Lecture 5: Orbit and Clock Products, Networks, Reference Frames and Time Series

GEOS655 Tectonic Geodesy

Jeff Freymueller

Starter question: where do broadcast orbits and clocks come from?

- Always harder to predict orbits than to calculate them. Even harder to predict clock errors. Broadcast orbits and clocks are predictions.
- DoD tracking network (with real-time telemetry). Positions of sites known "well."
- Real-time data analysis
- Simple models (e.g. clock t and t^2 terms)
- Historically used only pseudorange data
- No mandate for cm-level precision.

Broadcast Orbits

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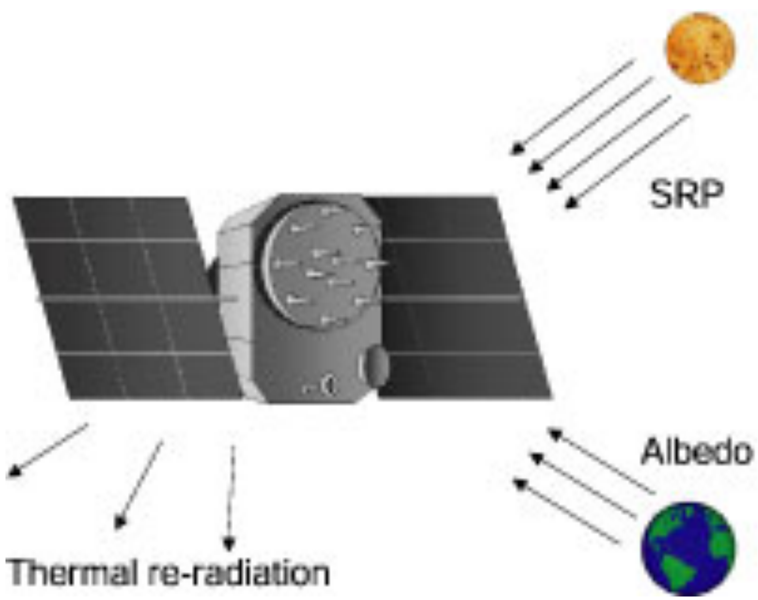
High Accuracy Orbits

- Most of the real-time processing for broadcast orbits is sub-optimal.
- IGS Centers produce much better orbits
  - Tracking site positions are much better known.
  - Many more tracking stations used
  - Better models are usedfor the space and ground segments.
  - Use carrier phase data (<5 mm precision instead of 50 cm precision).
  - Some IGS centers also produce precise satellite clock estimates
    - Given precise clocks you can do precise single station positioning
- IGS now moving to real time orbit and clock products, IGS-IP network.

Orbit Models

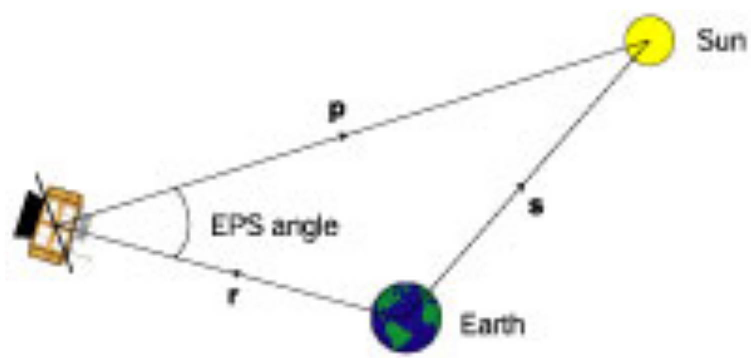
- Integrate equations of motion for satellites from initial conditions (position, velocity at some time), subject to earth's gravity field and other forces.
- Compute partial derivatives for satellite position with respect to initial conditions on orbit and adjustable parts of force models
  - This lets you compute partial derivatives of GPS observables with respect to initial conditions (by chain rule)
- Most important non-gravitational forces are:
  - Solar radiation pressure (several components)
  - Earth albedo pressure

Solar Radiation Pressure



- Effect of sun on the satellite
- Need to know how much area is normal to sun-direction.
- How reflective are the surfaces
- Distance and luminosity of the sun

Design constraints



EPS = Earth-probe-sun

- Antenna boresight points at the geocenter. Why?
- Solar panels are oriented to point continually at the sun
- Y-axis is perpendicular to z and p.
- How well do we know attitude?

Eclipsing – Passing into Earth's Shadow

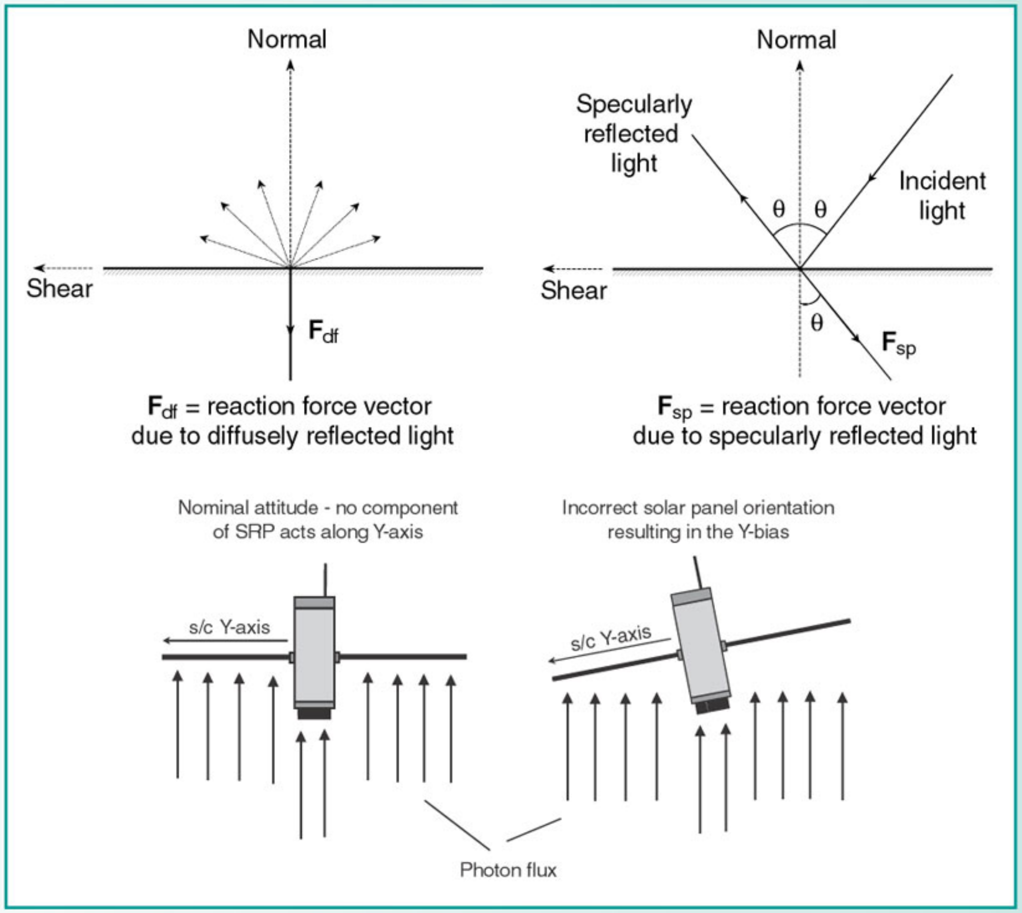
- SRP goes to zero - but it takes a while for the spacecraft to cool down.
- Attitude control system loses its bearings.
- Before 1994, it would yaw wildly. Yaw bias now applied by DoD.
- Satellites in eclipse season are more poorly modelled than other satellites. Many analysis centers remove the data entirely.

Terminology

Reflectivity (ν) – the proportion of radiation incident on a surface that is reflected, the reflected radiation being separated into diffuse (scattered) and specular (beamed) components.

Specularity (μ) – the proportion of reflected radiation that is reflected specularly. Specular reflection implies that the surface behaves like a perfect mirror.

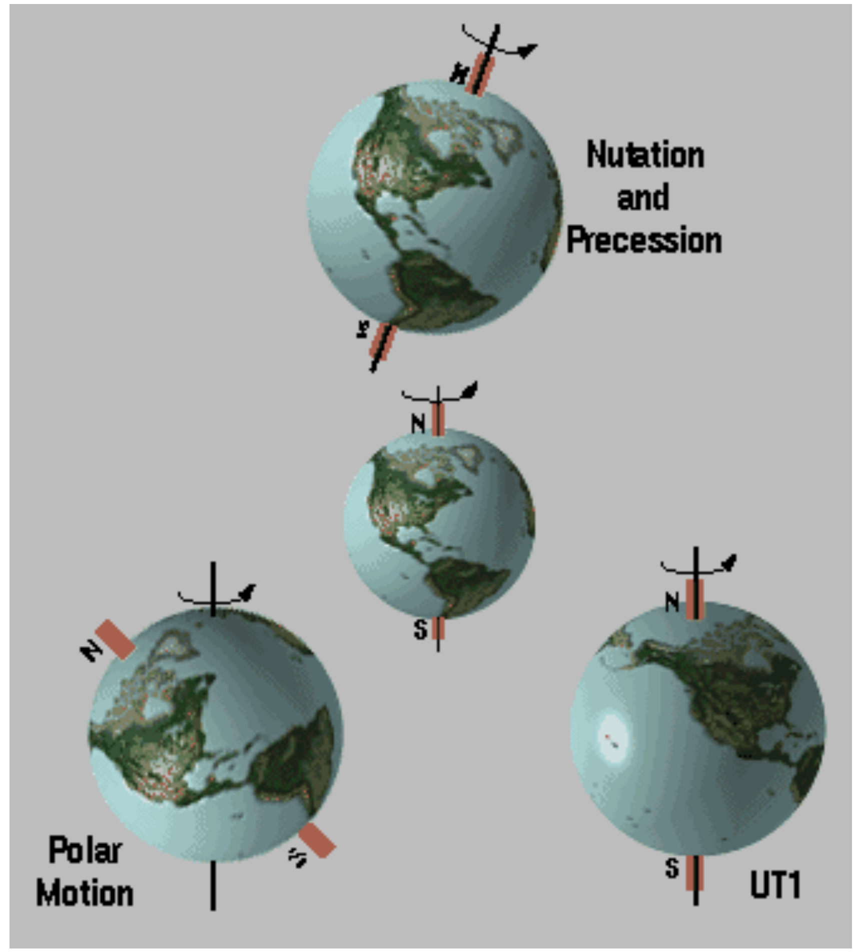
Y-bias – a force acting along the spacecraft BFS Y-axis and believed to derive from NCF effects. A likely mechanism for the Y-bias is due to non-orthogonality of the solar panels with respect to the solar photon flux, as a result of attitude bias or variations. However, another possible contribution could come from heat dissipation effects of payload components.



Reflected radiation from a spacecraft may be separated into diffuse and specular components. If a spacecraft's solar panels are not oriented precisely orthogonal to the photon flux, an anomalous bias force is generated along the spacecraft Y-axis.

ECI to ECEF

- Orbits must be determined in an inertial coordinate system (ECI)
- Earth Orientation (EOP) relates ECI system to Earth Centered Earth Fixed (ECEF) system, which is convenient for users.
- IERS provides good enough estimates of EOPs a few weeks after the fact.
- To estimate orbits in real time you need to estimate EOPs

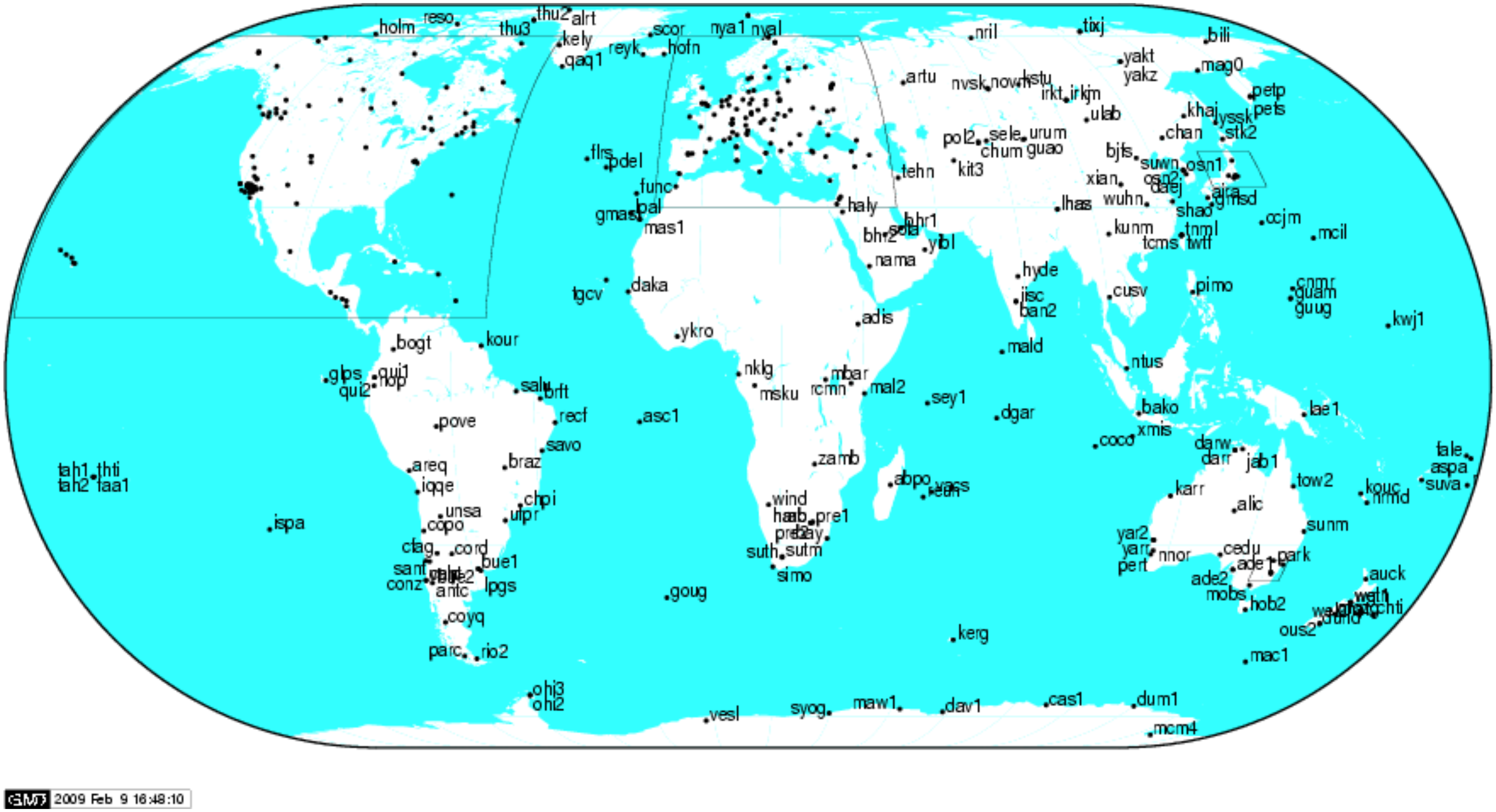


Orbits Provided in Tabular Form

- An example of an orbit file in the "SP3" format is given at right.
- Simply a listing of XYZ positions of each satellite every 15 minutes
- Easy to interpolate positions to intervening times.

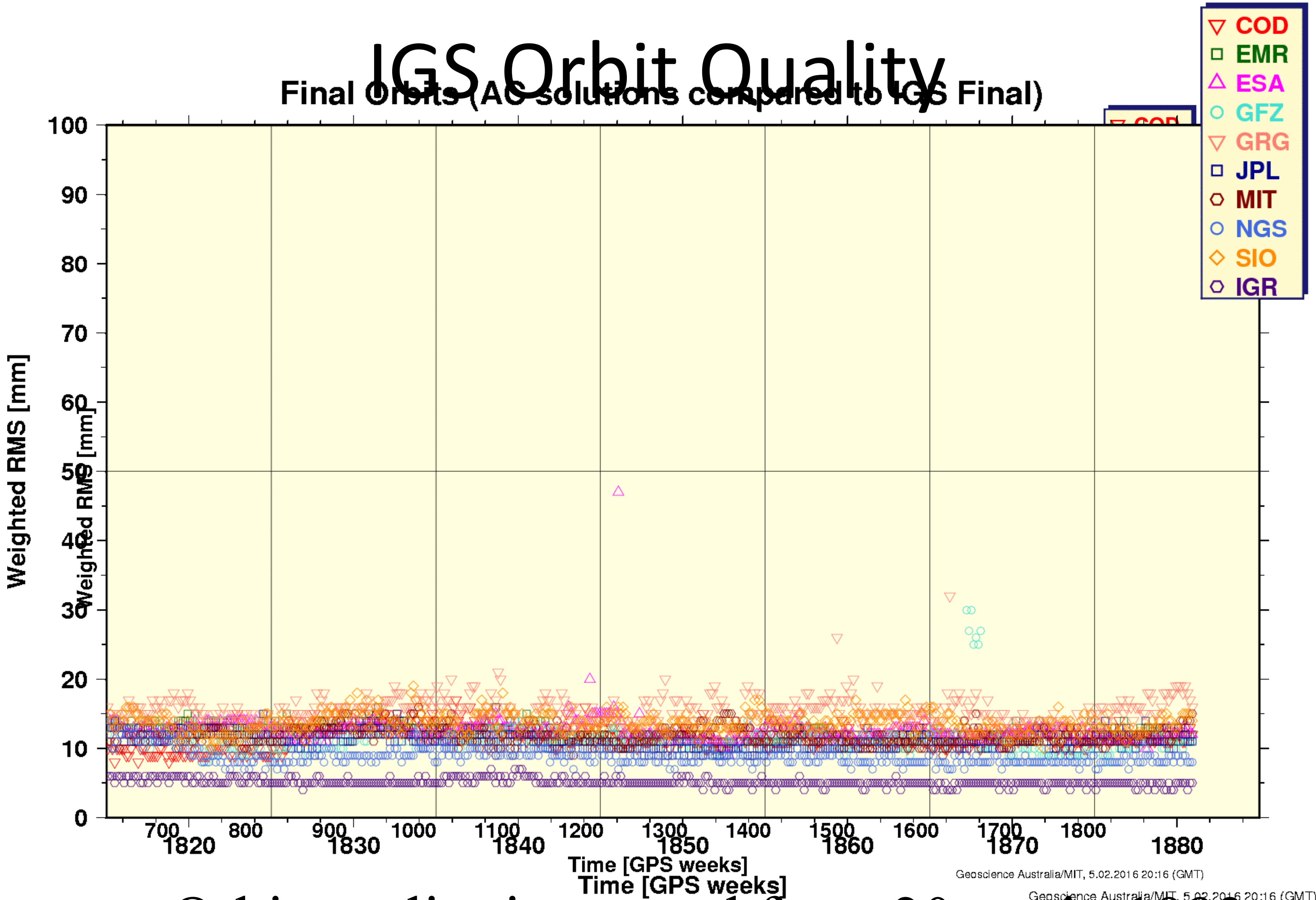
```
*  1994  1 30  0  0   .0000
P  1  14855.155527  16386.878708 -14550.286691     -4.615063
P  2 -22423.706675 -11782.265143   9029.111545    -67.501554
P  3   1338.337535  24076.878499  10293.879836    -79.176017
P  4 -17936.739089  -1271.746274 -19464.957912     11.058441
P  5  -8996.556075  13142.793907 -21211.654889     22.937360
P  7 -14454.335161 -18496.843697 -12600.968202     53.224722
P  9 -15818.456050  20713.864415  -4801.360532    -10.537669
P 12 -16280.510502  15688.364721 -13259.492948   -434.829088
P 13 -11440.106409  -2535.572979 -23741.548218    -85.065334
P 14   5573.018243 -14189.155057 -21769.226792      3.862495
P 15  15002.988949 -20837.737677  -7184.804271     57.253702
P 16 -22004.641914   3864.943488  14368.542278    -70.663987
P 17    288.594268  17655.082111  19587.182440    -42.582199
P 18  -6763.923337 -25702.853528  -1325.693585     -4.859222
P 19  -1279.483364 -18728.319597  18795.949273      5.319124
P 20   6057.491010  16104.265465 -20384.678011     43.187098
P 21  23263.132830  11216.200745   7075.459055    -18.649534
P 22  25405.283161    232.786437   8373.391831     92.679704
P 23  13297.613282  16140.121474  16708.348505      3.564807
P 25  18338.181107    774.736940 -19177.389393     -2.425358
P 26 -10853.016654  13742.331204  20150.293666    -33.488501
P 27  -9735.182026 -11922.730226  21373.047861     17.361817
P 28  14539.352810  -3746.429680  21863.849624     60.215516
P 29   1760.316358 -23510.933080 -12019.359667      8.625516
P 31   8837.368727 -16582.675561  18616.016999     70.666231
P 24 -21290.266242   9905.383975 -12119.624730 999999.999999
*  1994  1 30  0 15   .0000
P  1  15081.669255  17942.456881 -12321.177941     -4.687666
```

Tracking Network



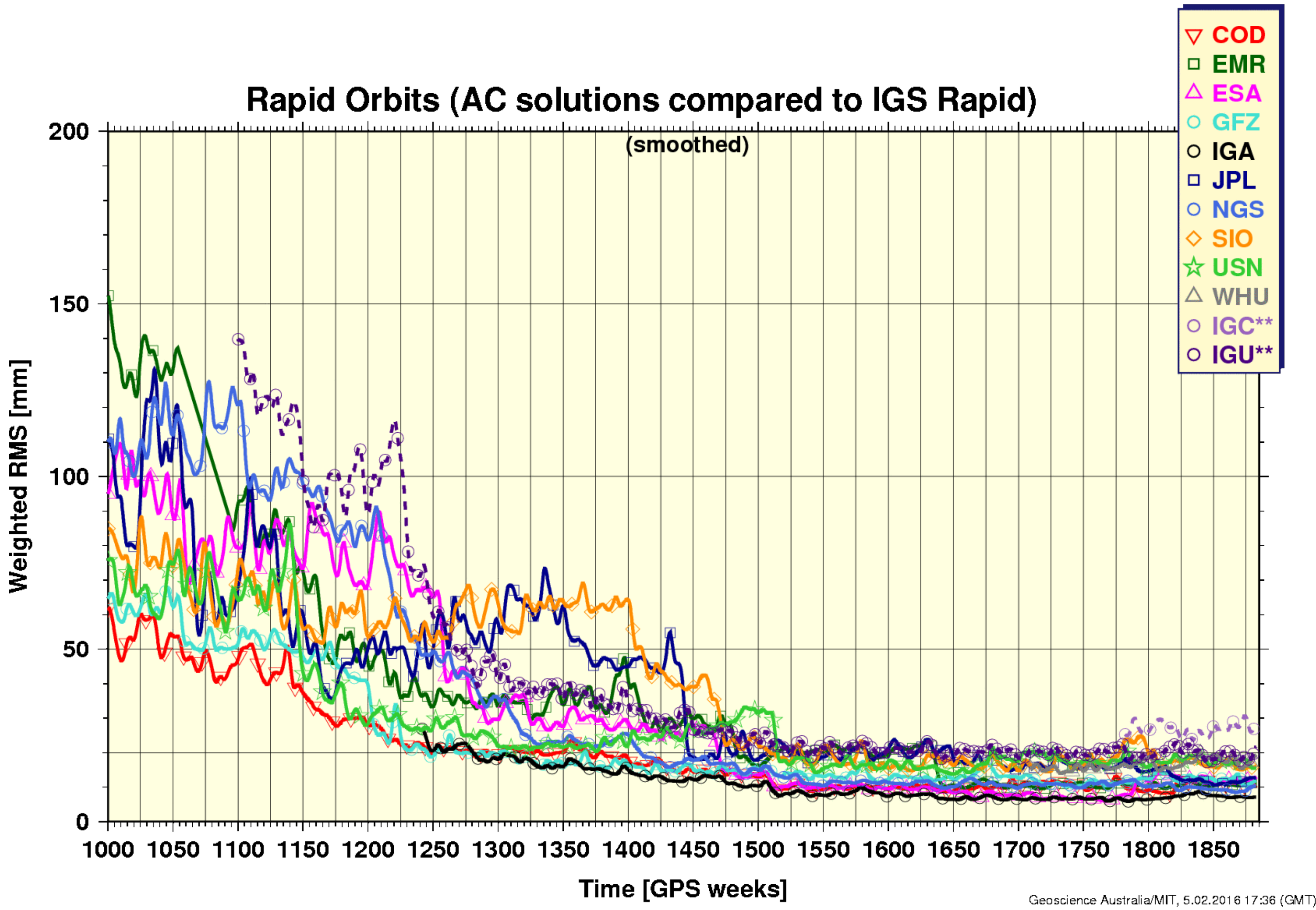
More sites means a better orbit and clocks, but more data to be dealt with.

IGS Orbit Quality



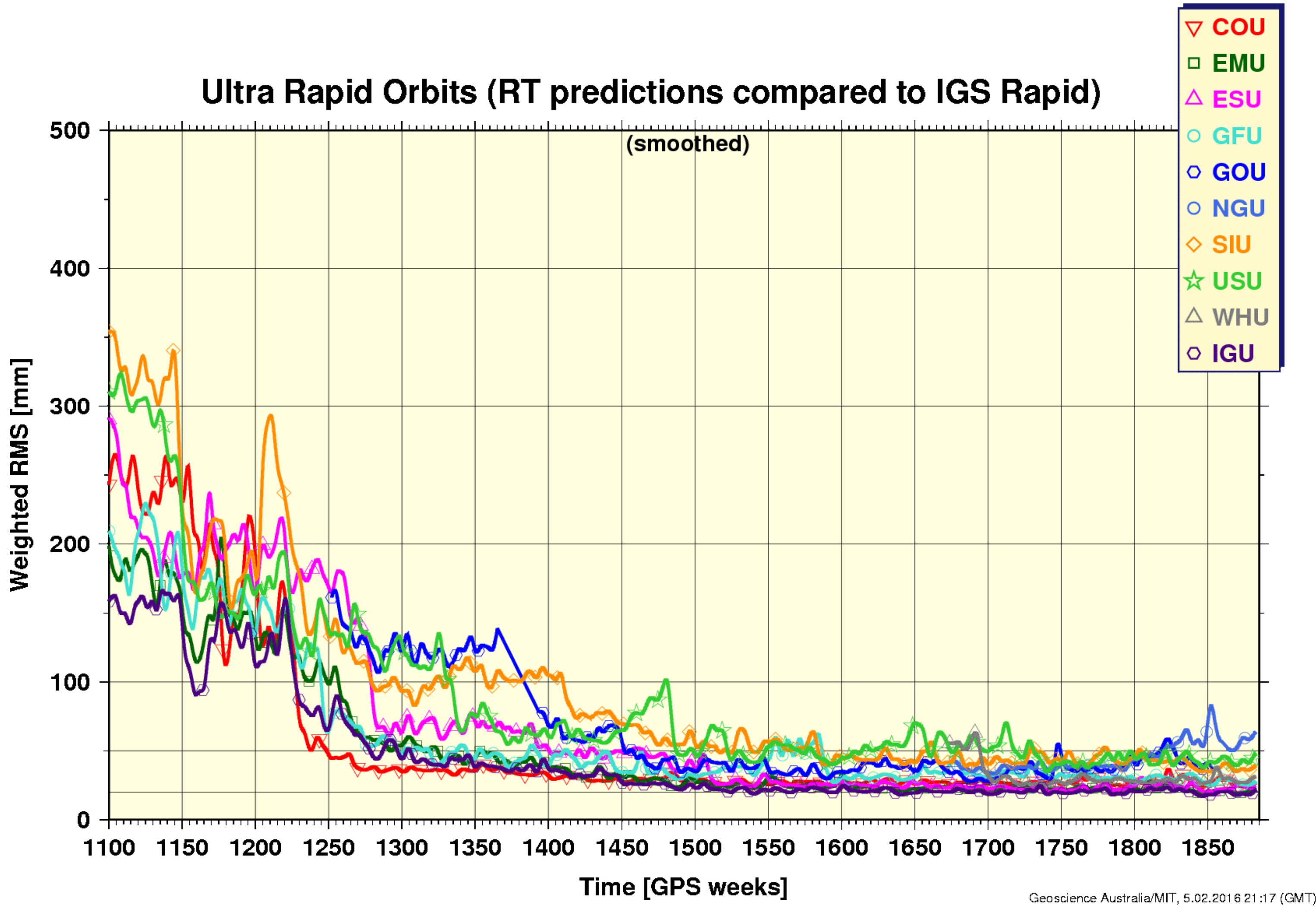
•Orbit quality improved from 20 cm in 1993 to 2-3 cm since 2004, approaching 10 mm.

Rapid Orbit Quality (1 day)



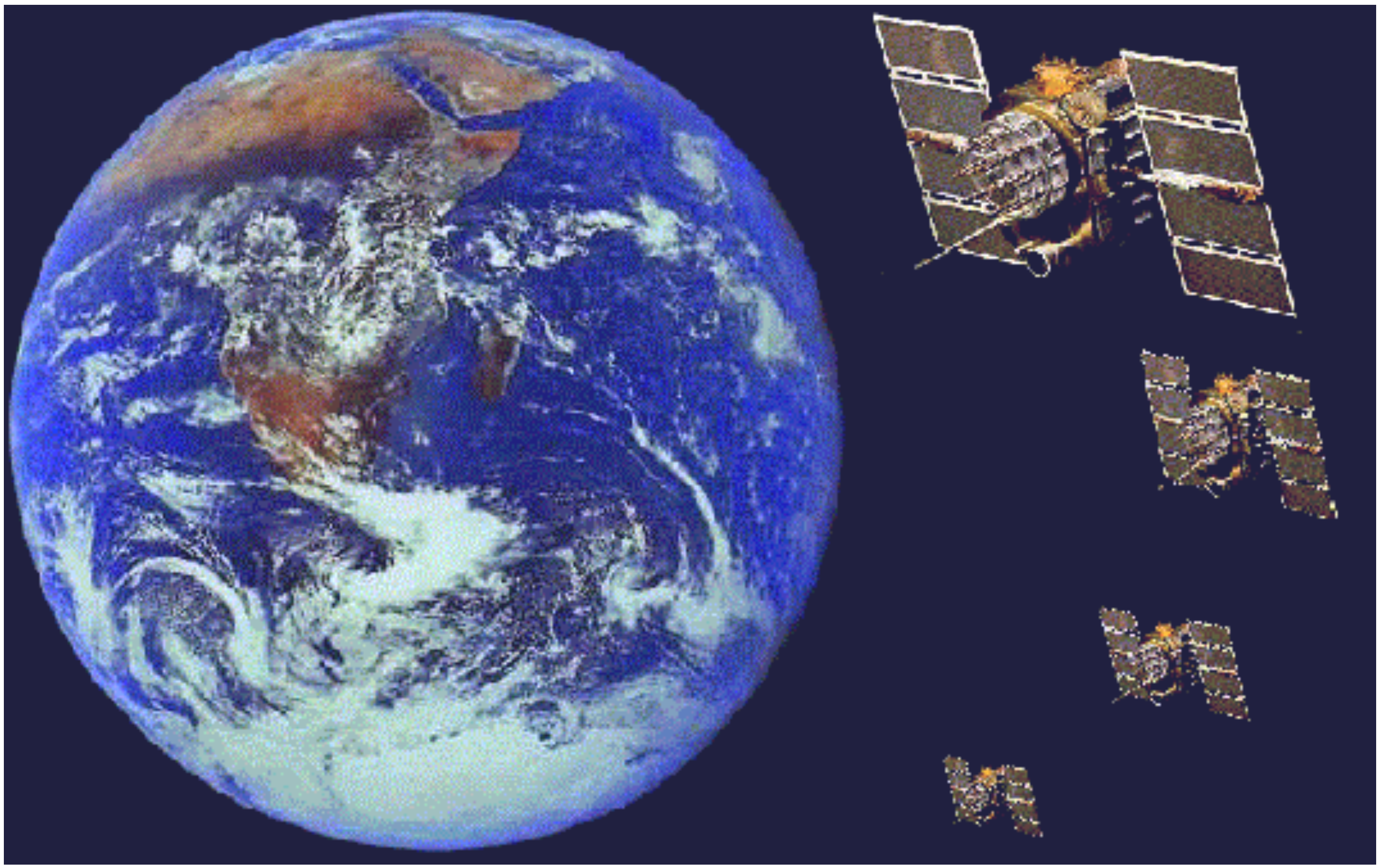
• Accuracy today < 1-2 cm.

Ultra-Rapid Orbit Quality



- Accuracy today < 5 cm.

GPS Data Analysis Sequence



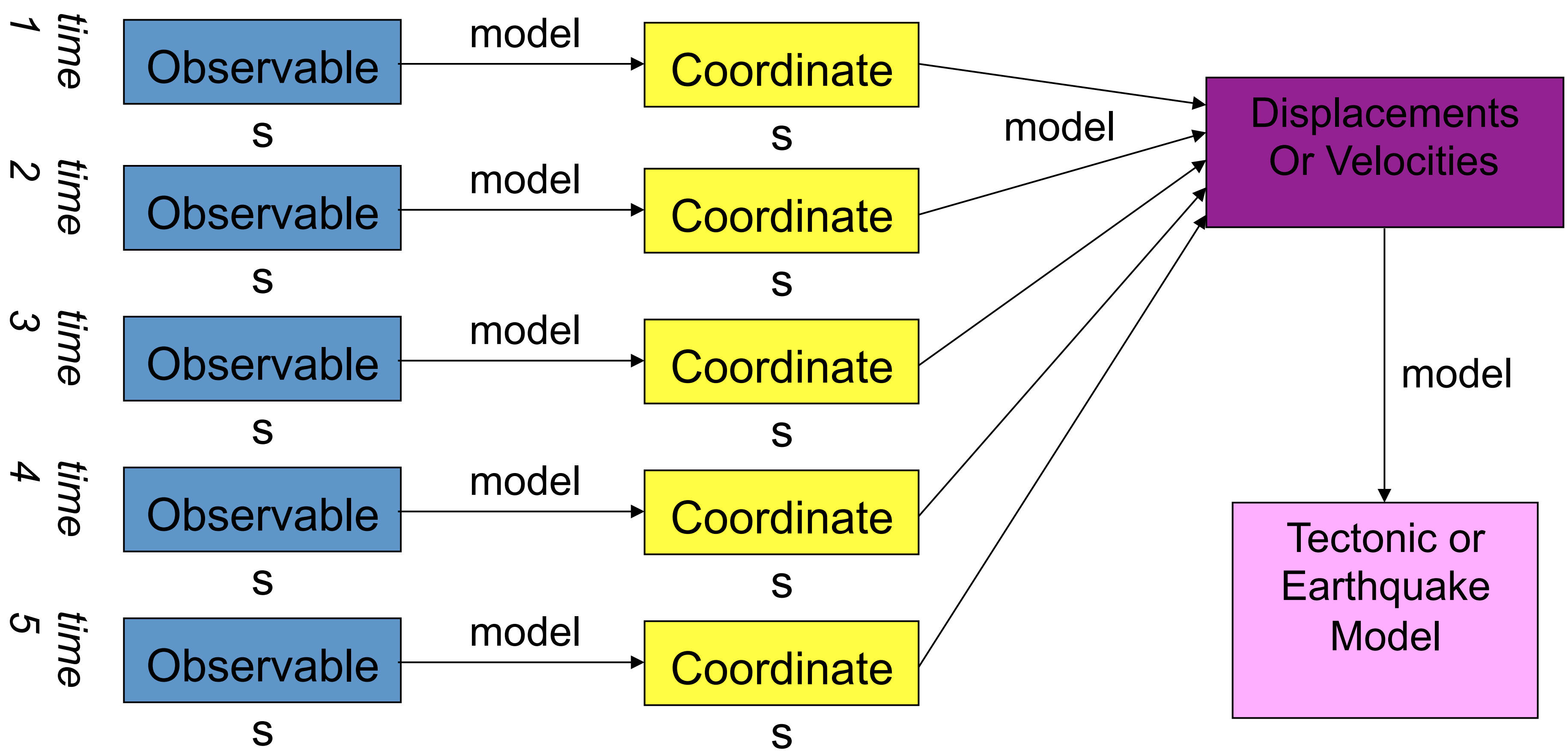
GPS Data Analysis Steps

1. Pre-processing (receiver-specific)
2. Data formatting (convert to internal)
3. Cycle Slip Detection and Fixing
4. Further Cycle Slip Detection and Fixing
5. Estimation (several options here)
6. Transformation into ITRF
7. Identify signal in time series
8. Model displacements, velocities
9. Write paper(s)
10. Become famous! (well, maybe not…)

5. Estimation

- Multi-Station
  - Combine data from several receivers
  - Estimate coordinates and other parameters for all receivers in one step
- Single-Station
  - If software estimates clocks, you can use a previous estimate of satellite clock errors to do single-station positioning
  - PPP (Precise Point Positioning)

Observation to Estimate to Quasi-Observation to …

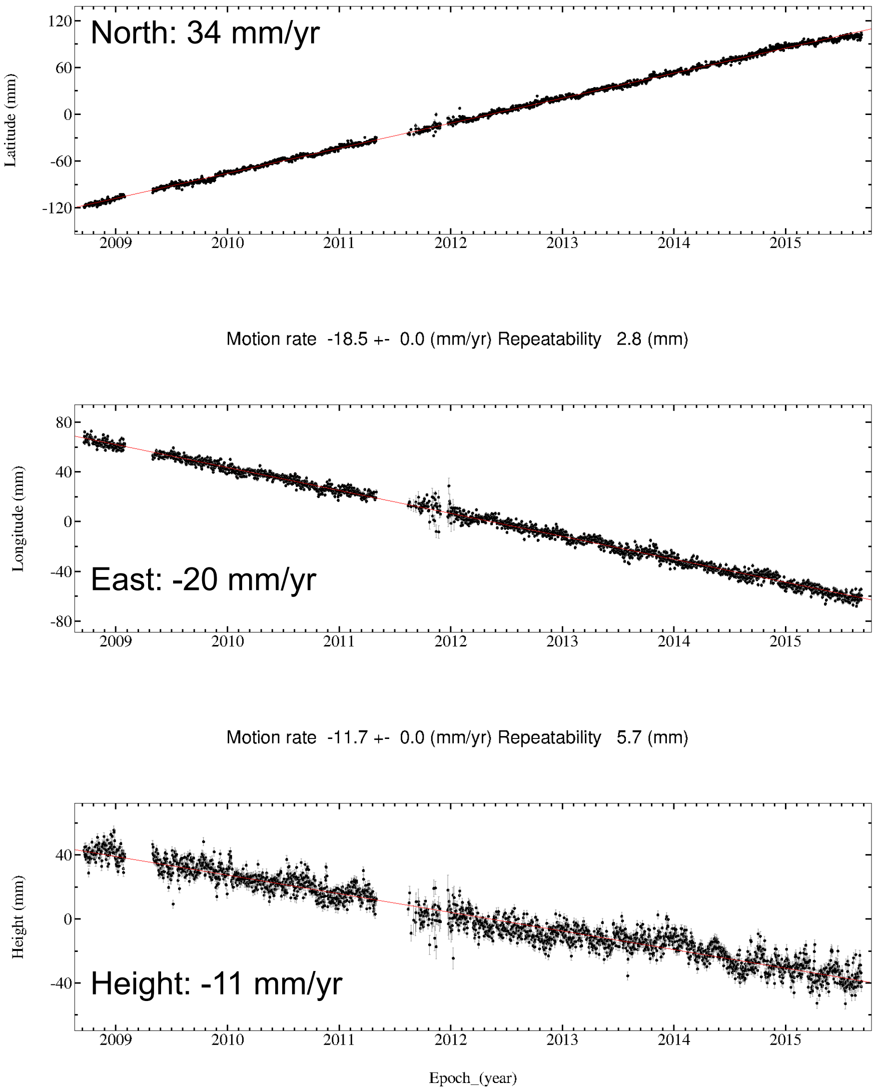


GPS Measurements

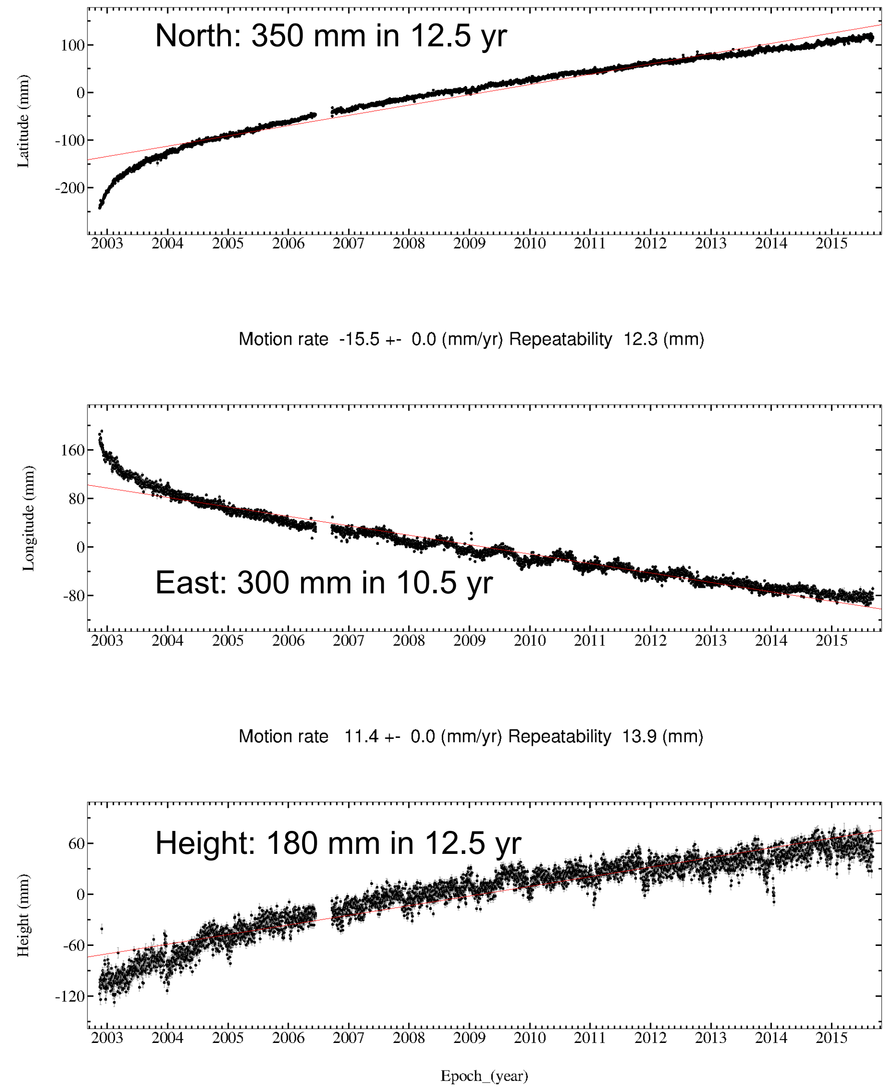

Continuous GPS Instrument

GPS Time Series

AC13 Chirikof Island

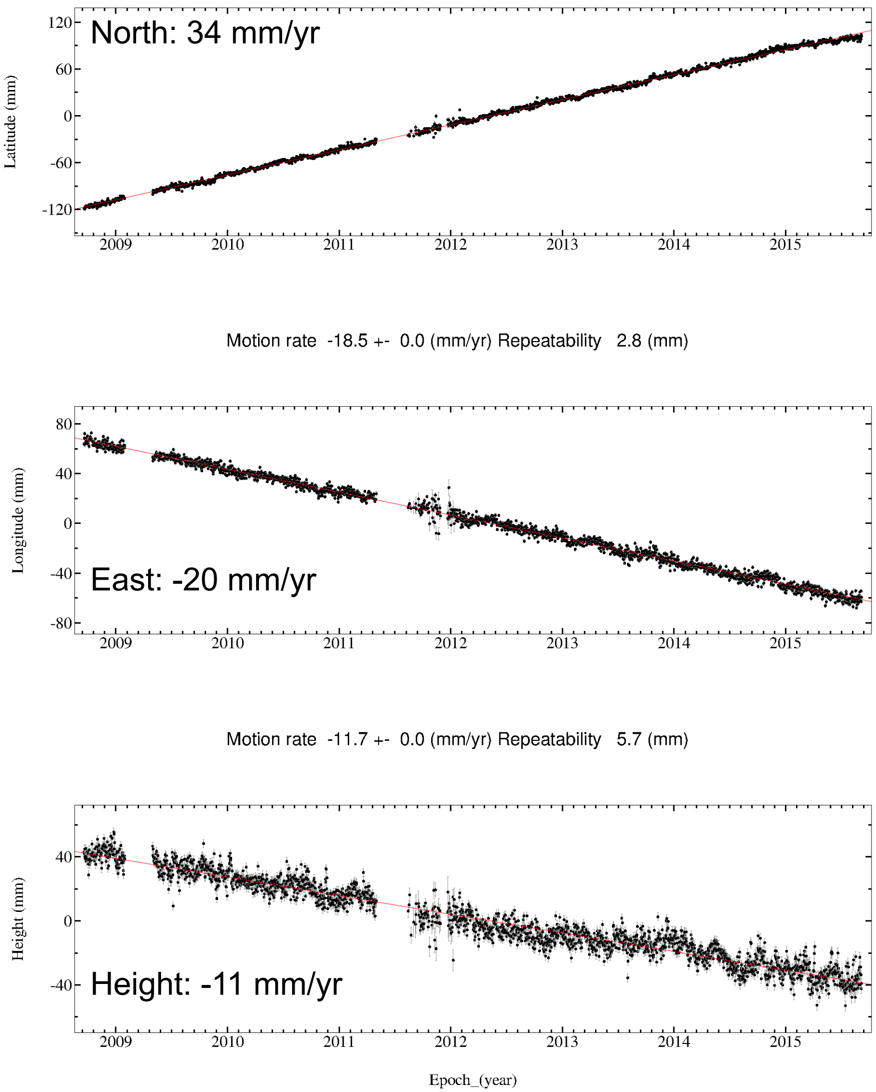


DRMC Drum View

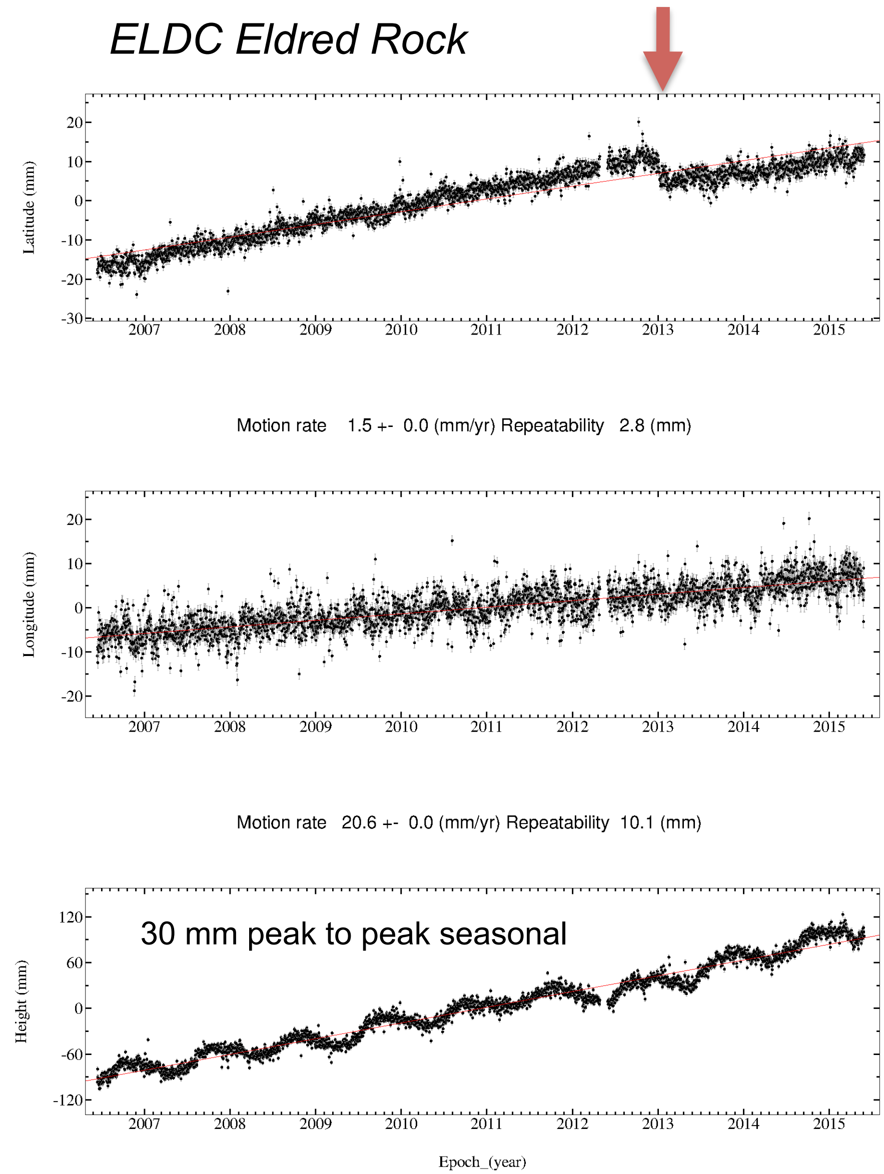


GPS Time Series

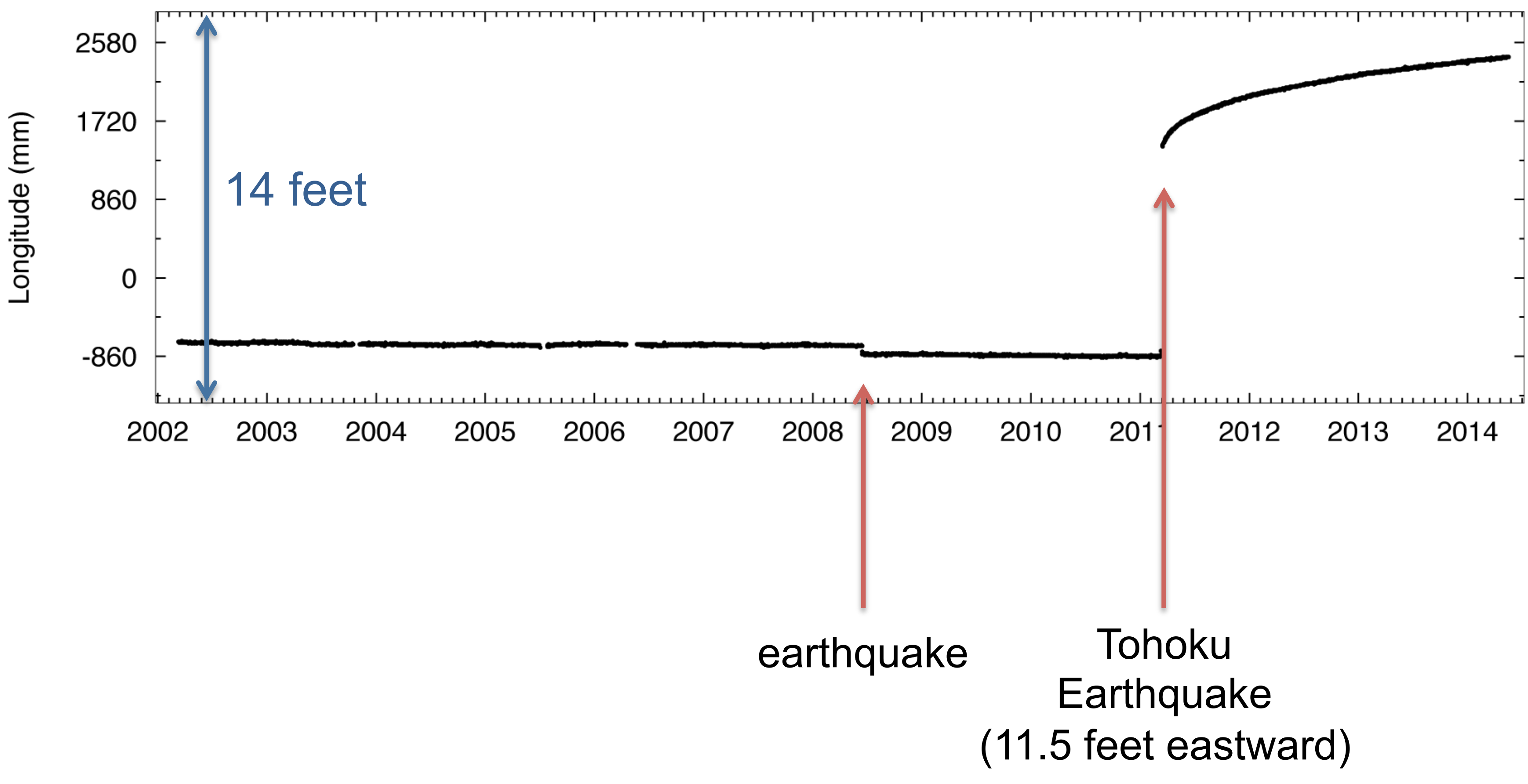
AC13 Chirikof Island



ELDC Eldred Rock



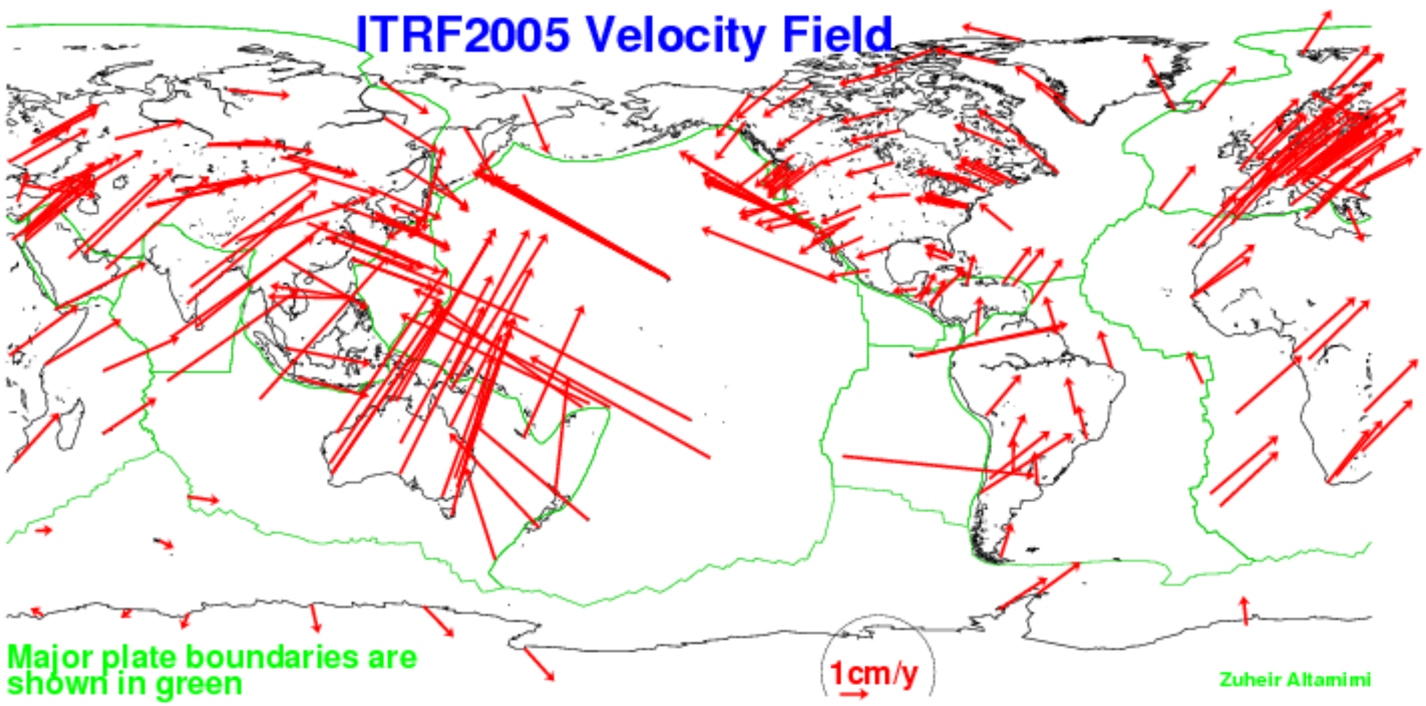
Great Earthquakes (Mizusawa, Japan)



Coordinates

- Need accurate coordinates for tracking sites, accounting for:
  - Site velocities
  - Any site offsets/discontinuities
- In practice, we can't have fully accurate (mm level) coordinates for all tracking sites. Two classes of sites:
  - "Frame sites" defining reference frame
  - Other sites used in solution, but positions estimated

Current Frame Velocities



Crust-based TRF

The instantaneous position of a point on Earth Crust at epoch t could be written as :

$$X(t) = X_0 + \dot{X}.(t - t_0) + \sum_i \Delta X_i(t)$$

X_0 : **point position at a reference epoch t_0**

$\dot{X}$: **point linear velocity**

$\Delta X_i(t)$: **high frequency time variations:**

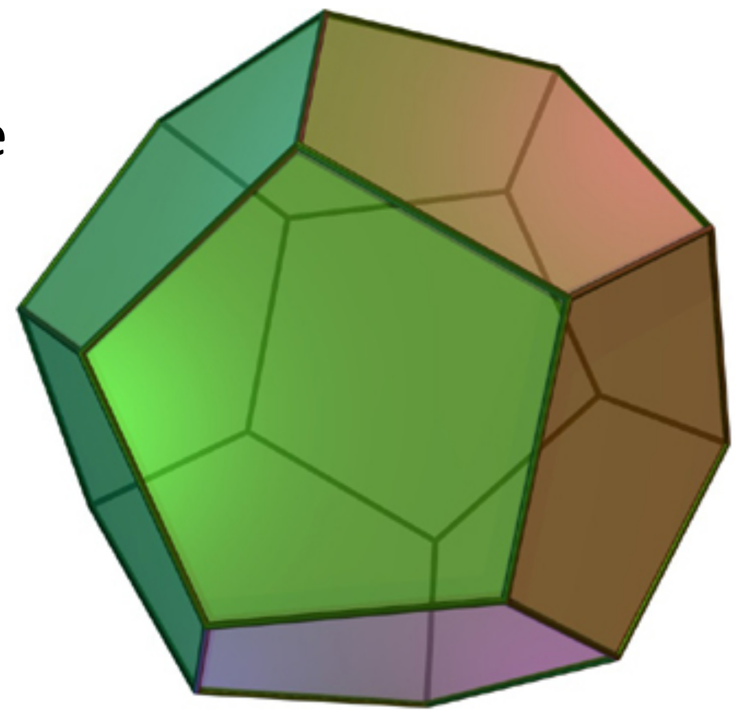
- **solid Earth tide**
- **ocean loading**
- **atmospheric or hydrologic loading**
- **geocenter motion**

Fixed (Fiducial) Sites

- One way to determine orbits is to constrain the coordinates of some (fiducial) sites
  - Frame sites constrained to 0.1 mm or similar
  - Other site coordinates estimated
- Satellite orbits estimated, along with the usual nuisance parameters
- Satellite clocks estimated for software that does not double-difference.

Frame-free (Free network) Solution

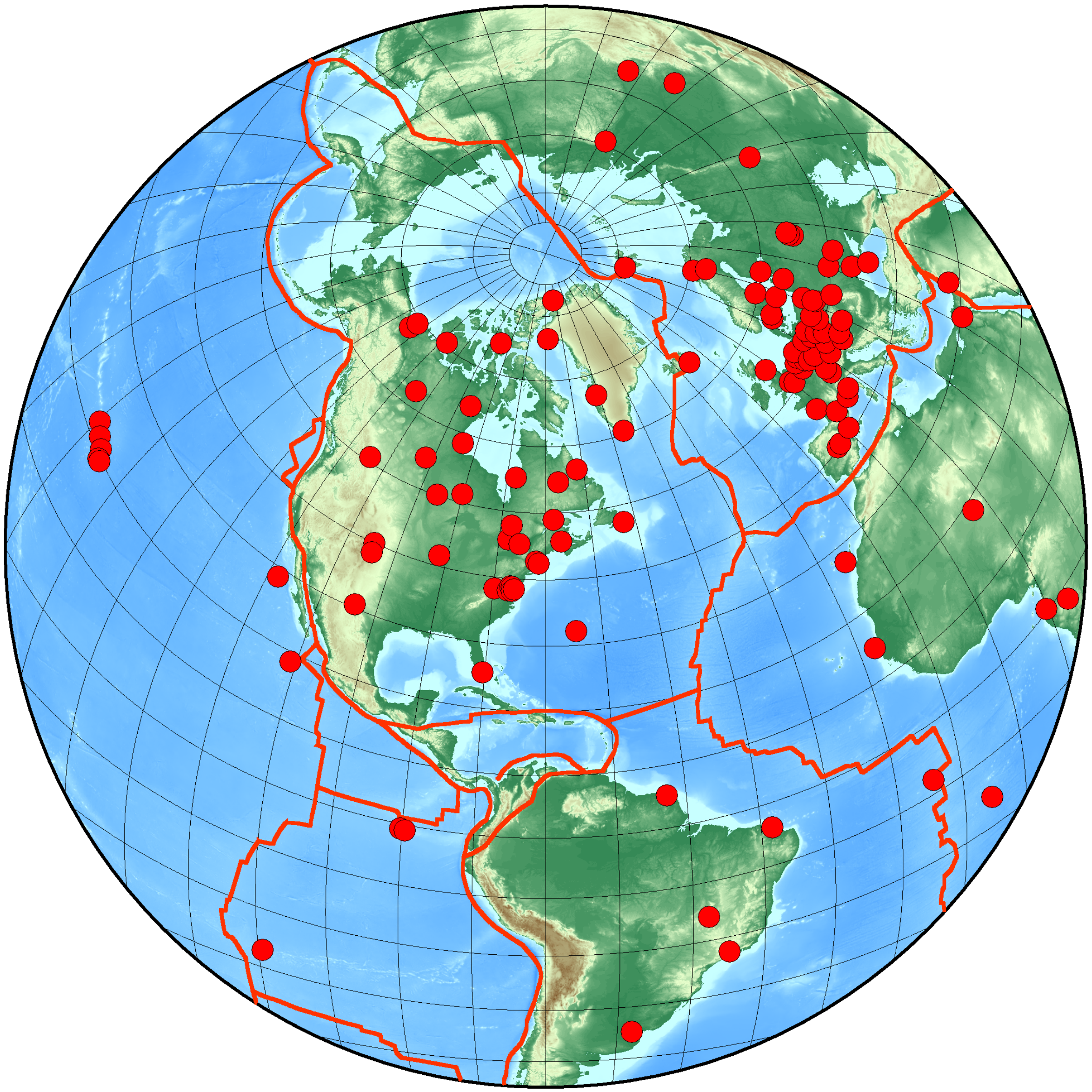
- Step 1: Free network solution
  - All site coordinates estimated without constraints
  - Reference frame indeterminate
  - ***Baseline lengths and geocentric heights* are still precisely and accurately estimated even when no coordinates are fixed.***
  - Network visualized as a polyhedron with sites at vertices
  - * Heights subject to some bias



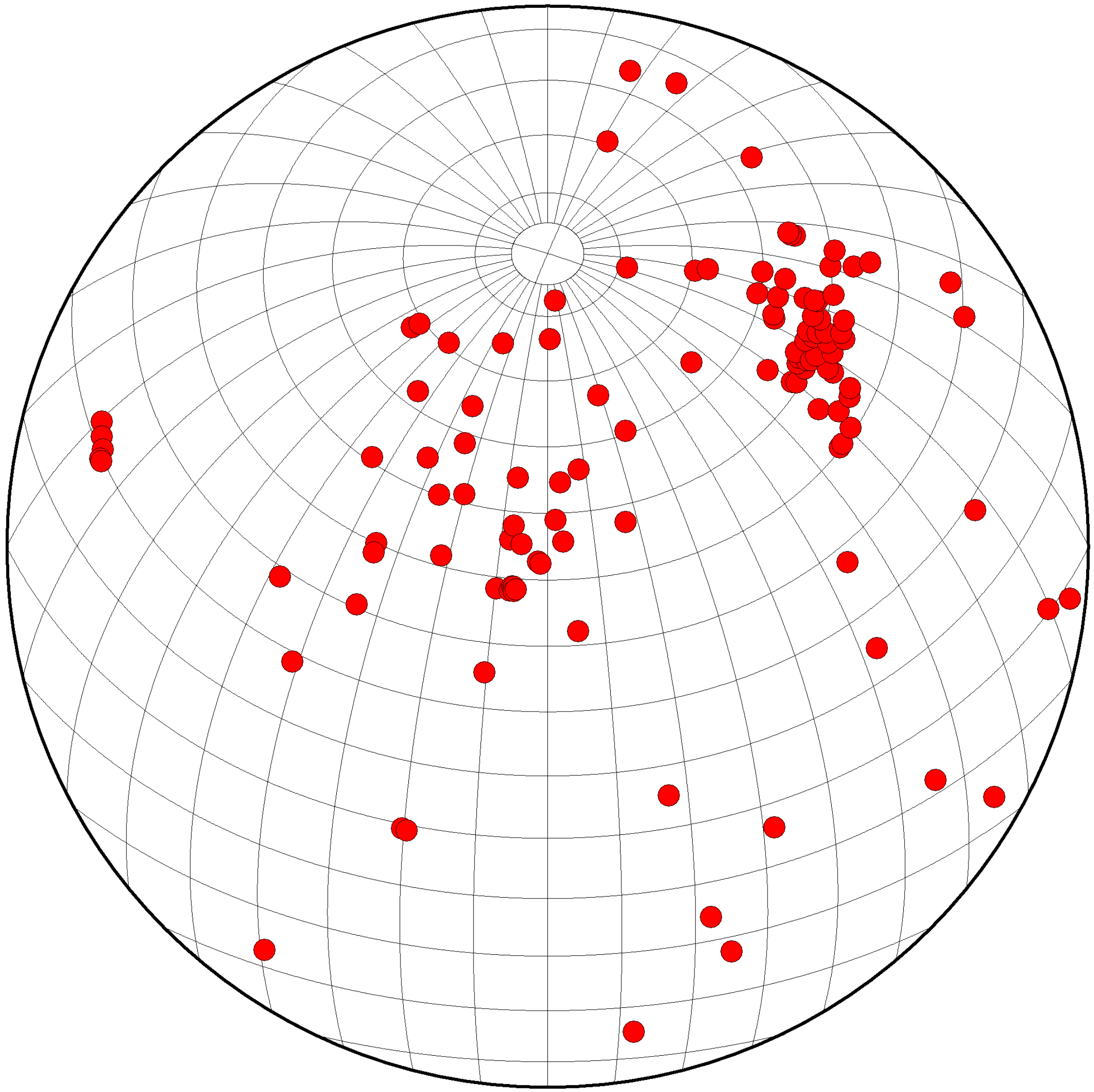
Frame-Free Orbits 2

- Step 2: Transform solution into desired frame
  - 3D reference frame requires 7 parameters to be specified
    - Origin (3), orientation of axes (3), scale (1)
  - Use reference frame model to compute coordinates for frame sites on day in question
  - Compute a frame transformation to transform the indeterminate frame of the solution to the known frame.

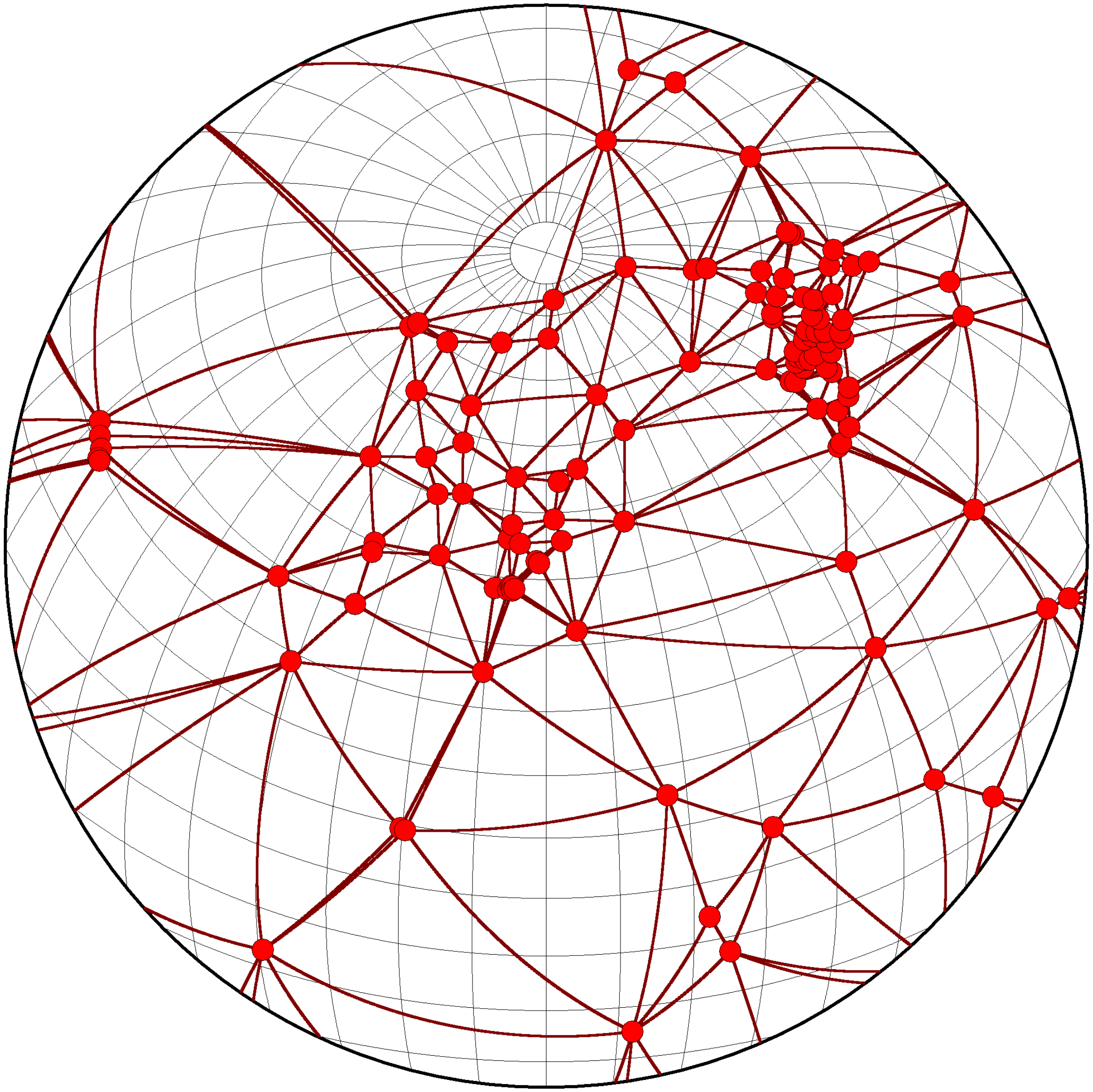
Global Polyhedron of GPS Sites



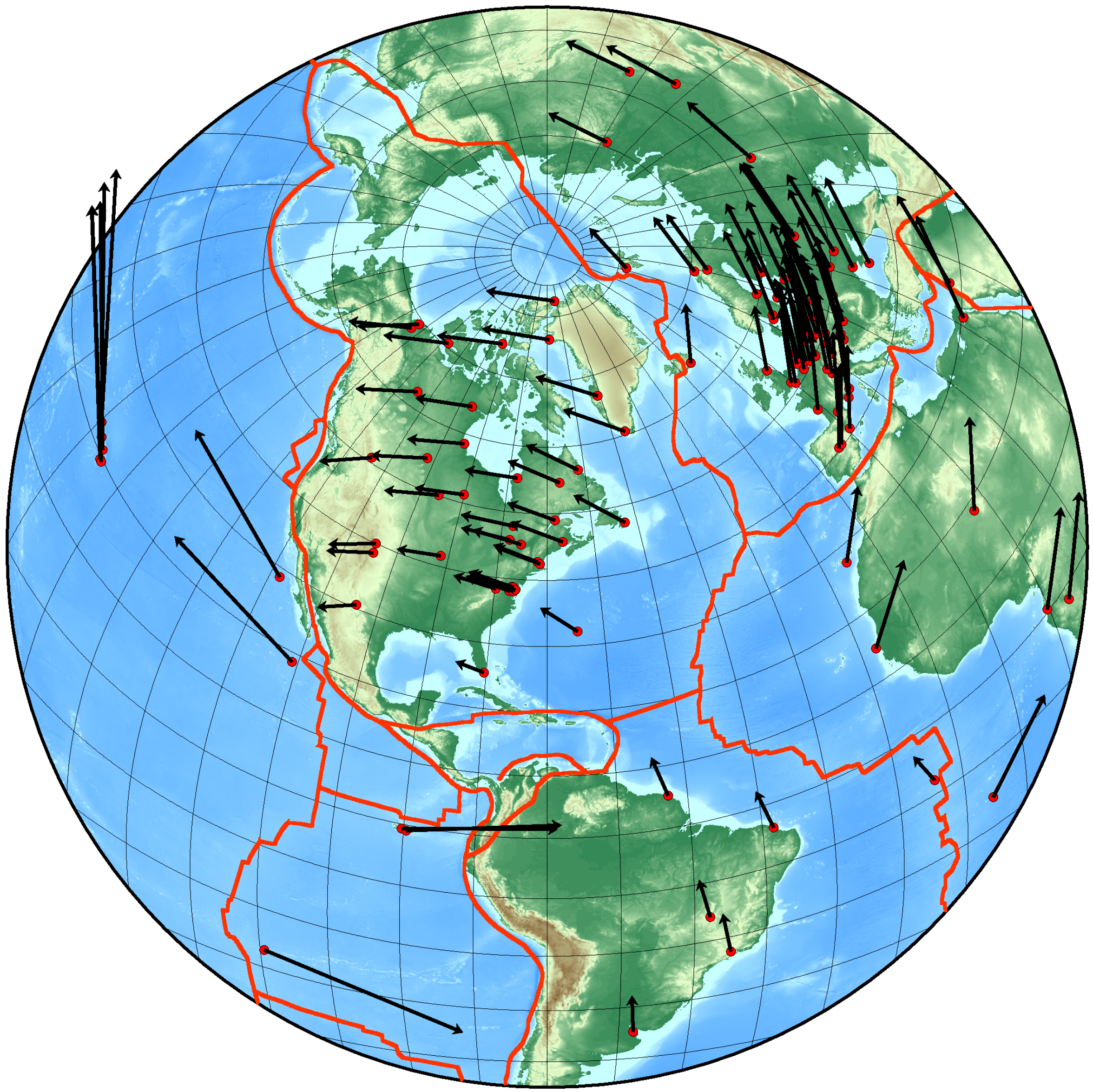
Global Polyhedron of GPS Sites



Global Polyhedron of GPS Sites

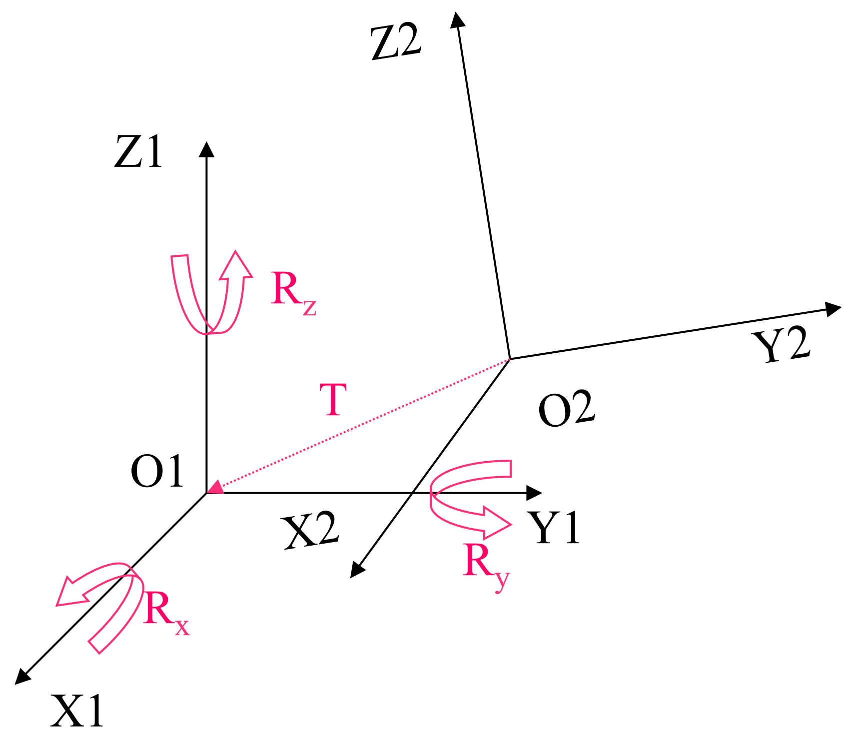


Global Polyhedron of GPS Sites



Reference Frame Transformations

- 7 parameters
  - Three translations
  - Three rotations
  - One scale change
- This 7 parameter transformation is called a Helmert Transformation
- This equation assumes rotations and scale changes are small



$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_2 = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_1 + \begin{pmatrix} T_x \\ T_y \\ T_z \end{pmatrix} + \begin{pmatrix} D & -R_z & R_y \\ R_z & D & -R_x \\ -R_y & R_x & D \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_1$$

Comparison of Two TRFs

Estimation of the Transformation parameters between the Two

$$X_2 = X_1 + T + DX_1 + RX_1$$

or

$$X_2 = X_1 + A\theta$$

$$\theta = \begin{pmatrix} T1 \\ T2 \\ T3 \\ D \\ R1 \\ R2 \\ R3 \end{pmatrix}$$

$$A = \begin{pmatrix} 1 & 0 & 0 & x & 0 & z & -y \\ 0 & 1 & 0 & y & -z & 0 & x \\ 0 & 0 & 1 & z & y & -x & 0 \end{pmatrix}$$

θ is solved for using Least Squares adjustment

$$\theta = (A^T W A)^{-1} A^T W (X_2 - X_1)$$

And in case of velocities

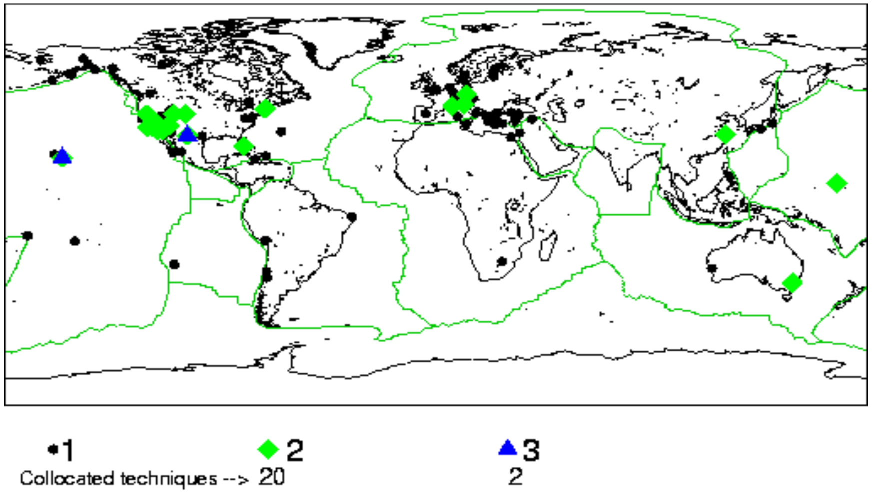
$$\dot{\theta} = (A^T W A)^{-1} A^T W (\dot{X}_2 - \dot{X}_1)$$

ITRF Frame Versions

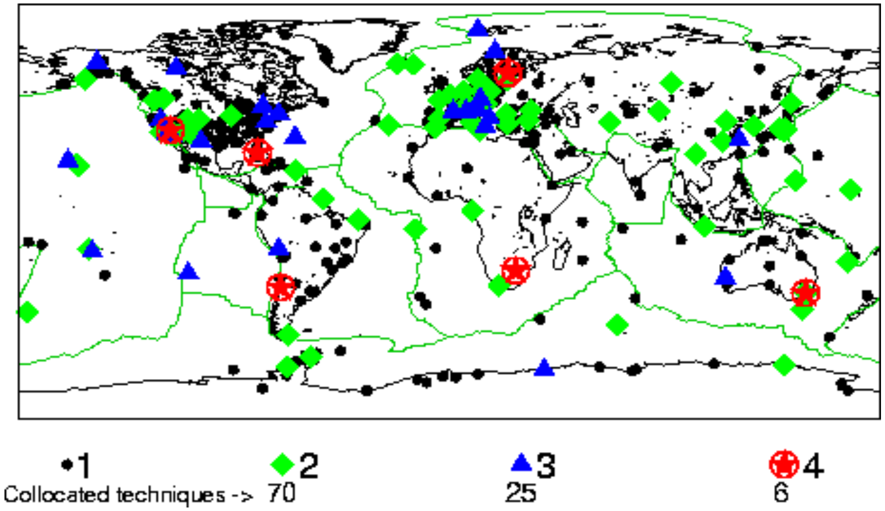
- Present frame is ITRF2008. Based on data collected up through 2009.0 (2009.5 for GPS)
  - Positions, velocities and offsets at various times based on combined weekly GPS, VLBI and SLR time series
- Past versions of ITRF
  - ITRF92, ITRF93 (very bad), ITRF94, ITRF97, ITRF2000, ITRF2005
- All attempt to realize the same underlying frame, each one better than the last (except 93)
  - Transformations between frame parameters are provided

ITRF Network Evolution

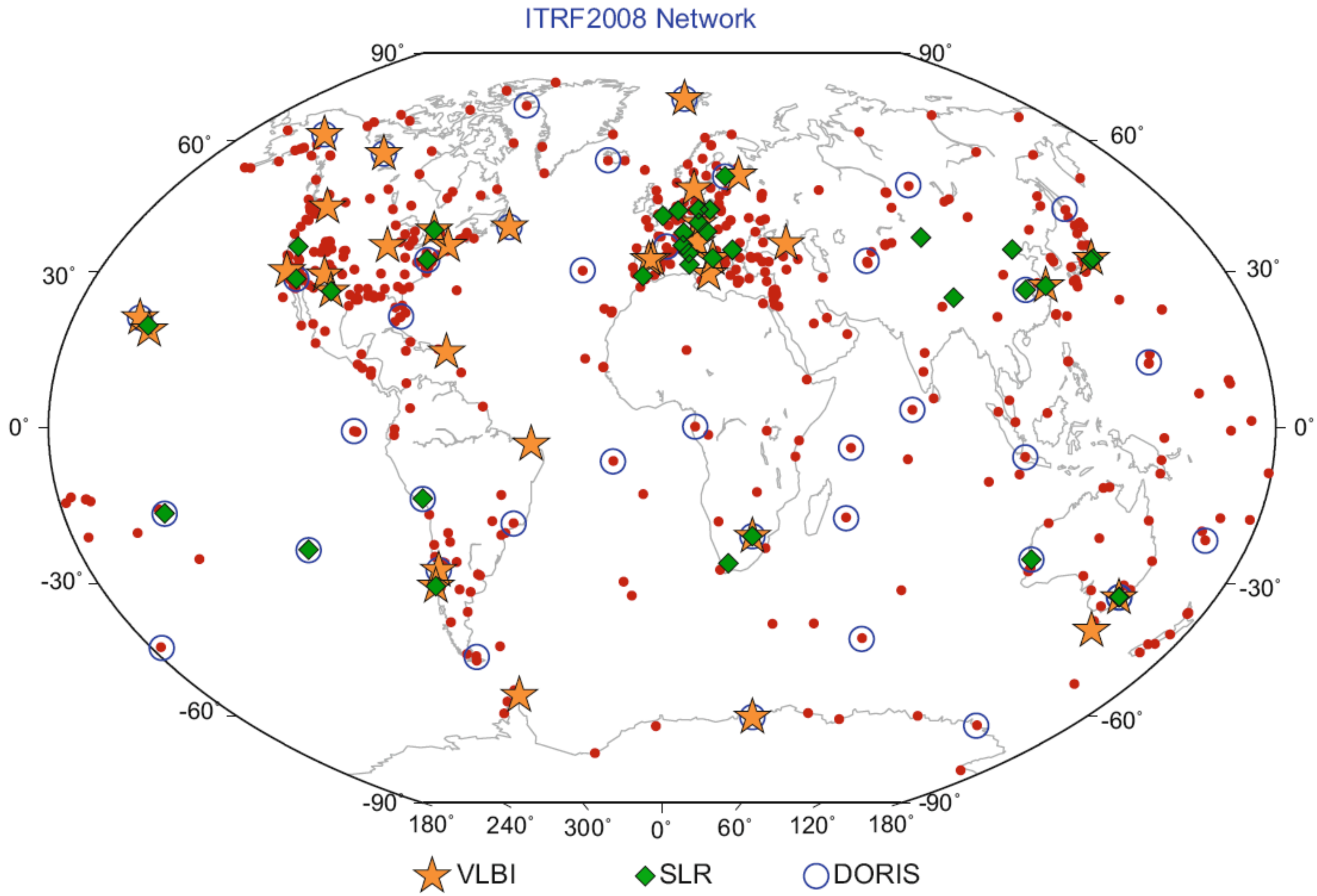
ITRF88



ITRF2000

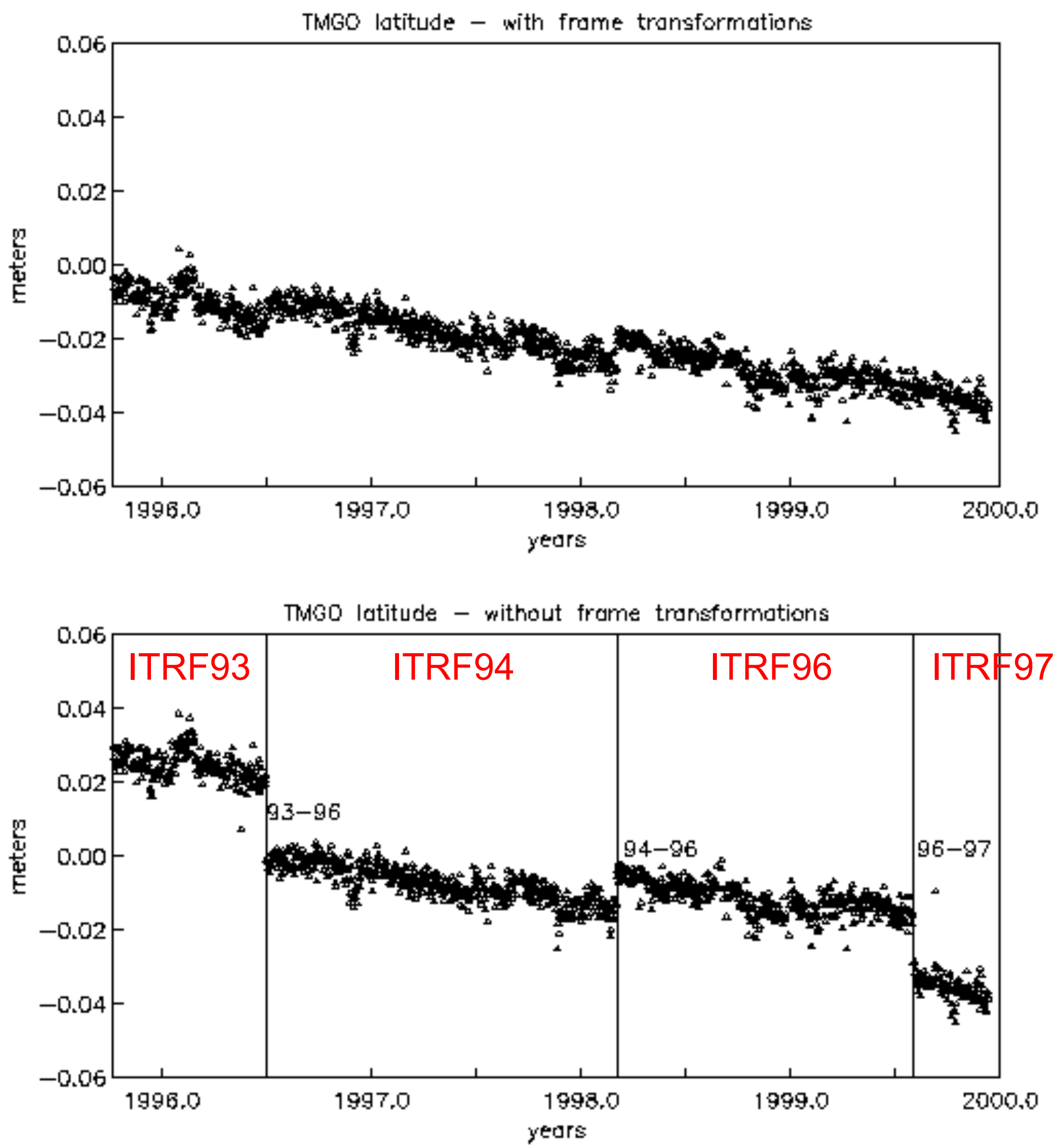


ITRF2008



ITRF2008 Network
90˚
90˚
60˚
60˚
30˚
30˚
0˚
0˚
-30˚
-30˚
-60
-60˚
-90
-90˚
180˚
240˚
300˚
0˚
60˚
120˚
180˚
VLBI
SLR
DORIS

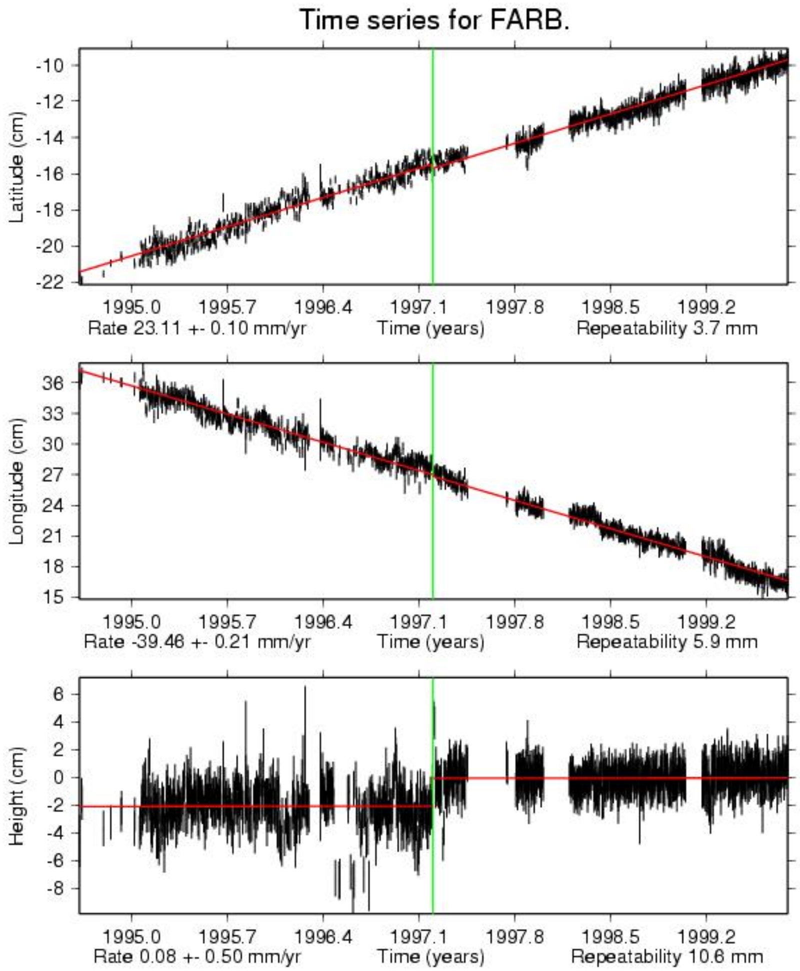
Old ITRFs had more inconsistencies



Putting Yourself in ITRF

- IGS satellite orbits are nominally in ITRF, but you still need to define coordinates
- Start with a network solution that includes several sites in the ITRF
- Calculate the ITRF positions on the date of your data from ITRF model
- Estimate a transformation of your solution to minimize disagreement with ITRF
- Can fix a site instead, but ***this is bad practice***

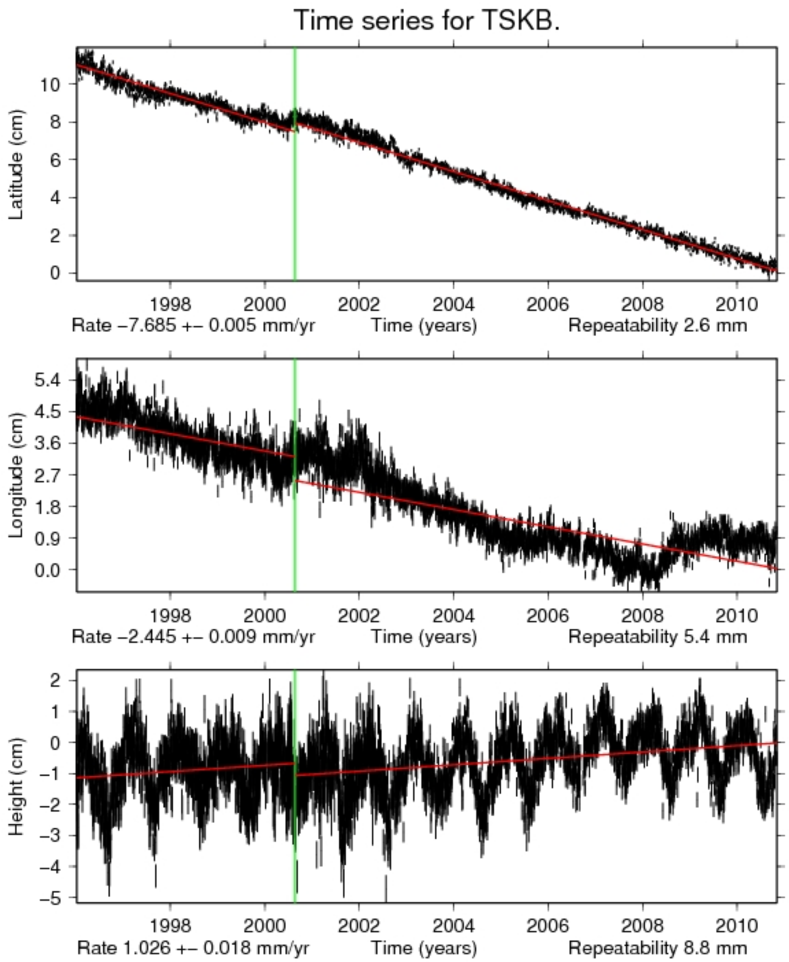
Repeated Observations Give Time Series



- Each daily position in ITRF one point in time
- This time series shows an offset from equipment change
- Shows motion in ITRF
- Can be rotated into a frame relative to any plate if plate motions known in ITRF

Mike Heflin, JPL, http://sideshow.jpl.nasa.gov/mbh/series.html

Common Features of Continuous GPS Time Series



- Daily position noise is NOT WHITE (random, uncorrelated)
- Annual and semi-annual periodic signals
  - Seasonal loading
  - Aliasing of ocean tidal loading
- Correlation of noise over several days
  - Tropospheric errors

Time Series Properties

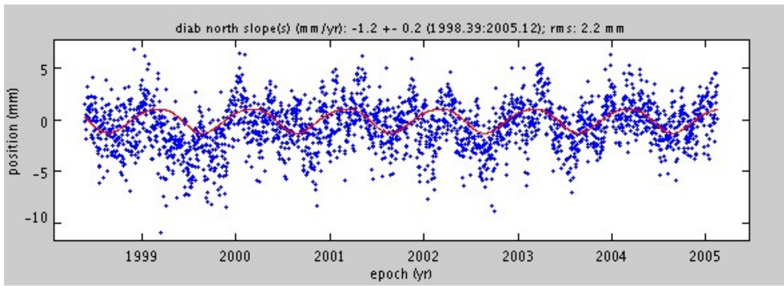
- GPS noise spectrum very complex
  - (seconds) multipath
  - (hours) troposphere, satellite geometry, tidal loading
  - (days) troposphere
  - (months to years) seasonal and other loading
  - (years to decades) monument instability
- Must be understood to know precision of measurements for tectonics
- Critical to distinguish time-varying geologic signal from noise.

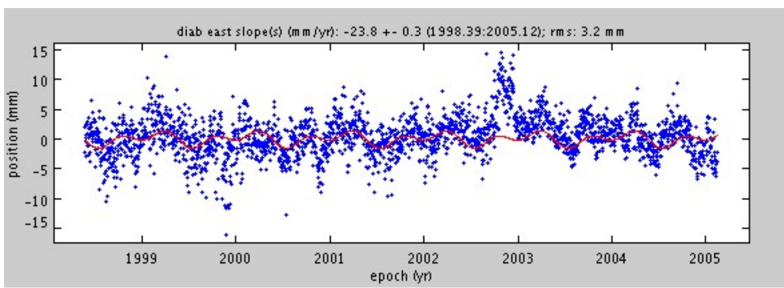
"Common Mode" Noise

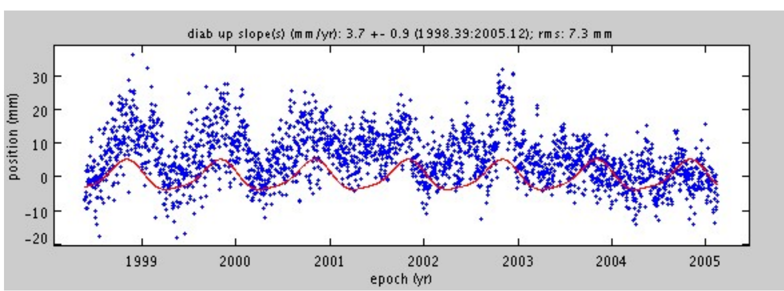
- Common Mode error
  - In a dense network, you can frequently see deviations from a linear trend that are the same or similar at several sites.
- Probably caused by errors in reference frame definition, orbit mismodeling, etc.
- Filtering devised to remove this
  - Stack residuals at many sites to emphasize common elements
  - Subtract stack of common mode residuals from original time series
  - WARNING: This can subtract signal as well as noise
  - WARNING: This can subtly shift reference frame
  - WARNING: One bad station can corrupt all time series

Common-Mode Filtering

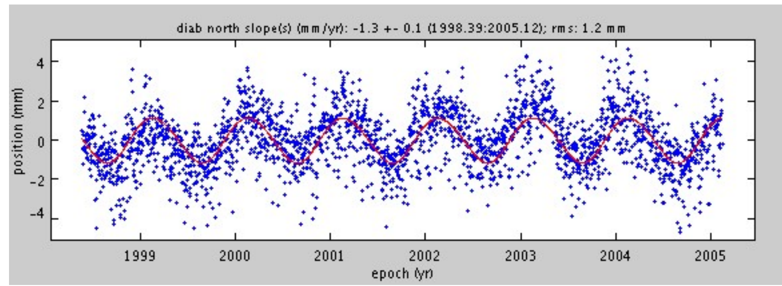
DIAB – unfiltered

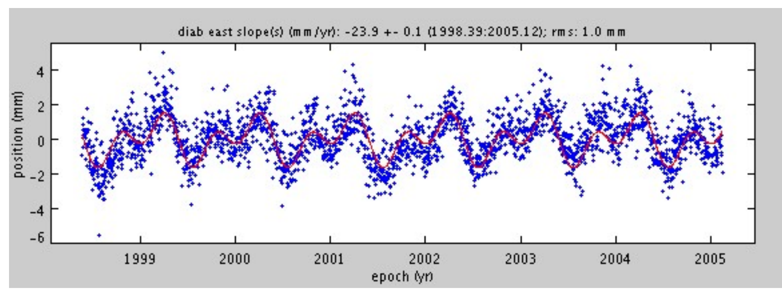


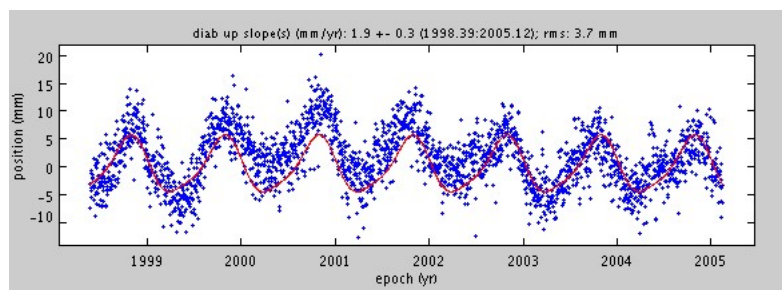




DIAB – filtered



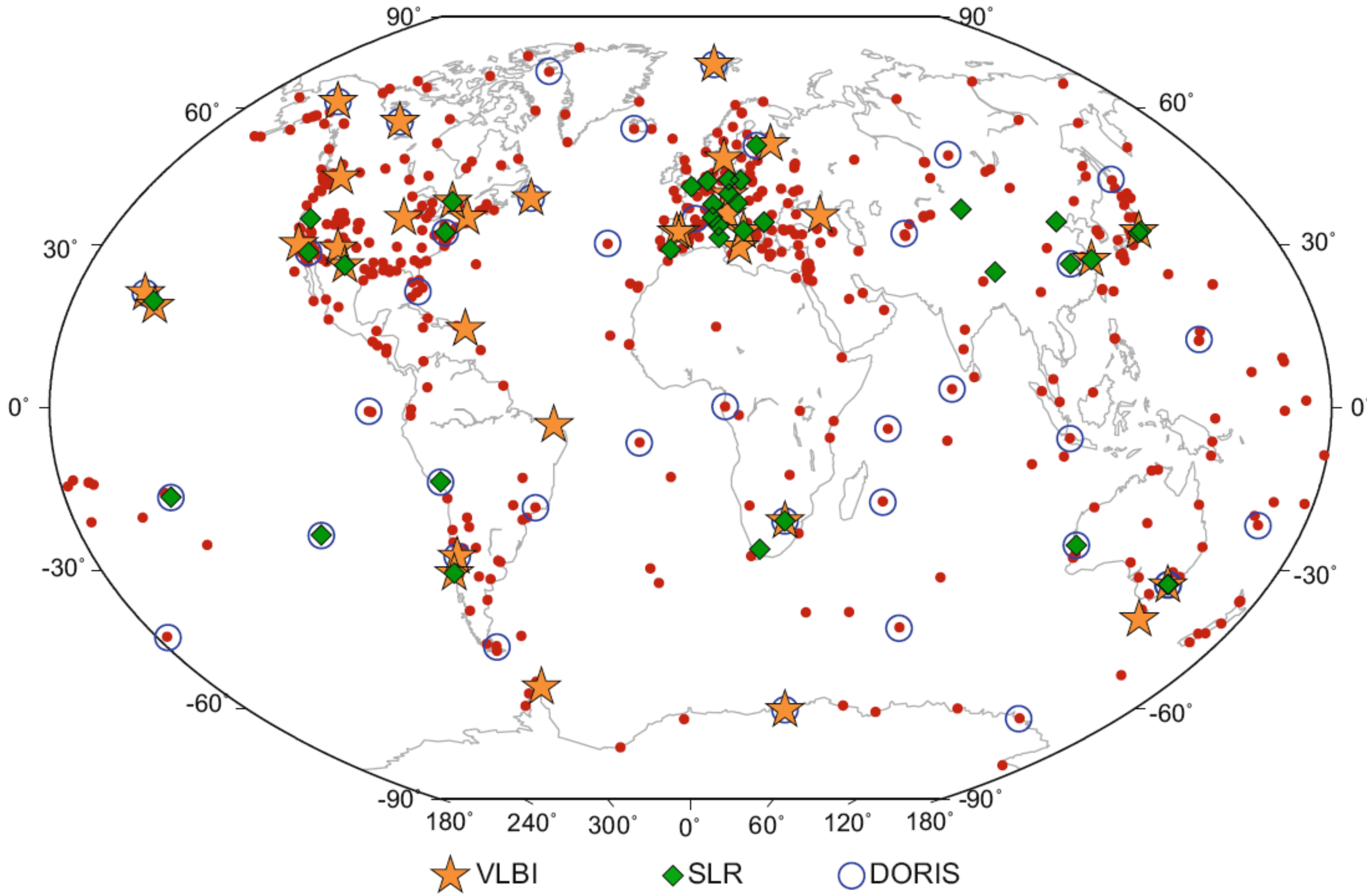




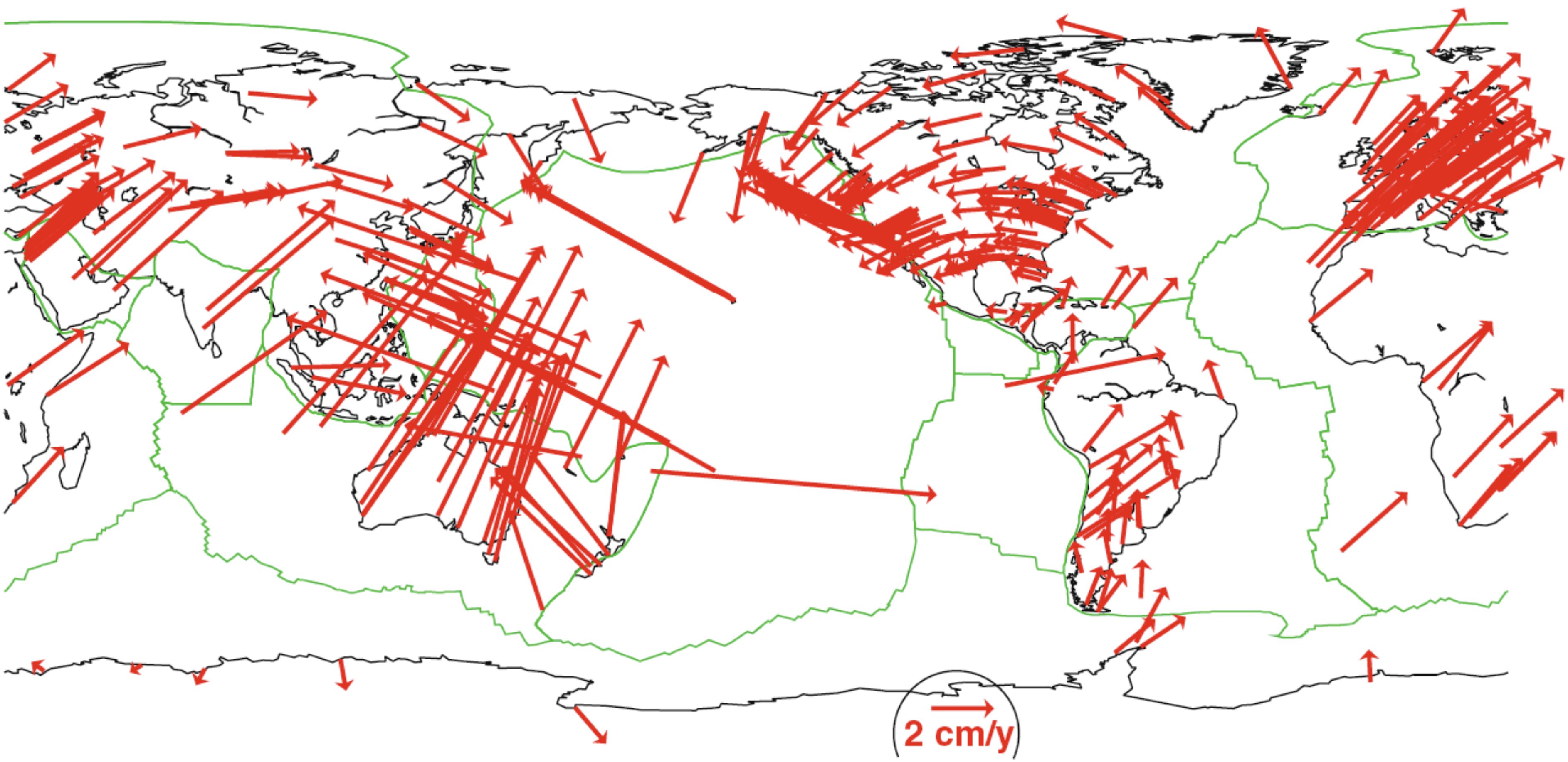
Velocity Reference

- To know what is moving, you must know what is fixed (zero motion)
- But all plates are moving
- Solution is to define plates within ITRF and choose a global rotation rate that makes plate rotations consistent with the NUVEL1A-NNR plate model
- Result is set of positions and velocities

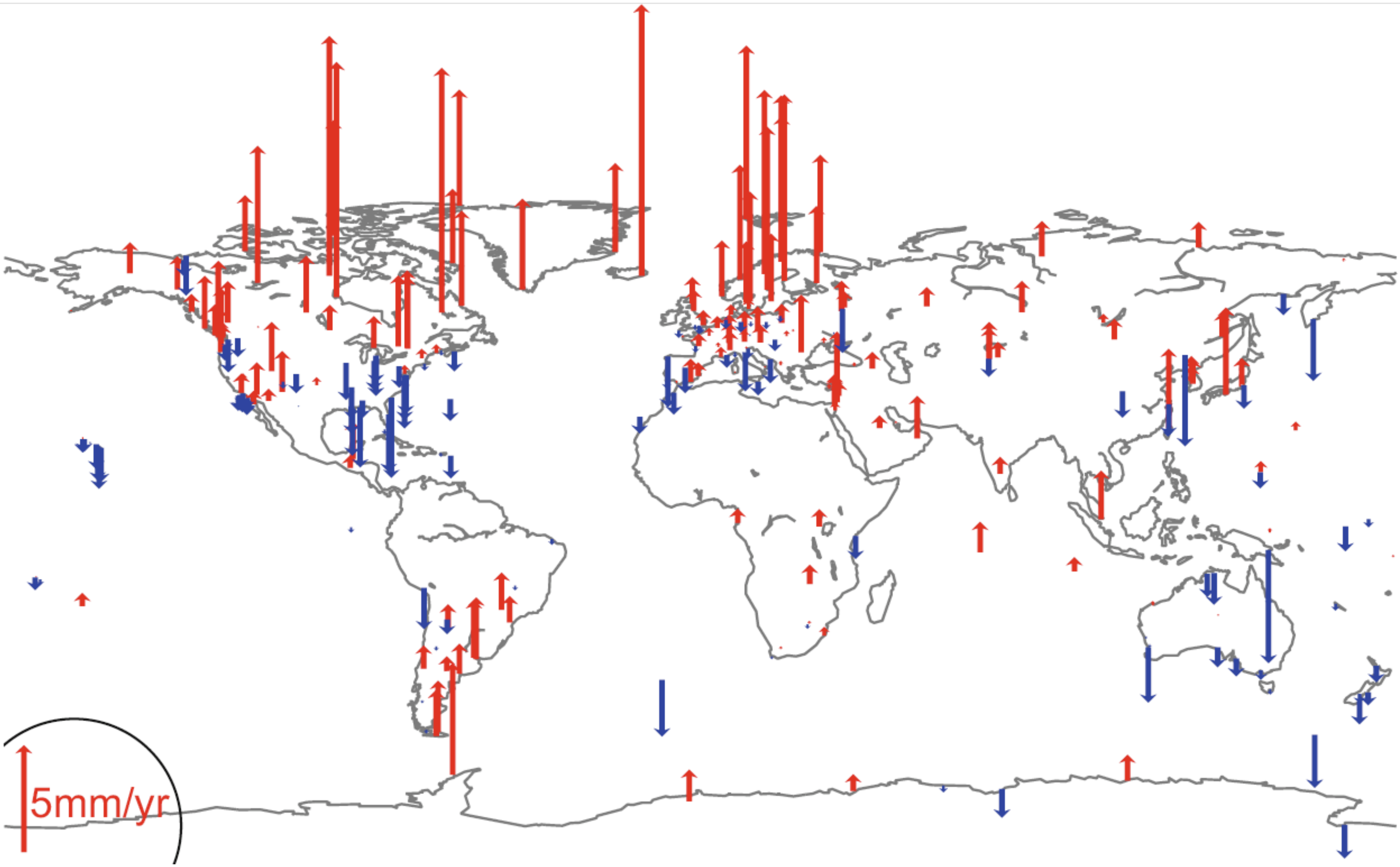
ITRF2008 Network



ITRF2008 horizontal velocities



ITRF2008 vertical site velocities

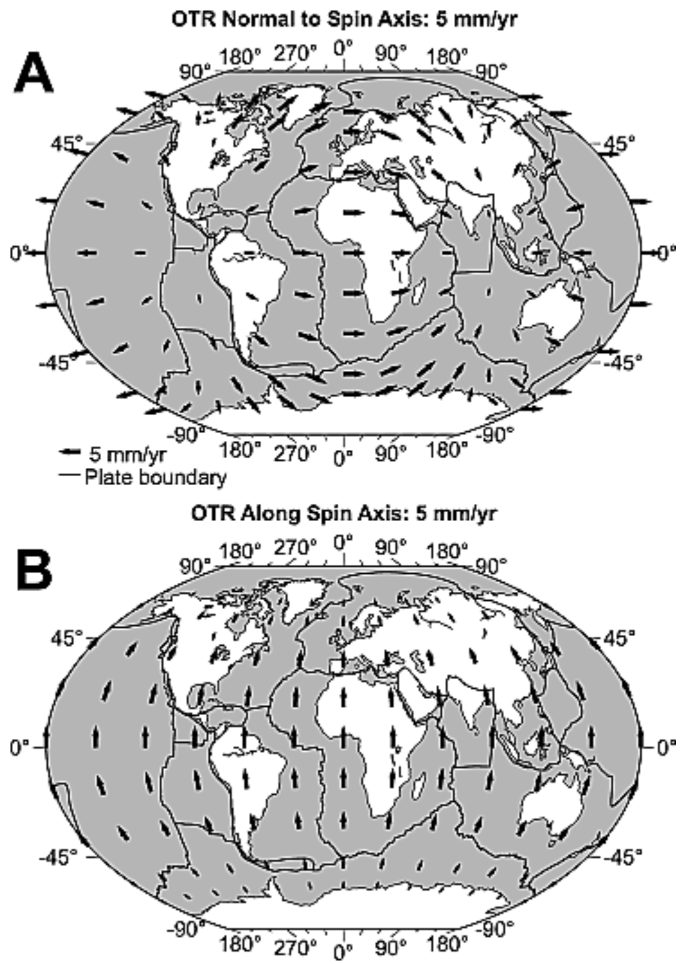


Geocenter Motion

Translational motion of the tracking network due to variation of the CoM position induced by mass redistribution

- Likely involves periodic and secular components
- Satellite techniques have limited abilities to accurately measure this motion
- TRF origin from satellite techniques coincides with the CoM averaged over the period of the used observations

Impact of Geocenter Error



- Suppose our frame has an error in the geocenter. How are site velocities affected?
  - Such an error produces a combination of vertical and horizontal motion, depending on site location.
  - The error affects each plate differently
  - Impact on angular velocity depends on site distribution.