
```



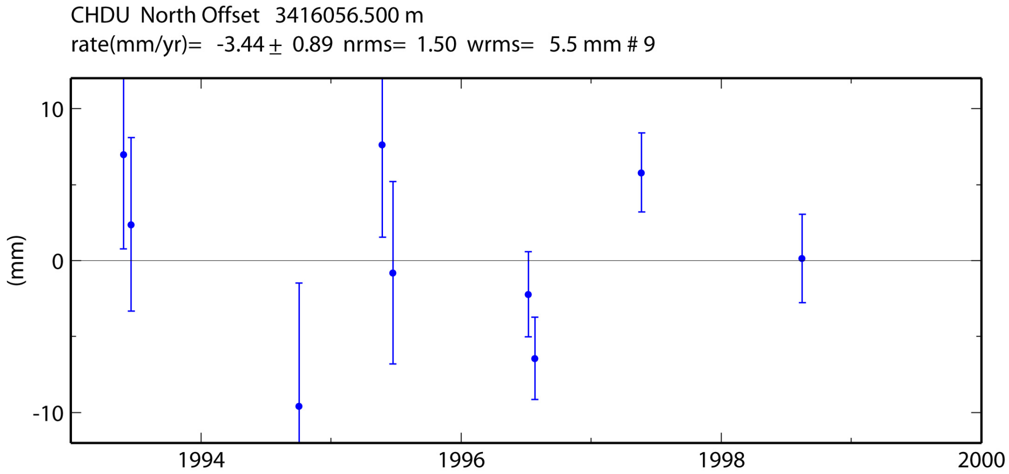
After stabilization, glorg will estimate a rotation vector (‘Euler pole’) for each plate with respect to the frame of the full stabilization set and print the relative poles between each set of plates

Use sh_org2vel to extract the velocities of all sites with respect to each plate

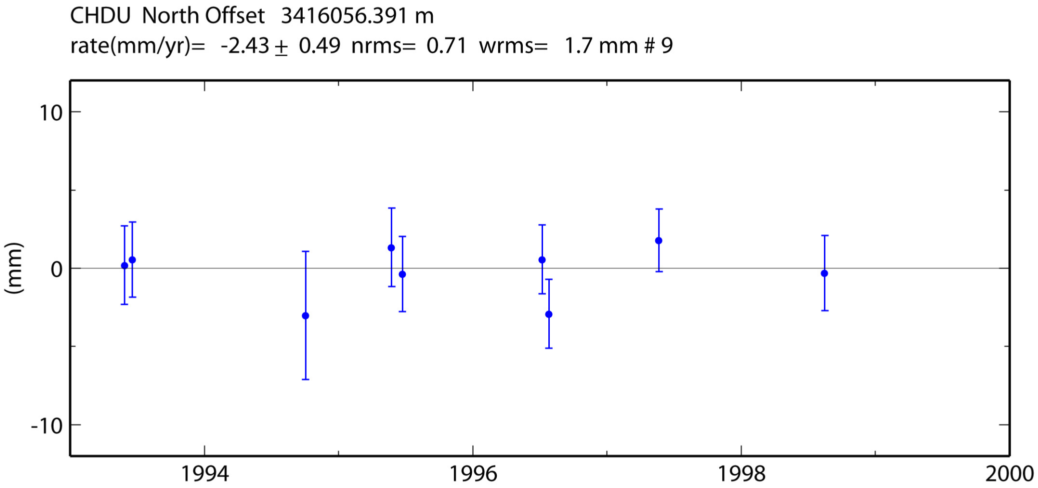
Rules for Stabilization of Time Series

- Small-extent network: translation-only in *glorg*, must constrain EOP in *globk*
- Large-extent network: translation+rotation, must keep EOP loose in *globk;*
- if scale estimated in *glorg*, it must estimate scale in *globk*
- 1st pass for editing:
  - "Adequate" stab_site list of stations with accurate a priori coordinates and velocities and available most days
  - Keep in mind deficiencies in the list
- Final pass for presentation / assessment / statistics
  - Robust stab_site list of all/most stations in network, with coordinates and velocities determined from the final velocity solution
- System is often iterated (velocity field solution, generate time series, editing and statistics of time series; re-generate velocity field).

Reference Frames in Time Series

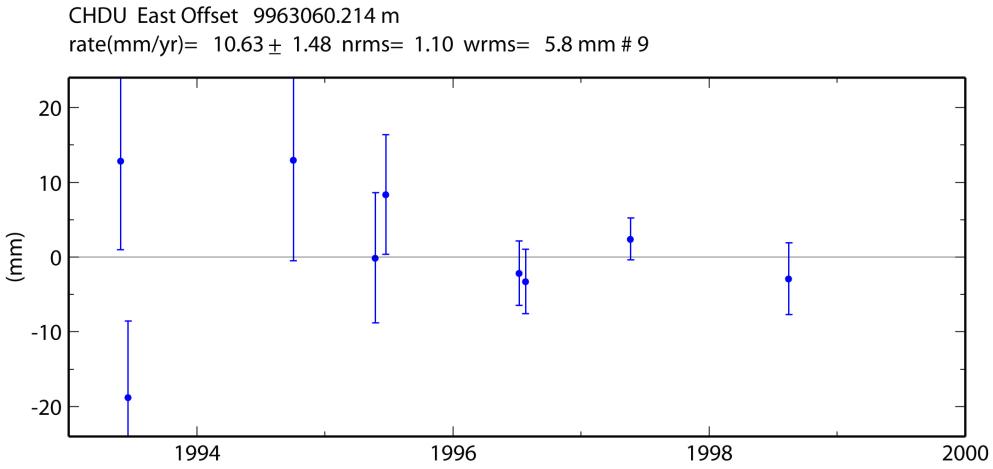


Stabilization with respect to a pan-Eurasia station set

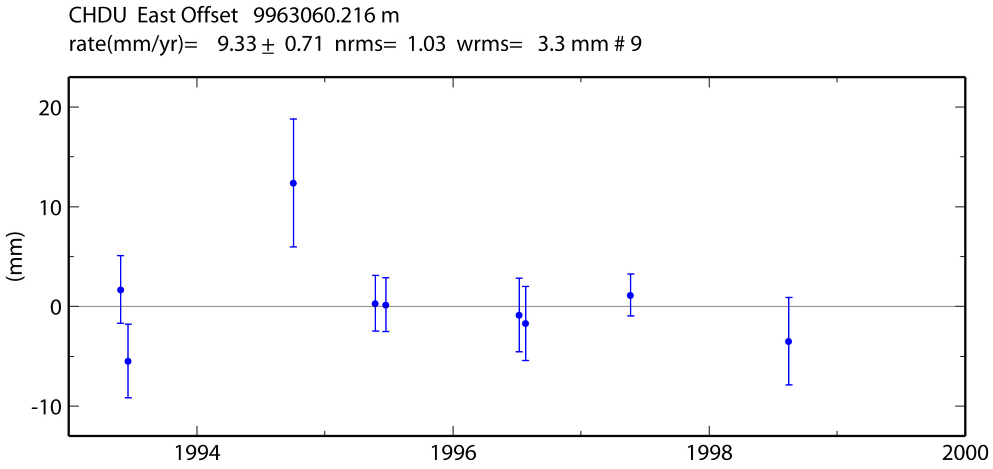


Stabilization with respect to a SW-China station set: spatially correlated noise reduced; this time series best represents the uncertainties in the velocity solution

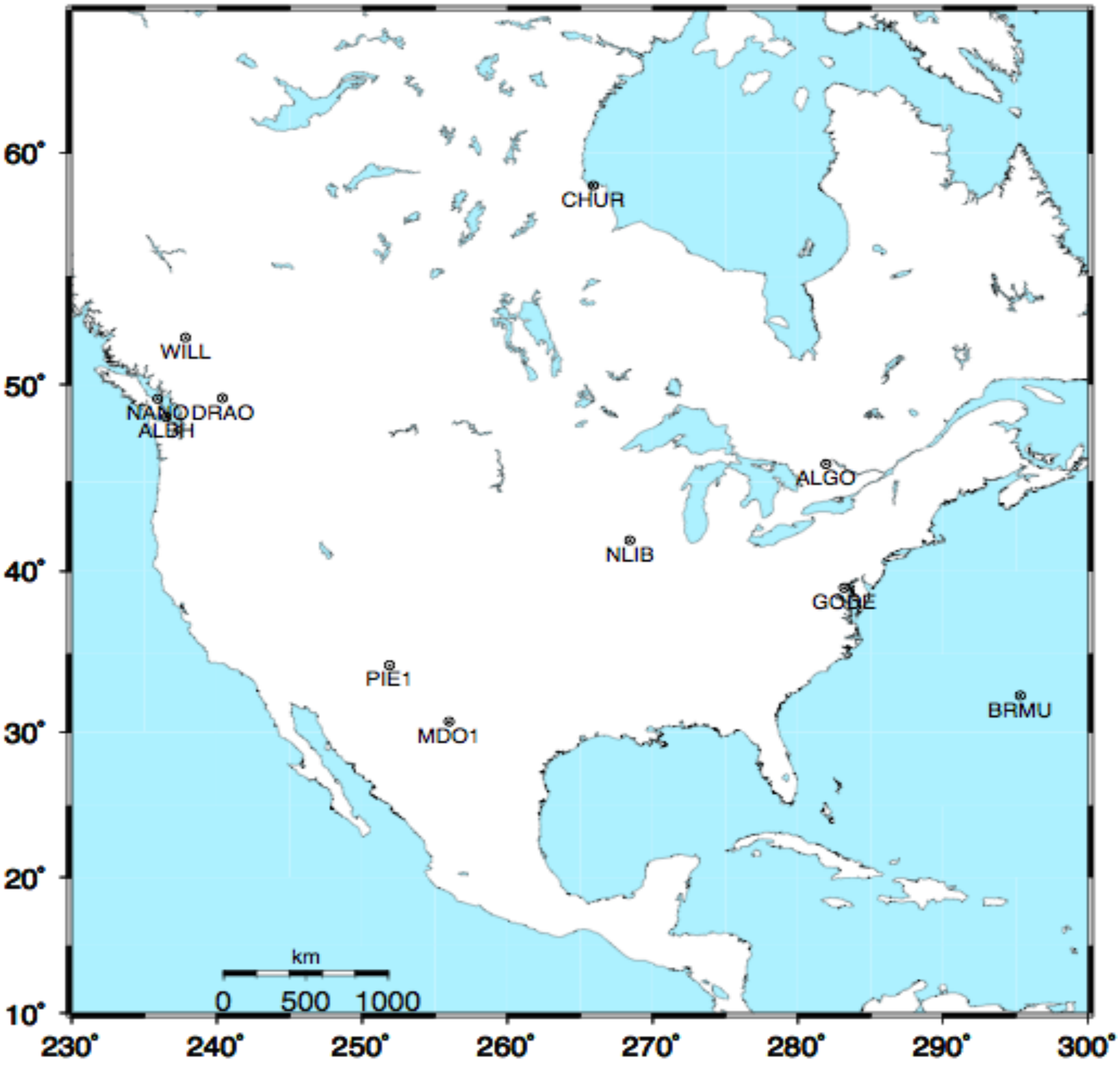
.. Same two solutions, East component


CHDU East Offset 9963060.214 m
rate(mm/yr)= 10.63 ± 1.48 nrms= 1.10 wrms= 5.8 mm # 9

Eurasia stabilization


CHDU East Offset 9963060.216 m
rate(mm/yr)= 9.33 ± 0.71 nrms= 1.03 wrms= 3.3 mm # 9

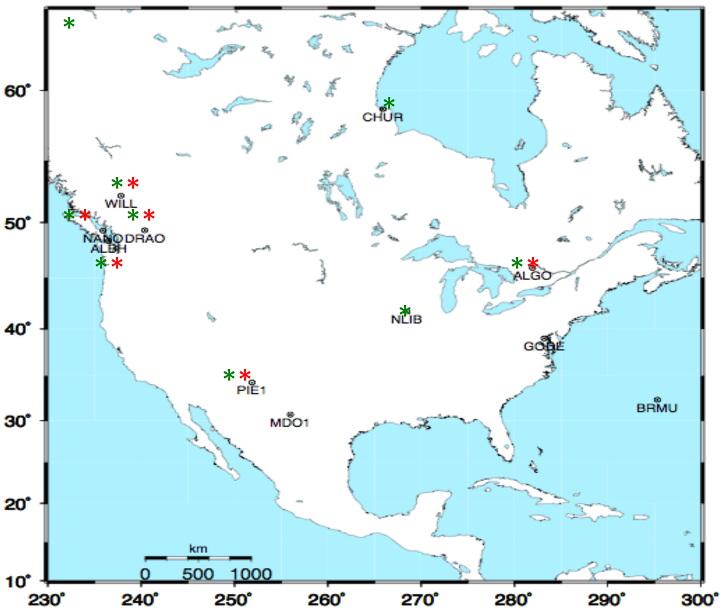
SW-China stabilization



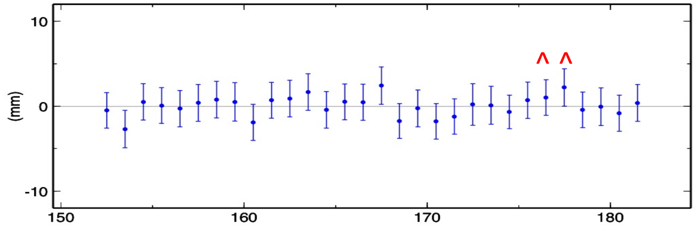
Stabilization Challenges for Time Series

Network too wide to estimate translation-only (but reference sites too few or poorly distributed to estimate rotation robustly)

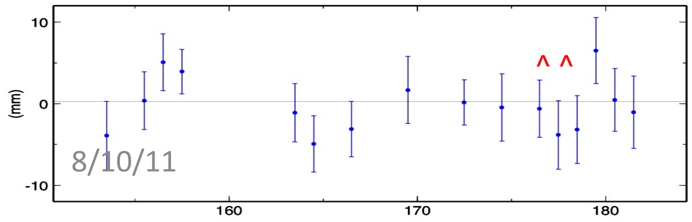
Stable reference frame



DRAO North Offset 5490568.916 m
wmean(mm)= 8916.81 ± 0.39 nrms= 0.54 wrms= 1.2 mm # 30



BRMU North Offset 3603456.226 m
wmean(mm)= 6229.64 ± 0.90 nrms= 0.91 wrms= 3.3 mm # 16

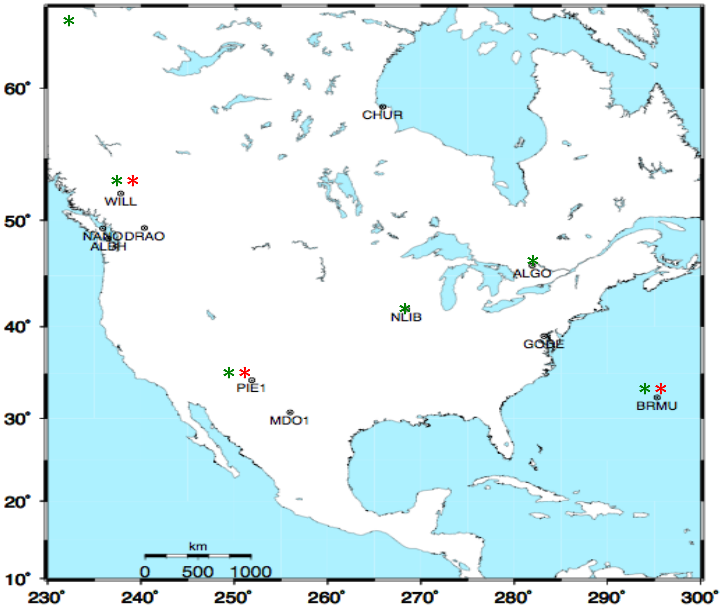


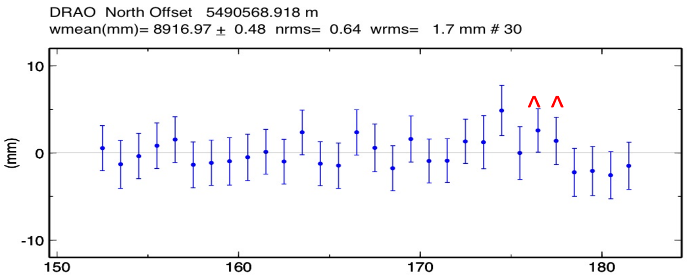
Example of time series for which the available reference sites changes day-to-day but is robust (6 or more sites, well distributed, with translation and rotation estimated)

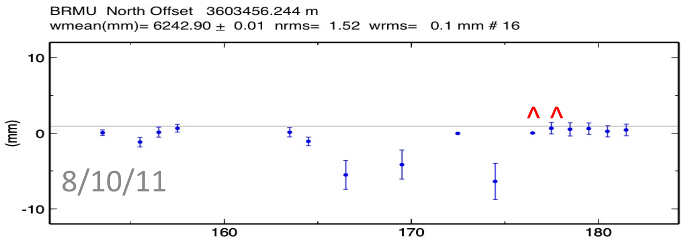
Day 176 ALGO PIE1 DRAO WILL ALBH NANO rms 1.5 mm

Day 177 ALGO NLIB CHUR PIE1 YELL DRAO WILL ALBH NANO rms 2.3 mm

Unstable case







Example of time series for which the available reference sites changes day-to-day and is <u>not</u> robust (only 3 sites on one day)
NOTE: Distant frame definition sites can have very small error bars when used and large error bars when not used.

Day 176 BRMU PIE1 WILL
rms 0.4 mm

Day 177 BRMU ALGO NLIB PIE1
YELL WILL
rms 2.0 mm

Use of Global binary H-files

- Include global h-files … or not ? For post-2000 data not needed for orbits

- Advantages
  - Access to a large number of sites for frame definition
  - Can (should) allow adjustment to orbits and EOP
  - Eases computational burden

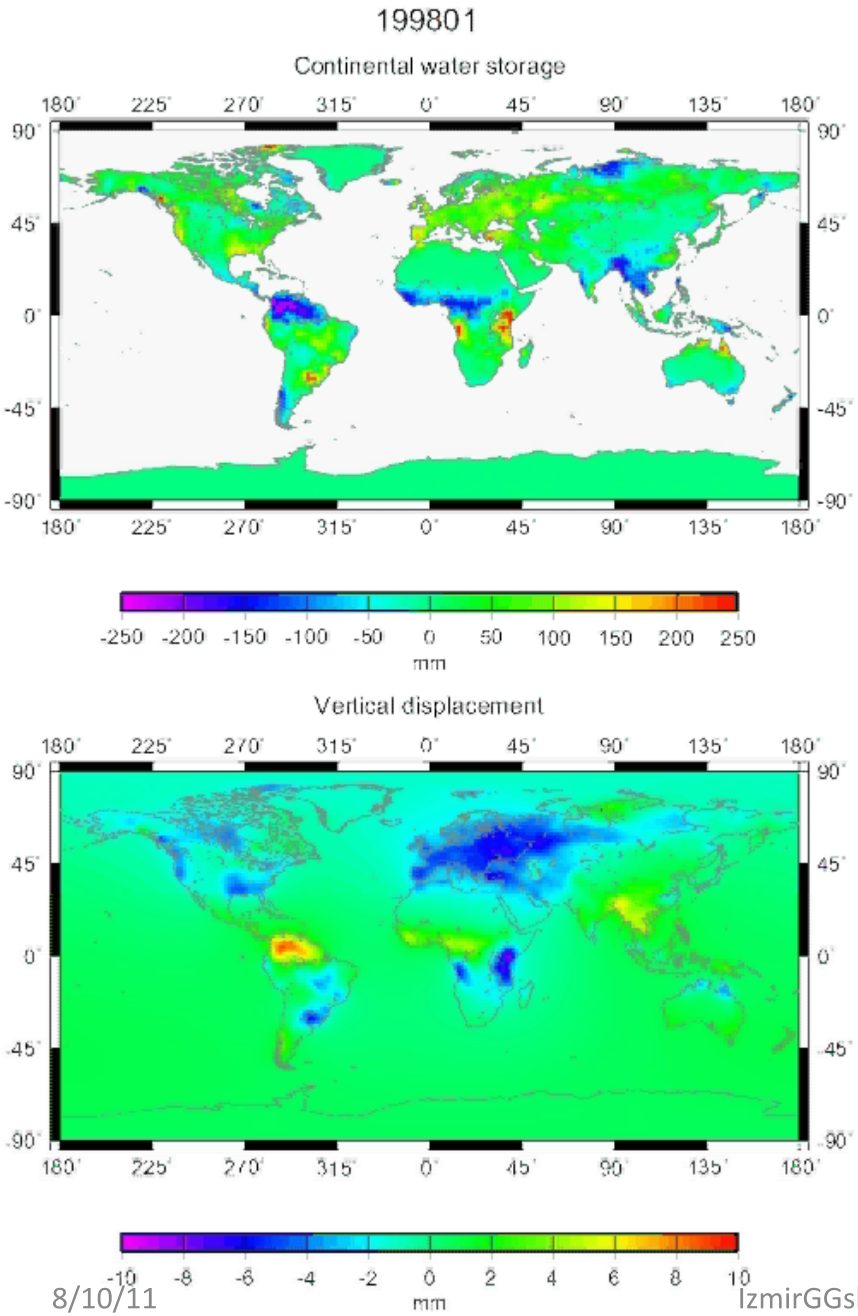
- Disadvantages
  - Must use (mostly) the same models as the global processing
  - Orbits implied by the global data worse than IGSF
  - Some bad data may be included in global h-files (can remove)
  - Greater data storage burden

Regional versus Global stabilization

- If not using external h-files, use 8 or more well distributed sites reference sites
- If combining with MIT or SOPAC* global h-files, use 4-6 well-performing common sites (not necessarily with well-known coordinates),
- MIT hfiles available at
  ftp://everest.mit.edu/pub/MIT_GLL/HYY
  When using MIT files, add apr_svant all F F F to globk command file to fix the satellite antenna offsets

- If SOPAC, use all "igs' h-files to get orbits well-determined

Seasonal Effects



Large seasonal signals due to hydrological loading in many regions of the world

May generates spurious signals in time series

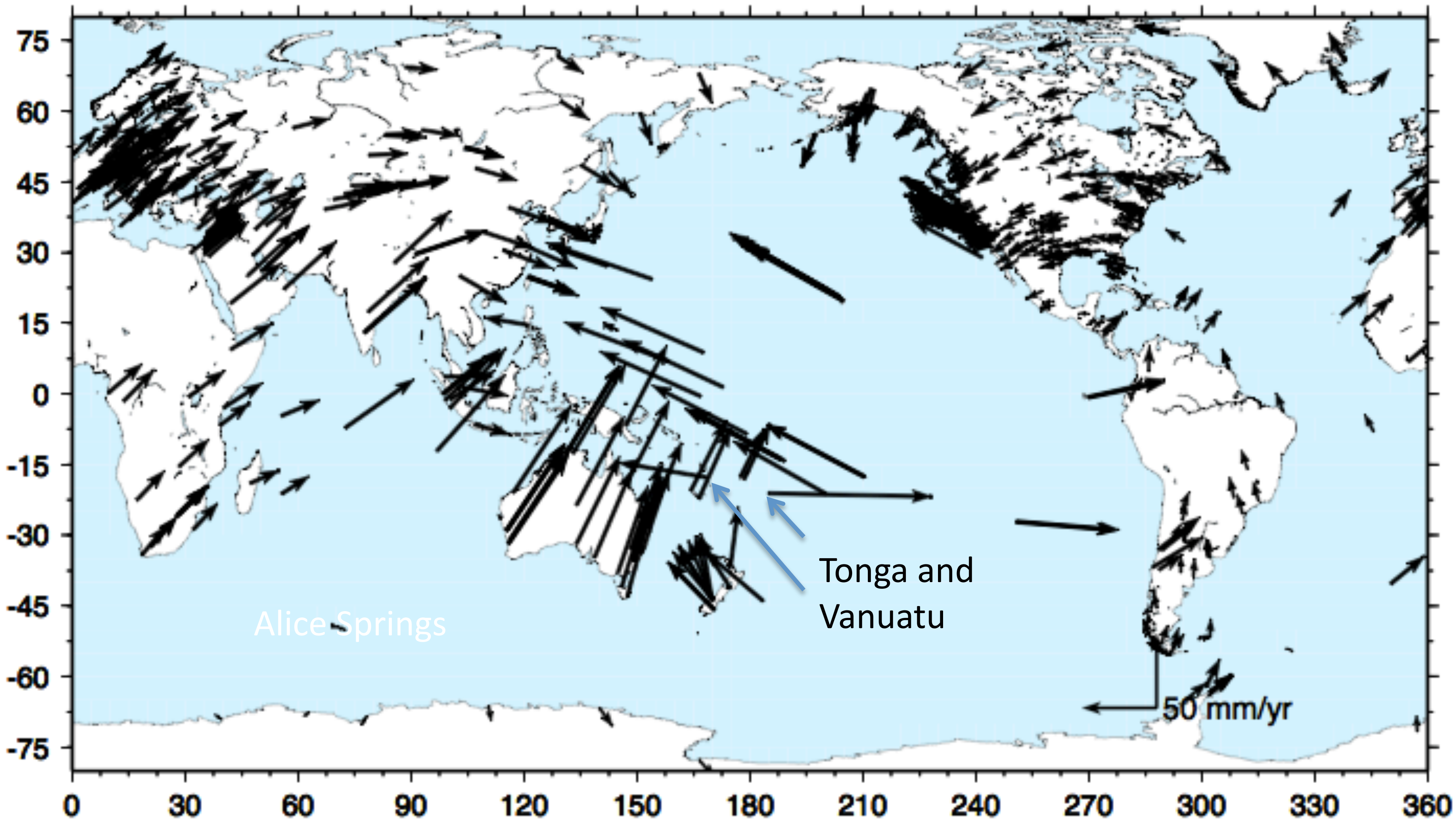
Courtesy J. P. Boy

GRACE Results

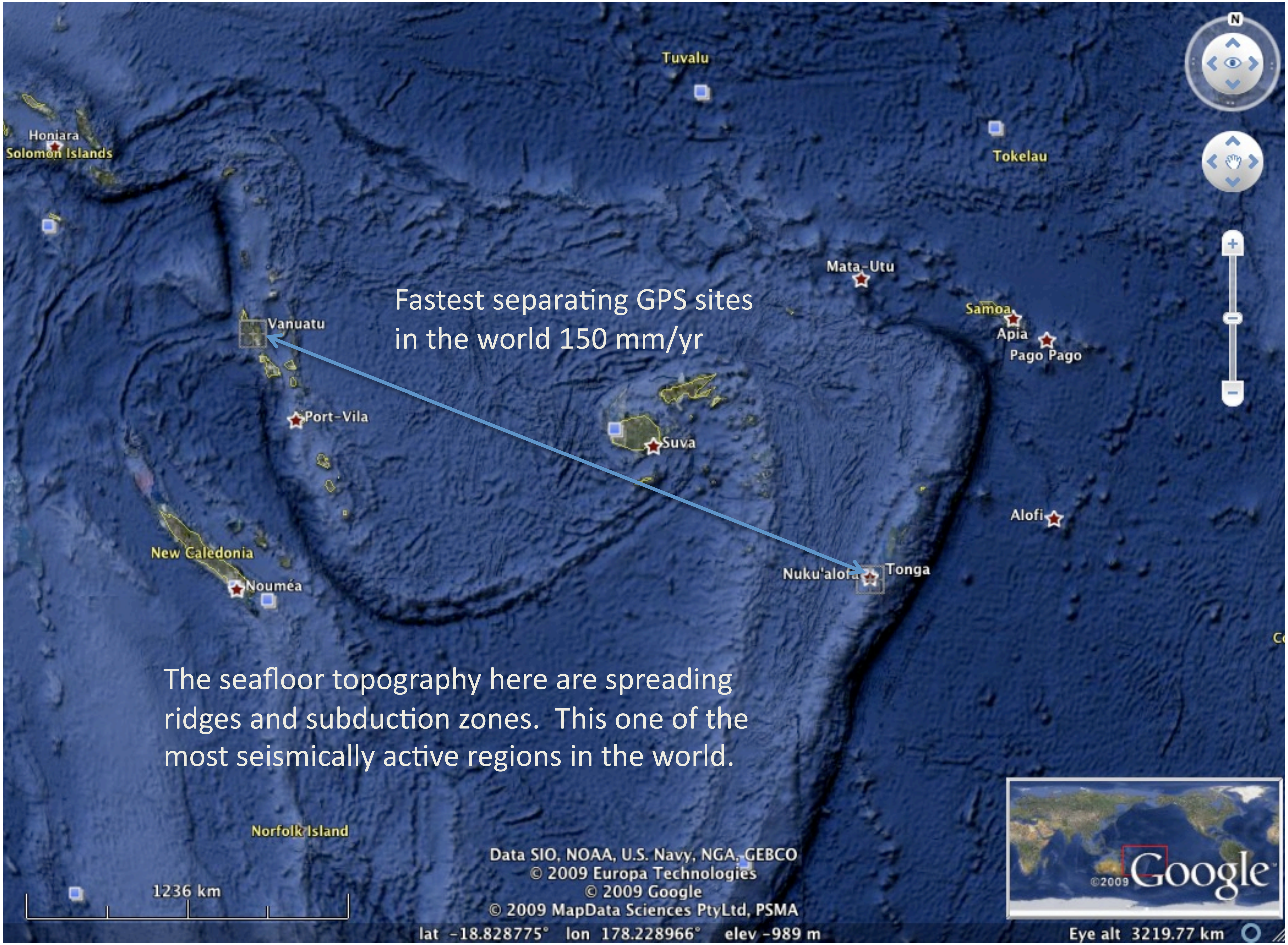
- There are number of web sites where GRACE results are available. For large-scale loading an approximate rule is 0.5 mm of vertical per mbar or cm of water
- Interactive site with graphics http://geoid.colorado.edu/grace/grace.php
- Also see site (select region and click on map): http://grace.sgt-inc.com/

Global site motions

Examine the fast motion between Vanuatu and Tonga



Tonga and Vanuatu

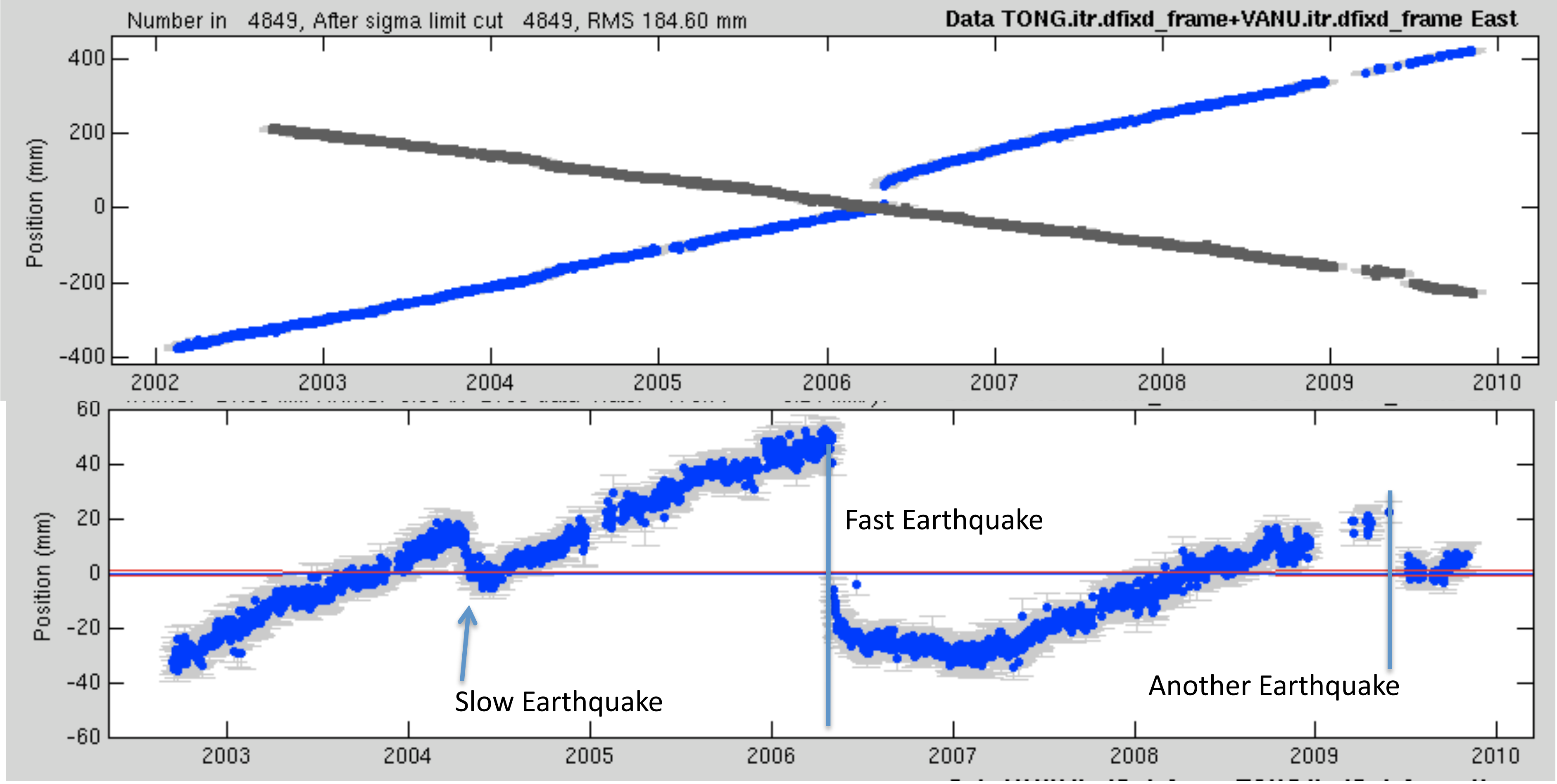


Fastest separating GPS sites in the world 150 mm/yr

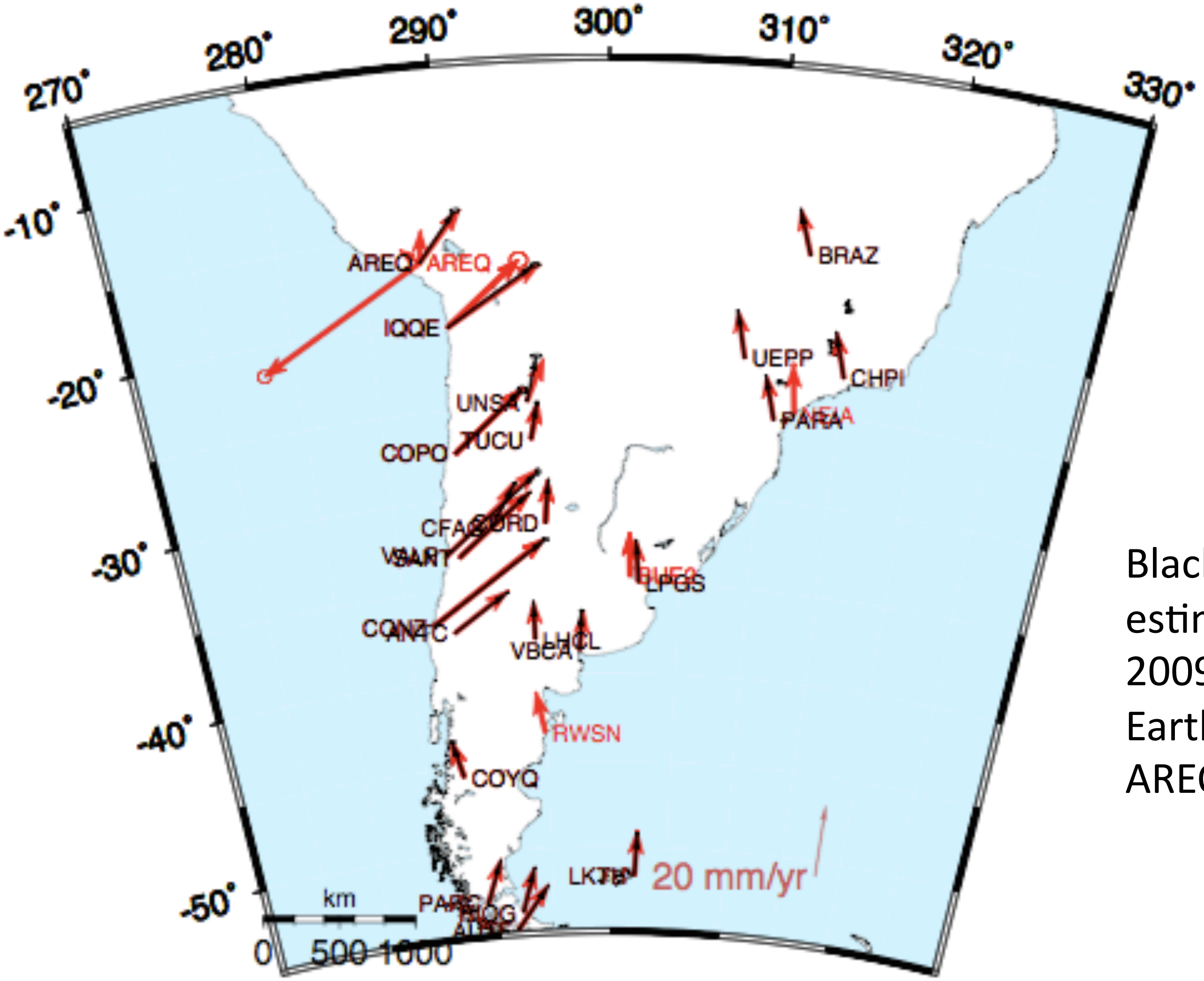
The seafloor topography here are spreading ridges and subduction zones. This one of the most seismically active regions in the world.

East motions at Vanuatu and Tonga

Figure below show east motions are Vanuatu (blue) and Tonga (black)
Bottom figure is difference with linear trend of 170 mm/yr removed. A fast earthquake on May 3, 2006, Magnitude 7.9, 150 km away from Tonga can see seen. A slow earthquake event in 2004 can also be seen.

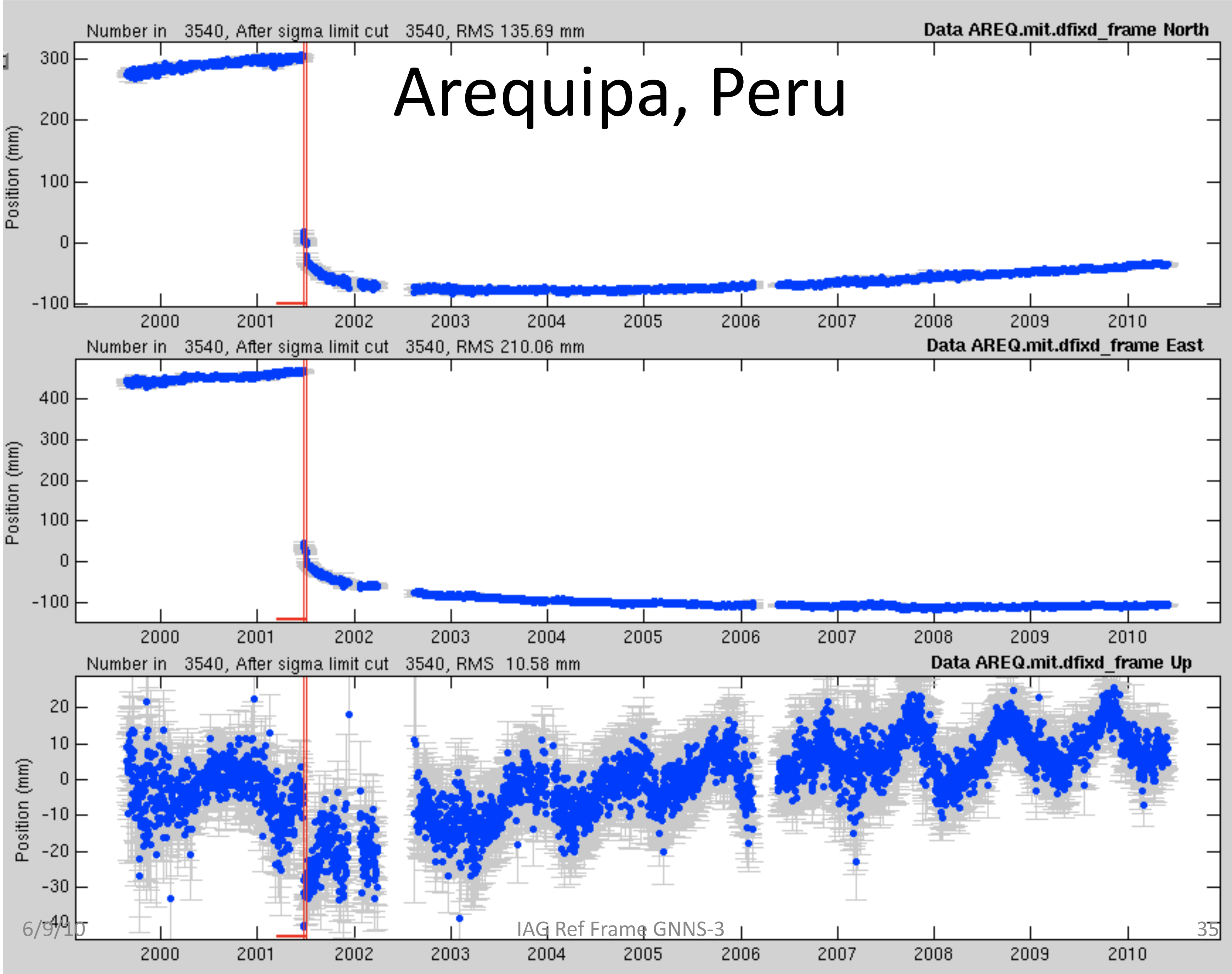


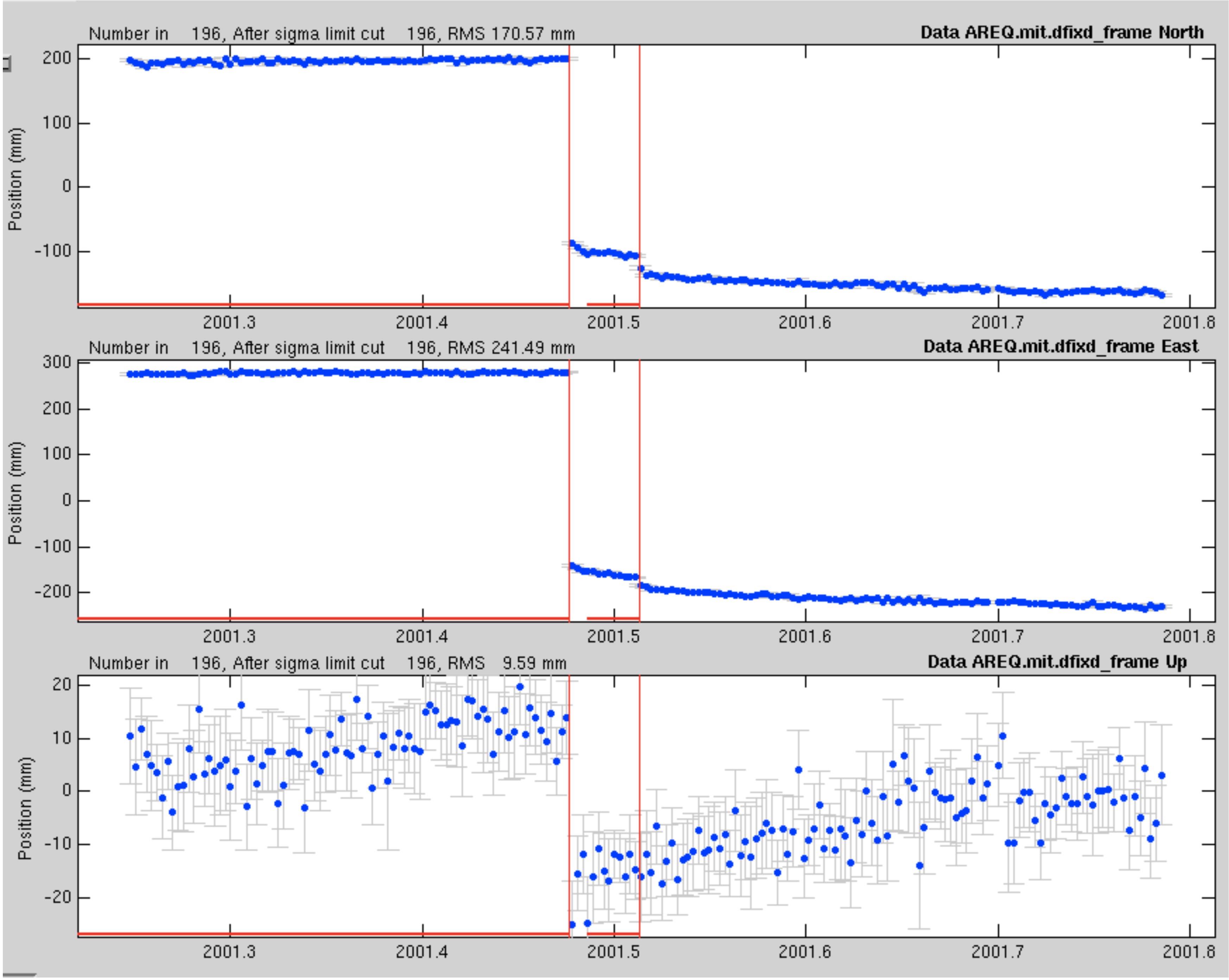
South America



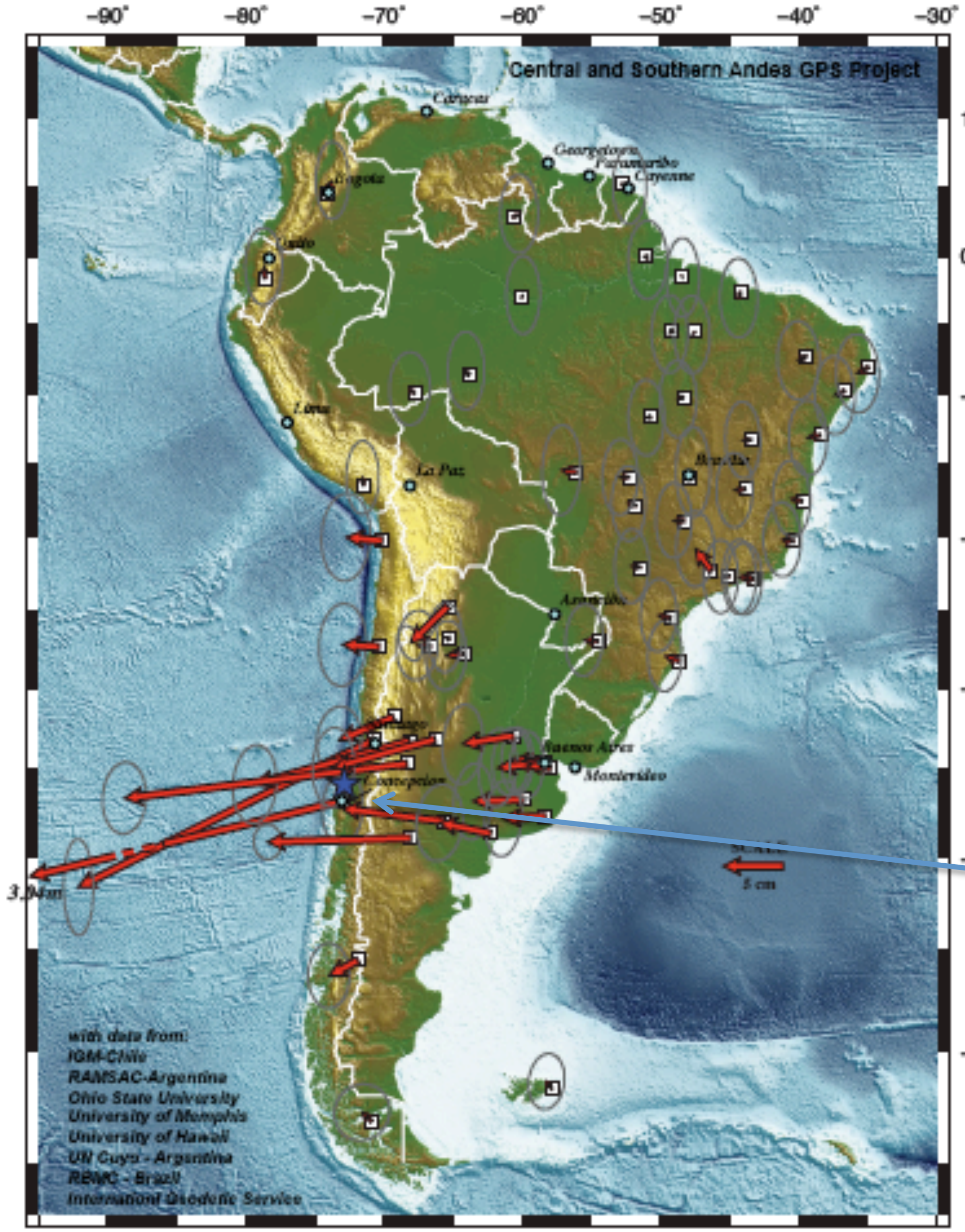
Black vectors are MIT estimates, Red ITRF 2009
Earthquake effects at AREQ

Arequipa, Peru



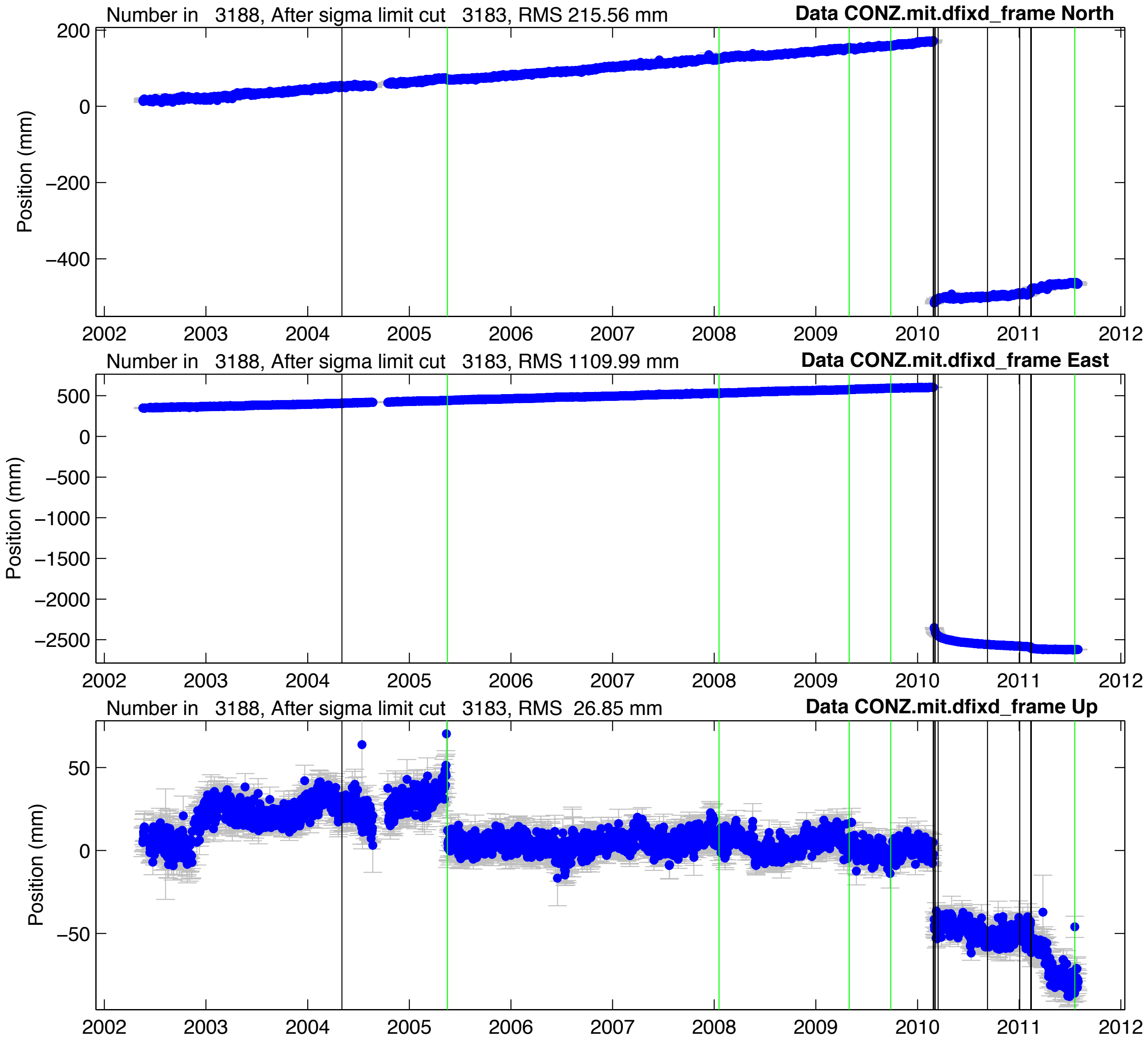

Number in 196, After sigma limit cut 196, RMS 170.57 mm
Data AREQ.mit.dfixd_frame North
Position (mm)
200
100
0
-100
2001.3
2001.4
2001.5
2001.6
2001.7
2001.8
Number in 196, After sigma limit cut 196, RMS 241.49 mm
Data AREQ.mit.dfixd_frame East
Position (mm)
300
200
100
0
-100
-200
2001.3
2001.4
2001.5
2001.6
2001.7
2001.8
Number in 196, After sigma limit cut 196, RMS 9.59 mm
Data AREQ.mit.dfixd_frame Up
Position (mm)
20
10
0
-10
-20
2001.3
2001.4
2001.5
2001.6
2001.7
2001.8

Feb 27, 2010 Chile earthquake



CONZ (GPS/VLBI/SLR)

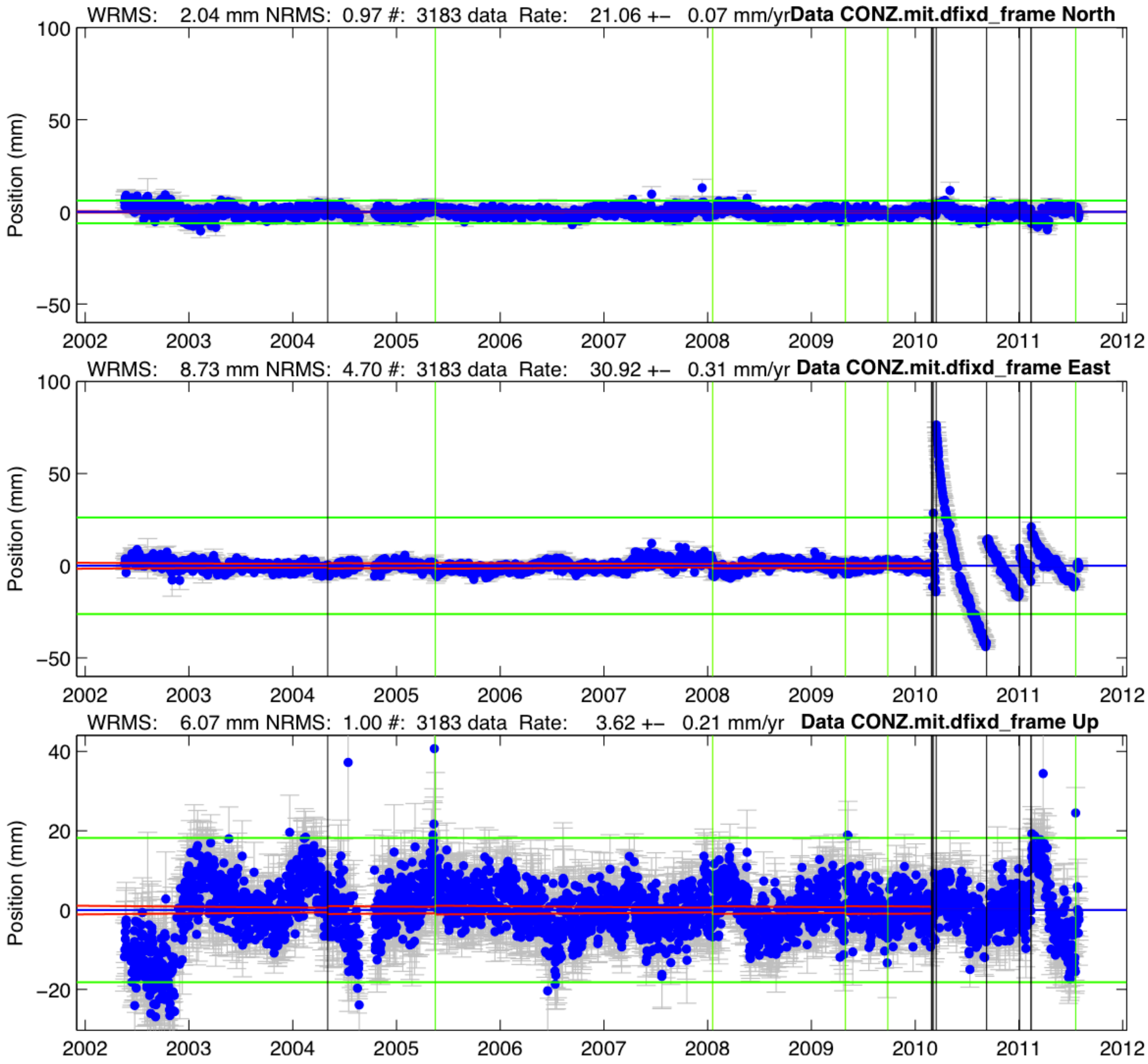
http://www.unavco.org/research_science/science_highlights/2010/M8.8-Chile_EQ_SAM.pdf



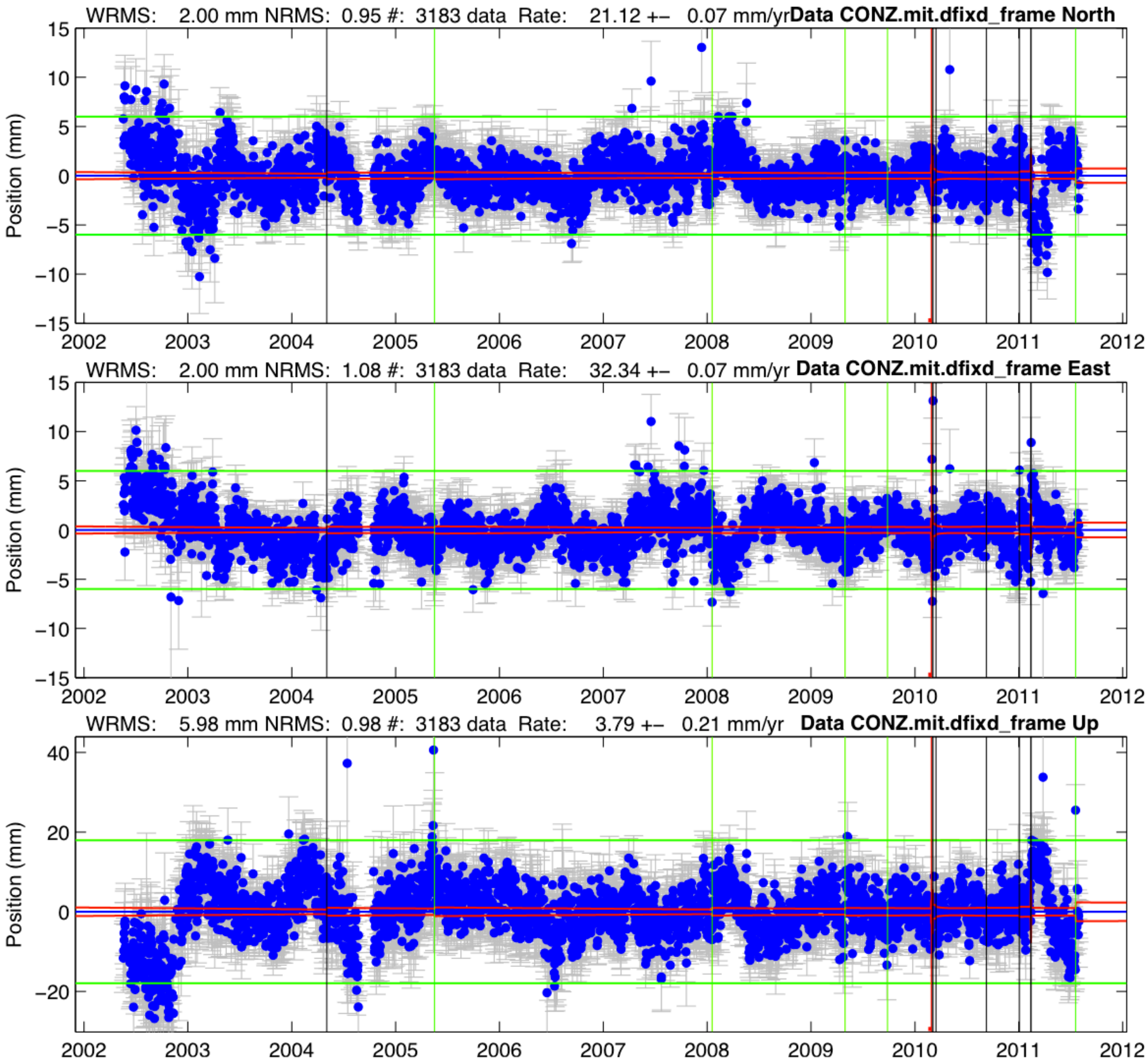
CONZ in Chile

Green lines are equipment changes; black are earthquakes

CONZ detrended



Large amount of post-seismic deformation clear evident here when simple offsets removed.



CONZ: Log

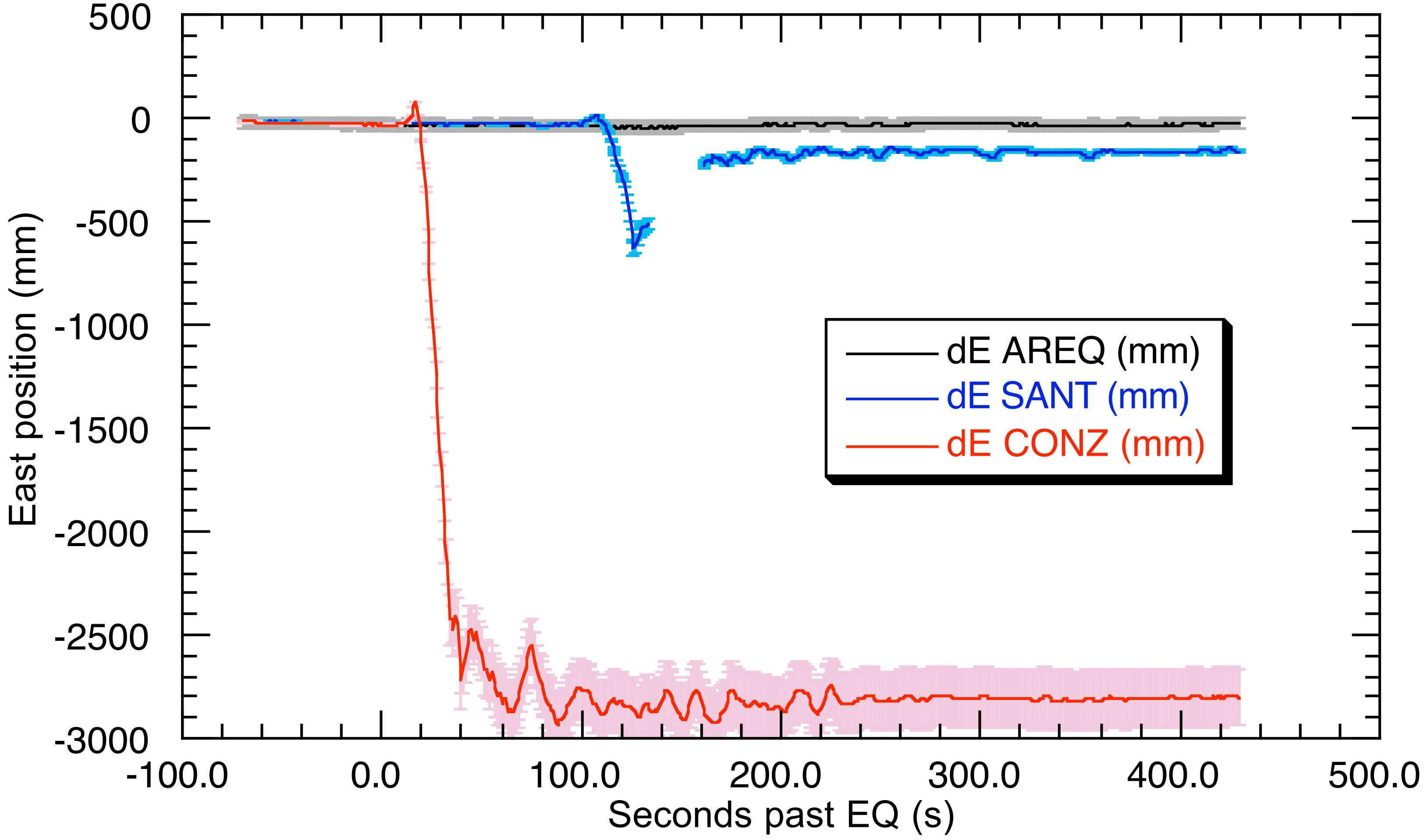
Adding a 10-day log post-seismic decay for the main shock makes the residuals much flatter.

CONZ: East parameter fit

```
Computing Realistic Sigmas
RealSigma white dchi   0.662946
NRMS Realistic    6.81; Correlation time    64.00 days
Detrend of CONZ.mit.dfixd_frame East
WRMS:    2.00 mm NRMS:  6.81 #:  3183 data
Mean                          460.66 +-   1.70 mm
Rate                           32.34 +-   0.45 mm/yr
EQBrk 2004  5  3  4 36                -0.00 +-   1.15 mm
OffLn 2010  2 27  6 34 dOf 10.0   -2950.92 +-   6.55 mm
Log   2010  2 27  6 34 dOf 10.0     -58.86 +-   1.56 mm
EQBrk 2010  3  3 17 44               -10.16 +-  13.38 mm
EQBrk 2010  3  5  9 19               -32.88 +-  12.21 mm
EQBrk 2010  3 16  2 21                -7.33 +-   4.28 mm
EQBrk 2010  9  9  7 28                -3.04 +-   2.10 mm
EQBrk 2011  1  2 20 20                -6.17 +-   2.50 mm
EQBrk 2011  2 11 20  4               -19.14 +-  16.55 mm
EQBrk 2011  2 13  8 51                -8.64 +-  16.45 mm
Break 2005  5 17 14 30                 1.79 +-   1.23 mm
Break 2008  1 18 13 59                 3.93 +-   1.11 mm
Break 2009  4 30 13 30                 2.74 +-   1.14 mm
Break 2009  9 26 13  0                -0.76 +-   1.28 mm
Break 2011  7 19 20 30                 0.36 +-   4.58 mm
```

Velocity effect of log term: 1/time; so in 50 yrs velocity will still be 1.1 mm/yr from inter-seismic value

Coseismic East Offsets



Summary

- Reference frame realization needs to treated carefully in order to extract the most information from your GPS data analysis.
- The caution here is to carefully select and to process data from well distributed “stable” sites that can be used for the reference definition:
  - When we say a site or group of sites is moving, the reference frame defines what we consider to be the non-moving system to which the movement is referenced.