Reference Frames: Definitions, Realizations, and Impacts

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Overview

- Reference frame definition (often called reference frame system, RFS)
  - Origin: Center of mass, Center of figure, Center of network
  - Orientation: Direction of axes: Aligned to the rotation axis (moves too much); moments of inertia (move too much)
    - Plates rotate, so plate choice affects orientation.
  - Scale: This is optional (length is defined by the speed of light) but often included and has a direct impact on height estimates. Uncertainty in GNSS transmit antenna patterns introduces scale uncertainties.
- Realization: How to achieve the RFS practically.
- Impacts: How do reference frame realizations affect the interpretation of results

Reference Frame Definitions

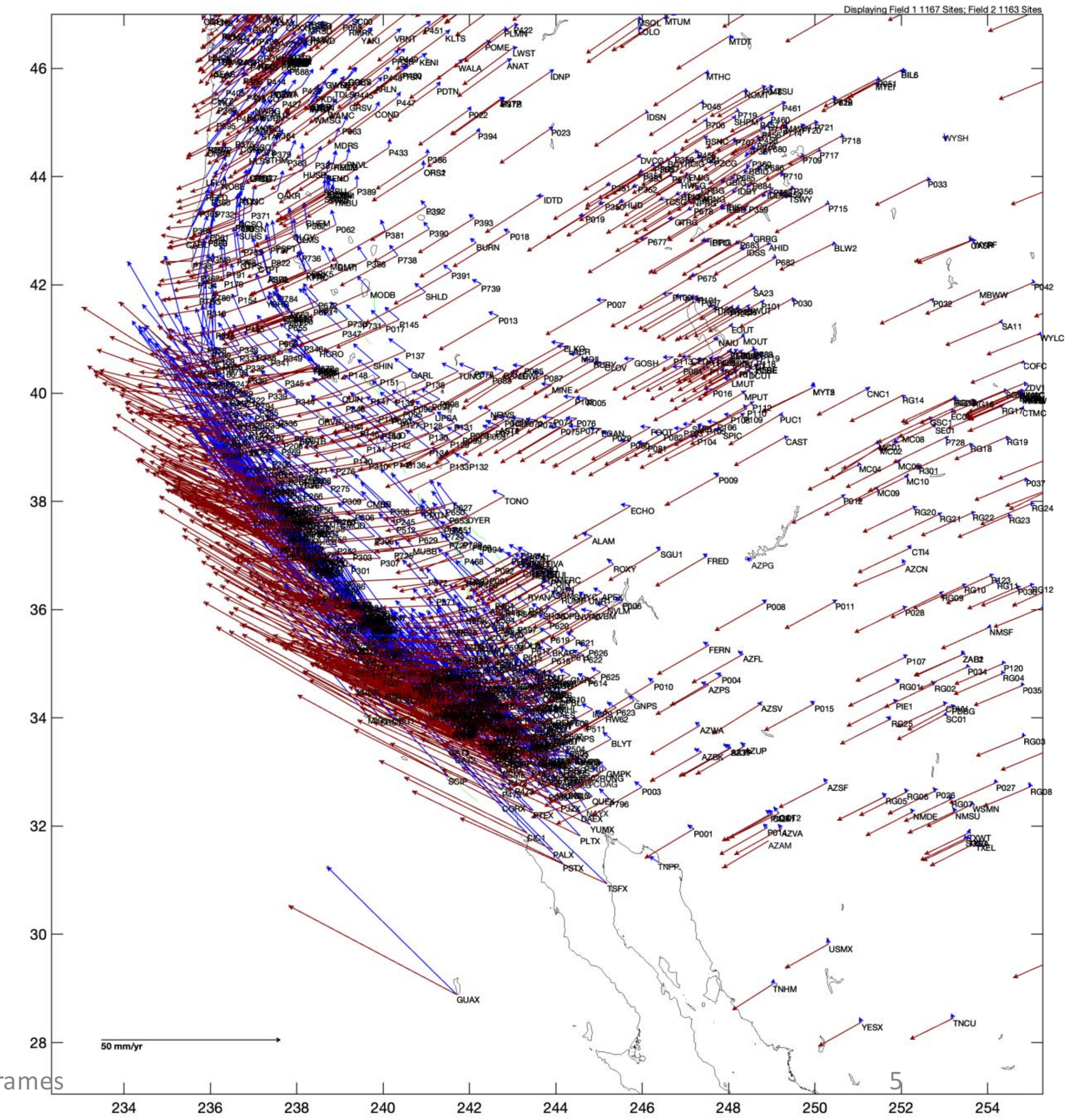
- One concept of a reference frame is that all motions that are understood are included in the reference frame definition so that deviations of motion from the reference frame reveal new physics about Earth.
  - Caveat: Mis-modeling in the reference frame can also result in deviations (current issue with including loading and seasonal terms in reference frame).
  - Models are also implicit in the frame definition e.g., For ITRF2020, new pole-tide model, new satellite phase center model).
- Origin: The center of mass for global systems has issues when masses move; site positions for "unaffected" sites change due to the motion of the center of mass (CoM) with respect to the center of figure (CoF).
- Orientation: No-Net-Rotation (NNR) concept uses mathematically defined rotation rate "averaged" over plates, but specific plate references (e.g., North America) often make more sense. For geodynamics, a hot-spot reference frame may be more useful).
  - All the international terrestrial reference frames (ITRF) are NNR frames , although plate rotation rates are estimated shortly after the ITRF is released.
- Scale: Direct effect on height estimates and rates. Always check to see how scale is treated, especially for GNSS time series.

Frame realization

- Minimum constraint methods
    - Estimate rotation, translation (and maybe scale) to align to coordinates and/or velocities of a set of sites. Choices here are:
        - Specific sites (hierarchical lists) to be used for estimates
        - Positions, velocities, and possibly extended time evolution models (e.g., post-seismic parameterizations, seasonal signals, offsets, etc.) of the "reference frame sites ."
        - Weight to be given to the heights when estimating transformation parameters (e.g., in CoF frame, loading affects the height primarily)
    - Preferred method because when scale not estimated, no changes to strain field except for rotational component)
- Constraints on site position and velocities. Possible distortions (and induced strains) if the coordinate model is incorrect (e.g., loading effects)
- Fix coordinates of a minimum number of sites. For translation only, 1 site; for rotation and translations, latitudes and longitudes of 3 sites (fixing all coordinate components would over constrain). Height of 1 site if scale included.

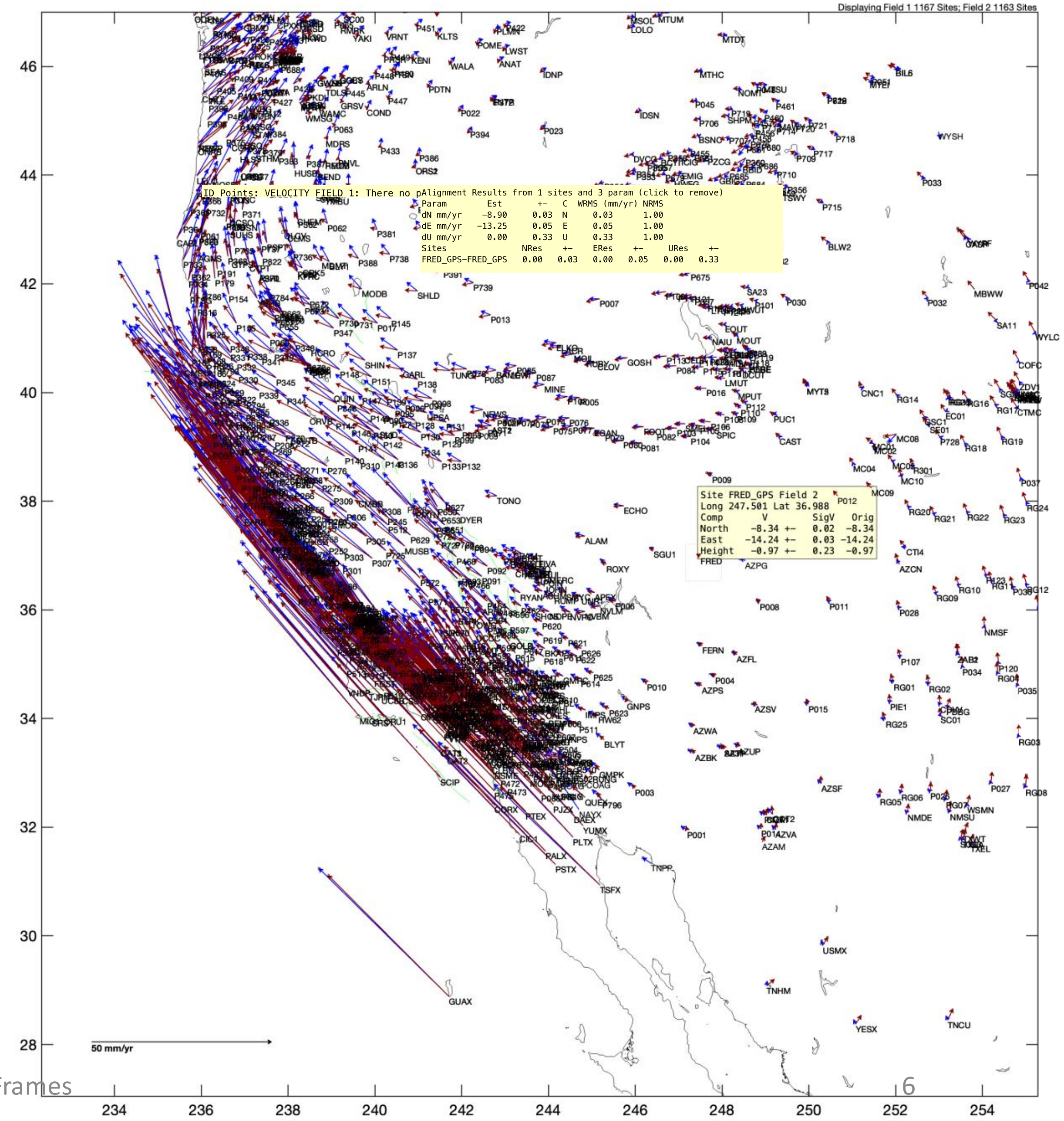
Impacts: Velocity fields

- Comparison of North America (NAM) fixed versus NNR frame for California region.
- Blue vectors are North America fixed, Red vector NNR frame.
- Vectors in the Eastern region are small but non-zero in the NAM frame. Small differences difficult to see in NNR frame



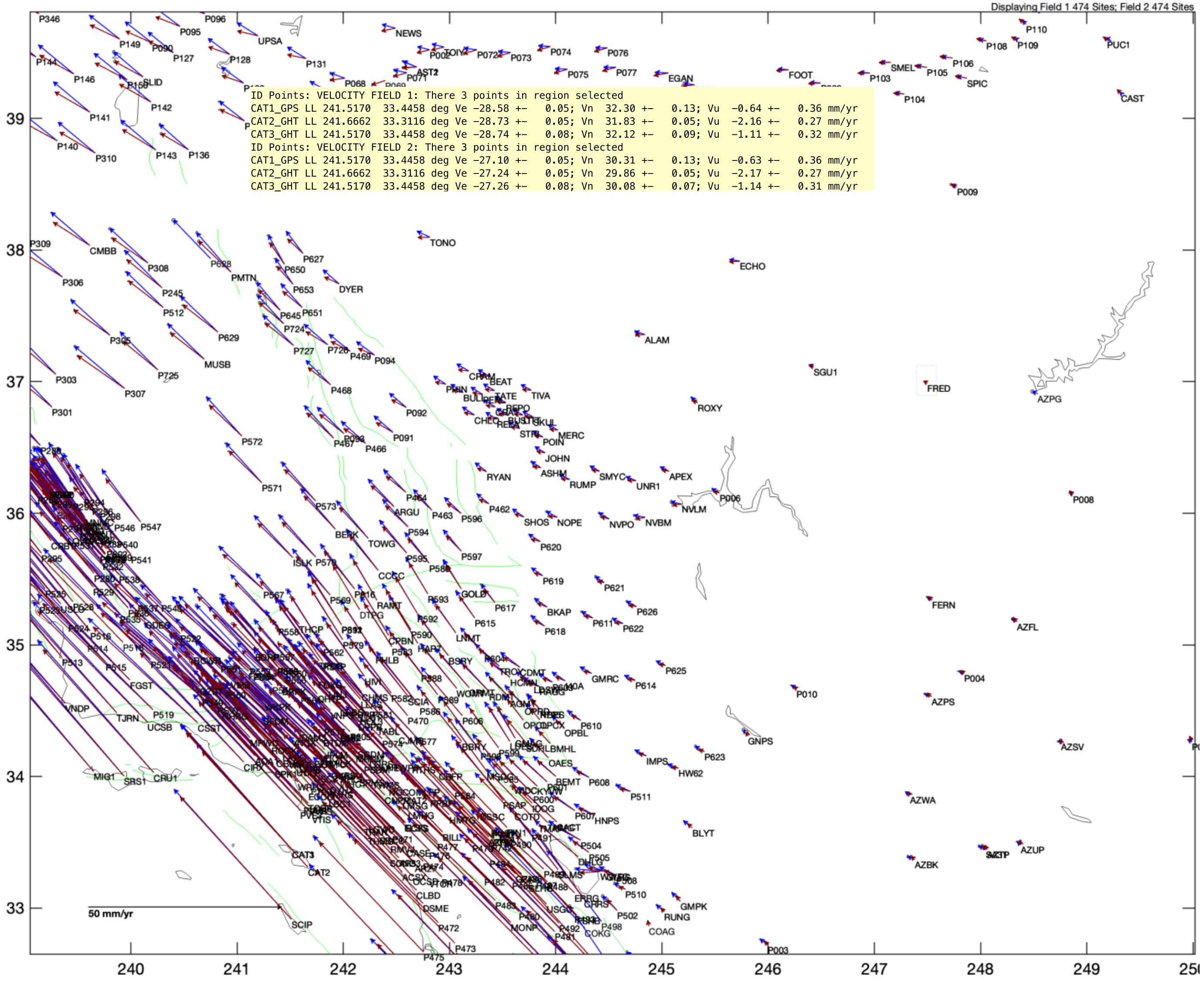
"Align" using translation only

- Comparison when "fixed" point used to align fields. Points close to the reference point are very similar, but rotation rates can be seen at distant points.
- GUAX: ENU Velocites (mm/yr)
  NAM -36.11 35.57 -0.04
  NEU -33.52 33.64 -0.09
  XYZ -34.13 34.19 -2.49
  (Shift in NEU velocity of FRED applied to all sites; Translation XYZ computed and re-projected to NEU velocities).
- Rotation would match exactly.



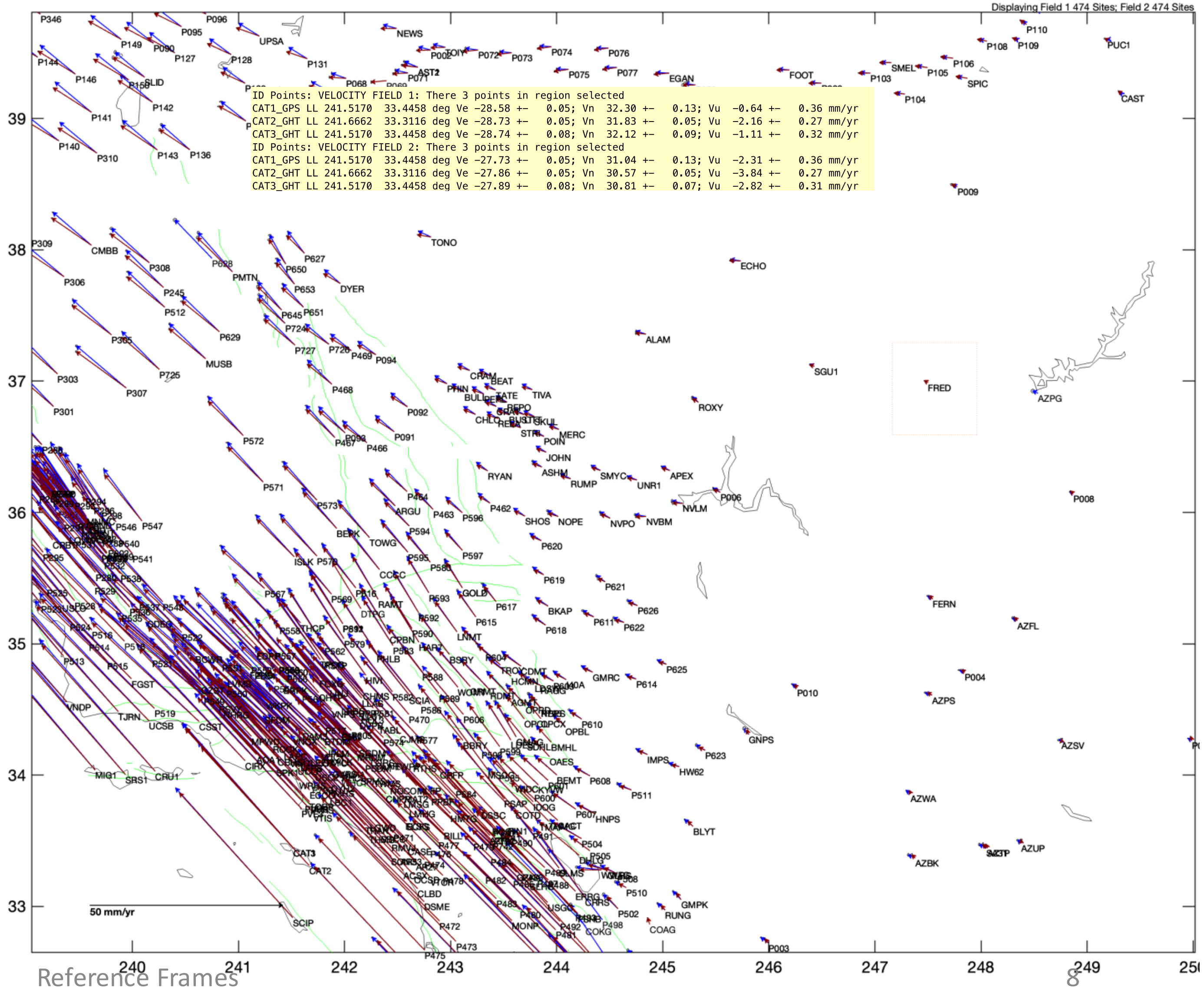
Zoom: NEU offsets

- More detail when we look
- Yellow box has velocities for sites on Catalina Island ~675 km from reference point (FRED).
- Differences are
  1.5 mm/yr EAST
  -2.0 mm/yr NORTH
  0.0 mm/yr HEIGHT



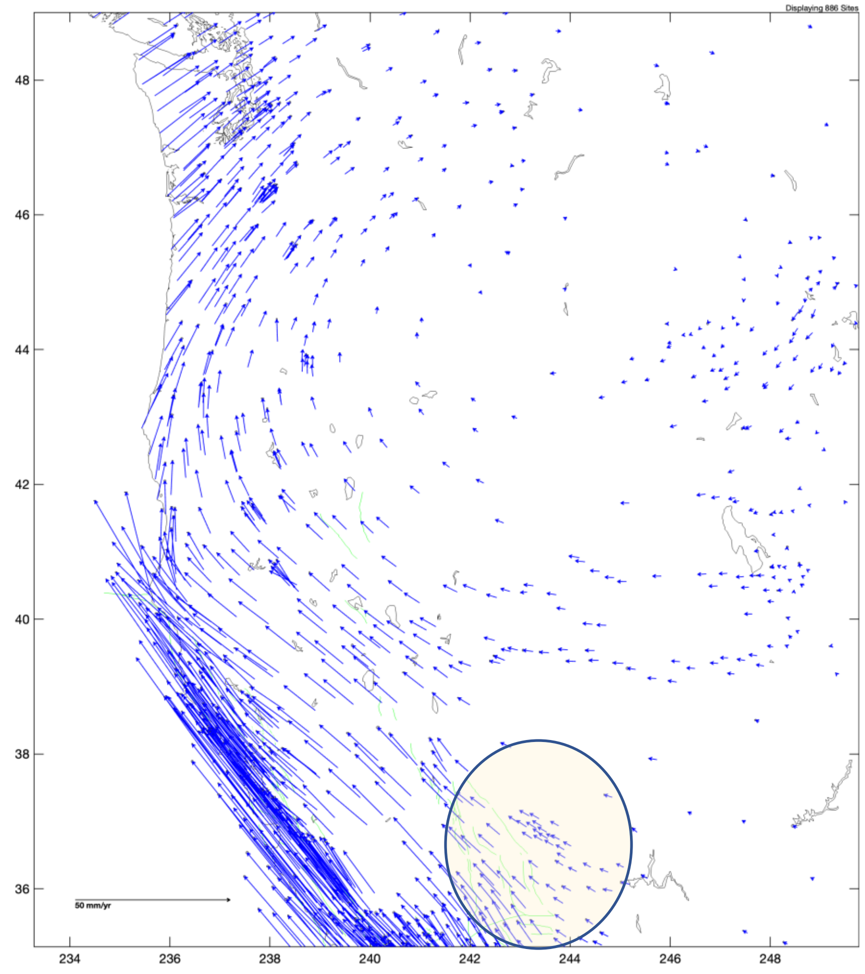
Zoom: XYZ offsets

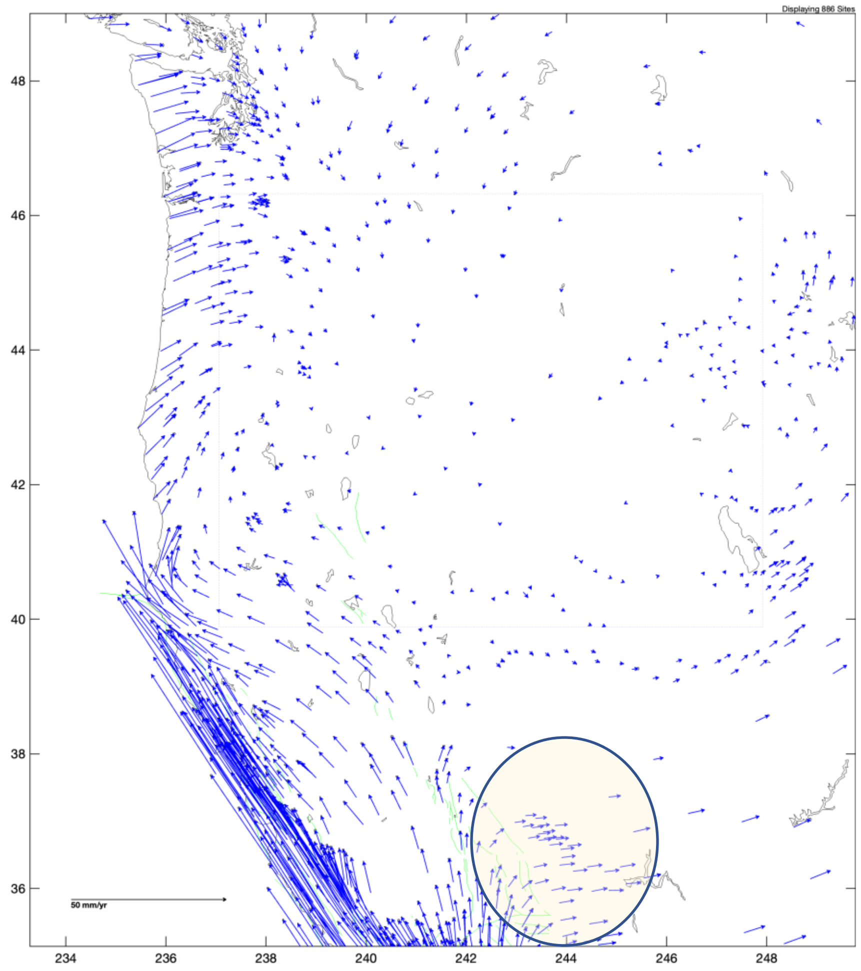
- More detail when we look
- Yellow box has velocities for sites on Catalina Island ~675 km from reference point (FRED).
- Differences are
  0.9 mm/yr EAST
  -1.3 mm/yr NORTH
  -1.7 mm/yr HEIGHT
- Heights are affected but not strain rates.



Example of seeing “new things”

- Remove Snake River Valley rotation
- Highlighted region: Extension much clearer in rotated frame.





Time series

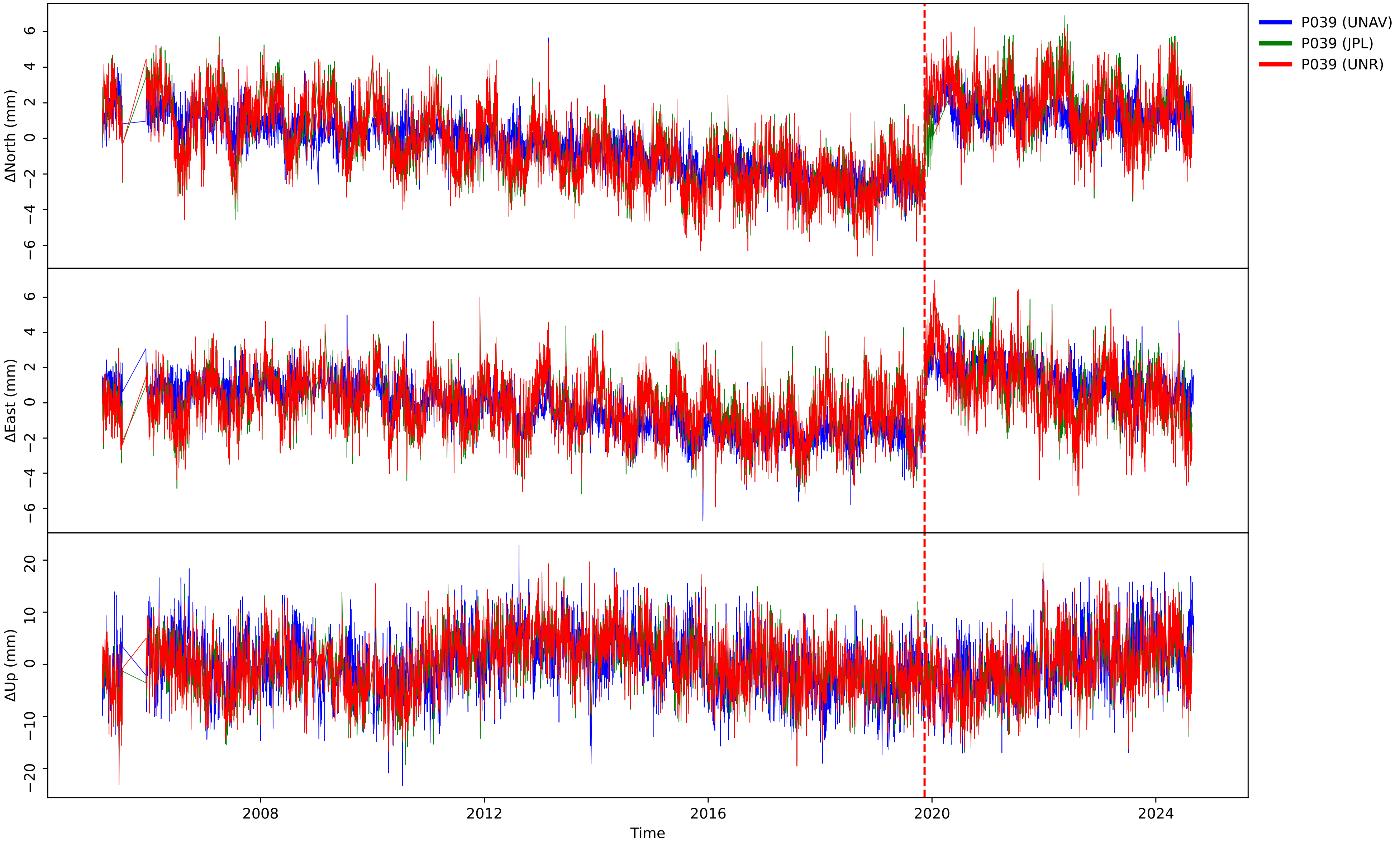
- GNSS time series need to be aligned to a reference frame each day, and the same methods are used as applied to velocity fields.
- For GNSS, the selection of the area used to define the reference frame is critical
  - Global site selections are common but result in "common mode error" (CME) that arise from the mis-modeling of satellite orbits, atmospheric refraction modeling, and aliasing of non-reference frame motions at the reference frame sites.
  - Regional reference frames reduce CME but can also remove signals that are common to the region (e.g., atmospheric loading, post-seismic transients)
  - Including scale estimates in transformation impacts height estimates.

Example: JPL, UNR, CWU processing

- URLs
  https://data.unavco.org/archive/gnss/products/position/P039/P039.cwu.nam14.csv
  https://sideshow.jpl.nasa.gov/pub/JPL_GPS_Timeseries/repro2018a/post/point/P039.series
  http://geodesy.unr.edu/gps_timeseries/tenv3/plates/NA/P039.NA.tenv3
- Sites P039 and P040 examined. These sites are in New Mexico and Colorado and are unaffected by earthquakes (allows frame issues to be more easily shown).
- These sites are also included in the CGM time series.
- JPL and UNR use global reference frame with scale estimated; CWU is a North American (Alaska, Caribbean, Western) frame.
- Linear trends removed

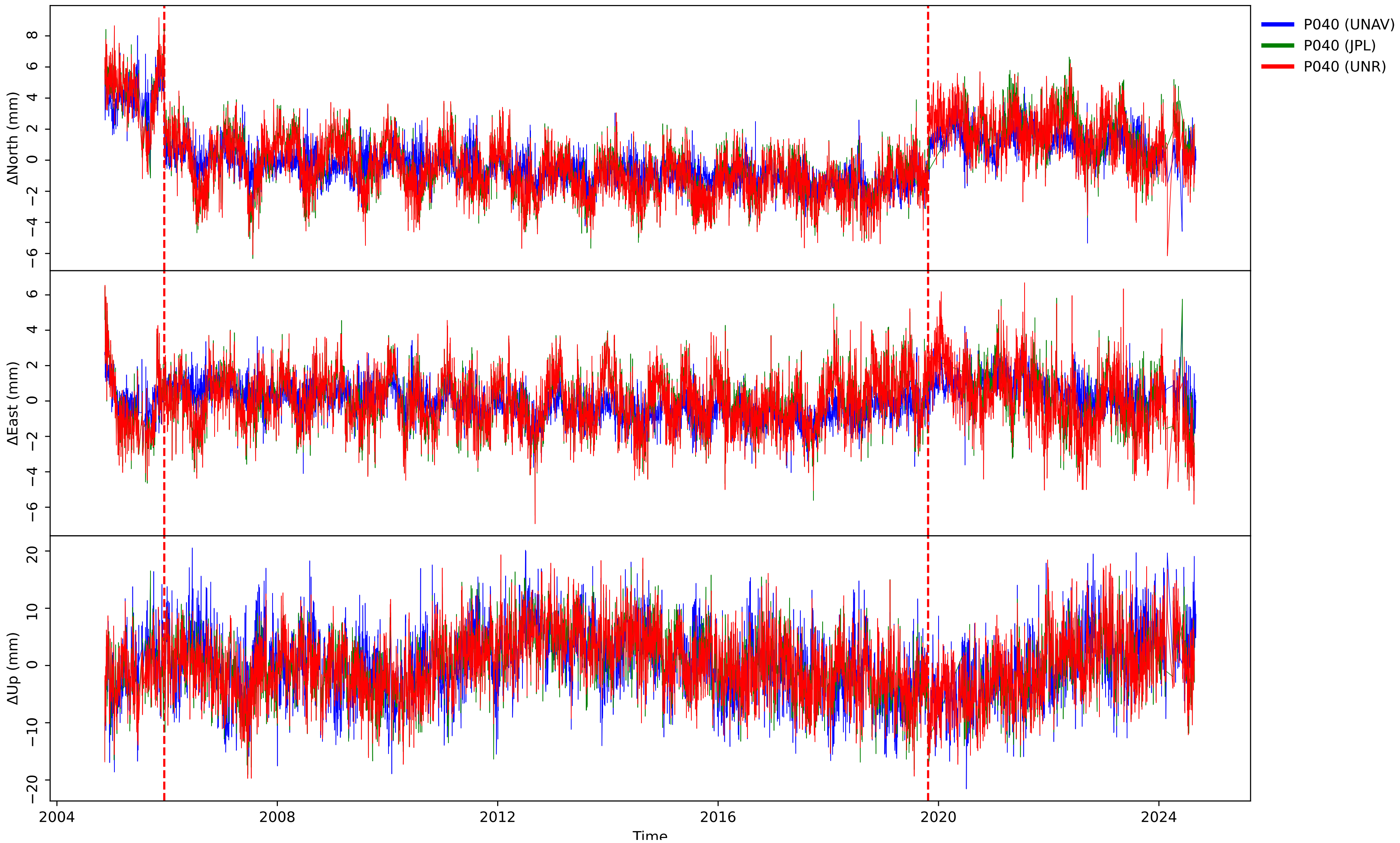
P039 Time series

- Time series
- Offset due to antenna change (another talk)
- JPL and UNR very similar and deviate from CWU.
- WRMS (mm)
  CWU 1.69 1.52 5.76
  UNR 2.18 1.69 5.46
  Trend only removed
  Breaks not removed



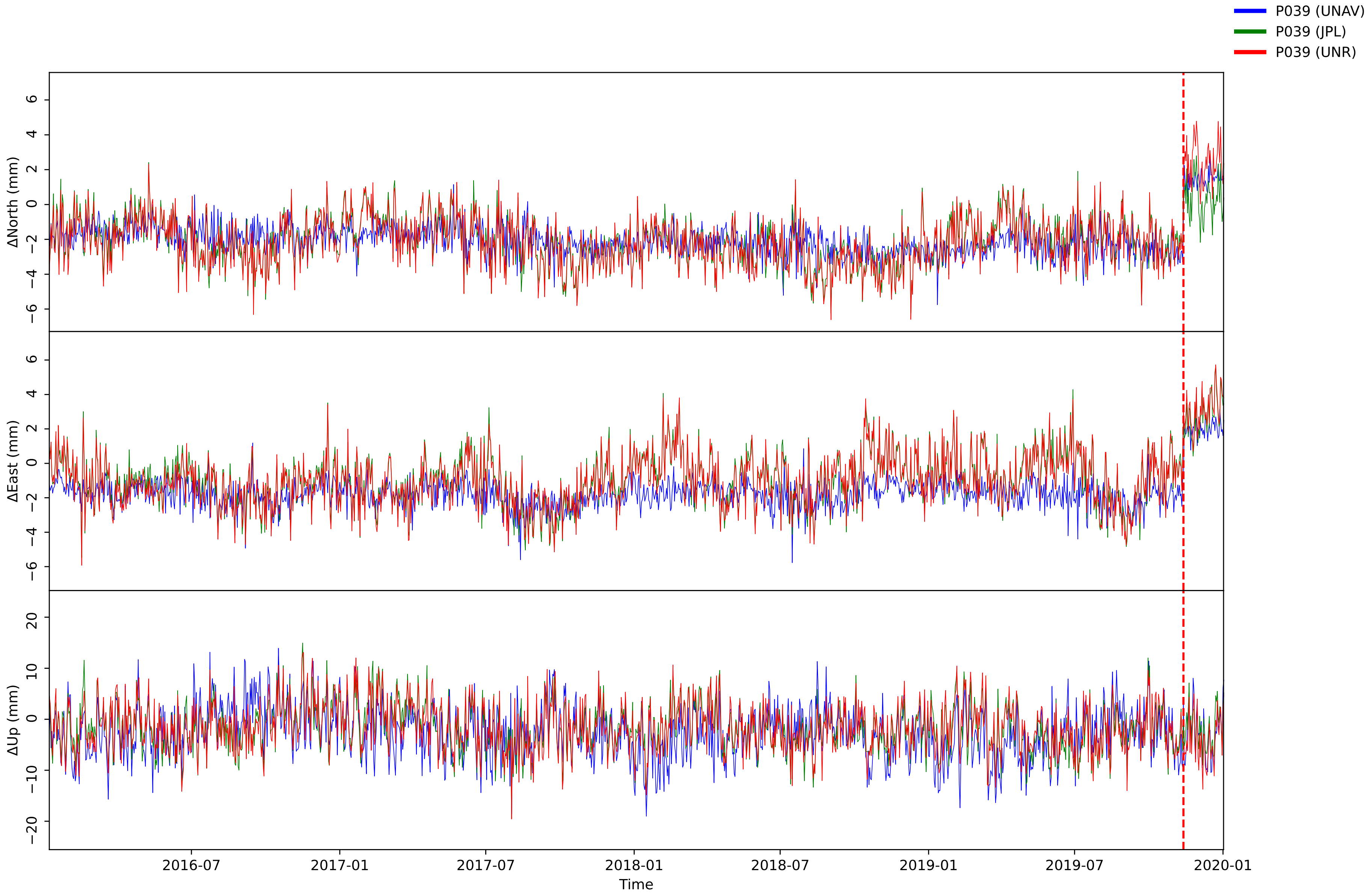
P040 Time series

- Time series
- Offsets due to antenna changes
- Very similar differences to those for P039.
- WRMS (mm)
  CWU 1.53 1.01 6.08
  UNR 2.16 1.59 5.55
  Trend only removed, Breaks not removed



Zoom of P039 time series

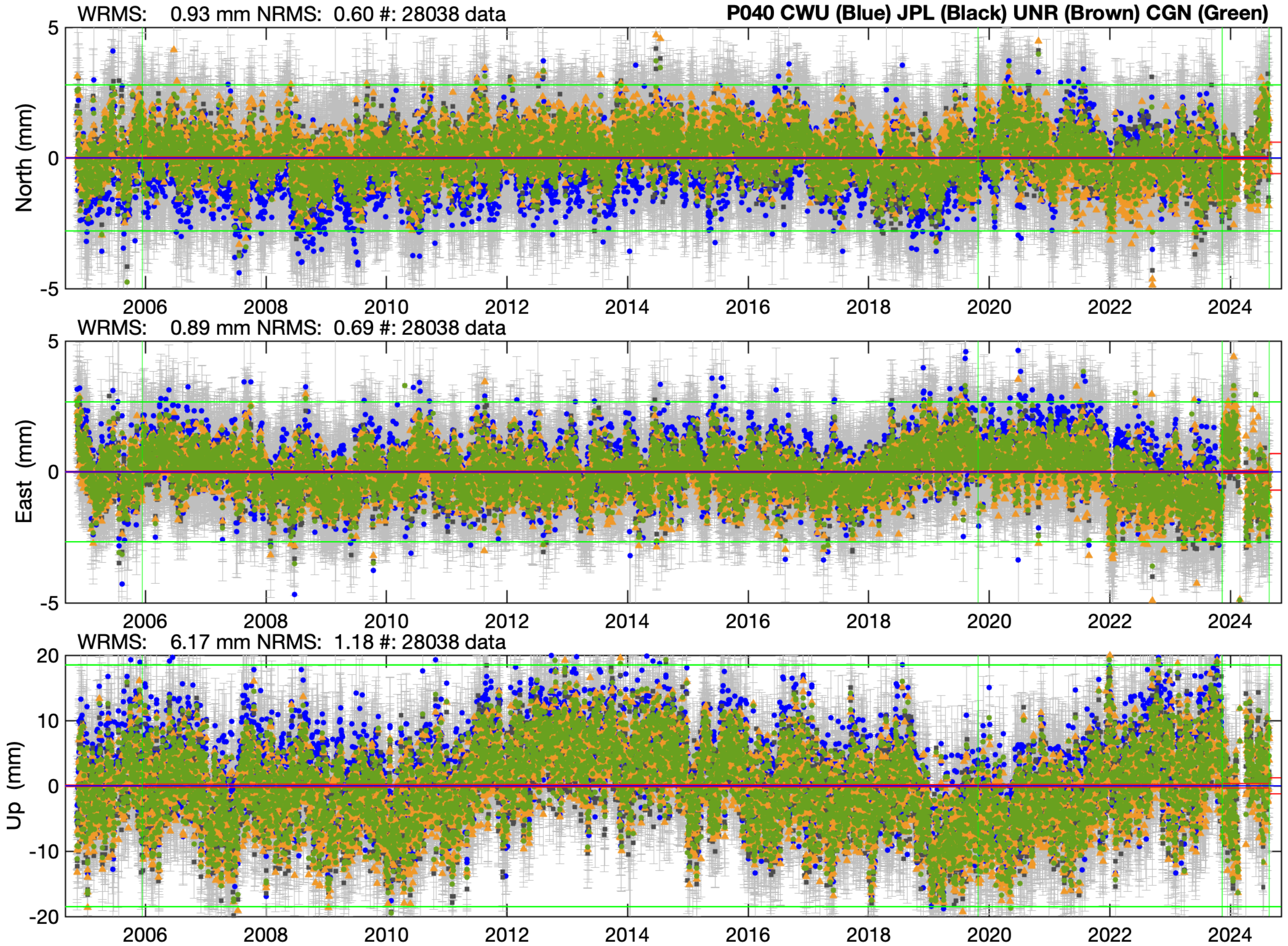
- Notice the close agreement between JPL and UNR until the antenna changes. The difference is possibly due to the wrong metadata being used by one AC



P040 from CGM with frame re-alignment

- These are absolute overlays; no mean differences have been removed.
- WRMS scatters (mm)
  CWU 1.03, 0.98, 6.49
  JPL 0.90 0.91 6.25
  UNR 0.94 0.91 6.29
  CGM 0.88 0.89 6.13

  NOTA CWU
  CWU 0.84 0.83 6.06



InSAR Reference Frames

- Final comments on InSAR frames
- Line of sight values based on satellite orbits: What reference frame are the orbits in? Referencing to a pixel removes much the impact but as we saw between NAM and offset NNR frames, differences of 1-2 mm/yr occur over 670 km distances.
- Why use a single pixel? Noise in that pixel is common to all points. If spatially uncorrelated pixels can be found, noise in the “reference frame” can be reduced by averaging over multiple pixels.
- **Reference frames are important and can introduce subtle and not-so-subtle artifacts in final results.**