Impacts of GNSS position offsets on global frame stability

OVERVIEW

- Brief overview of Earth orientation: theoretical and observational considerations
- IGS TRF rotation (thus PM) errors due to origin offsets in no-net rotation alignment approach *[Ray et al., IAG REFAG2014]*
  - IGS PM accuracy probably ~30 μas level
  - IGS formal errors at ~5 μas level
- First assessment of impacts of current level of IGS position offsets
- Results show GNSS position offsets impact
  - polar motion up to ~5.23 μas
  - station velocities up to 0.41 mm/yr
- Implications for ITRF accuracy and stability, along with local ground-motion monitoring

Jake Griffiths
Naval Center for Space Technology
Naval Research Laboratory
jake.griffiths@nrl.navy.mil

Jim Ray, retired
National Geodetic Survey

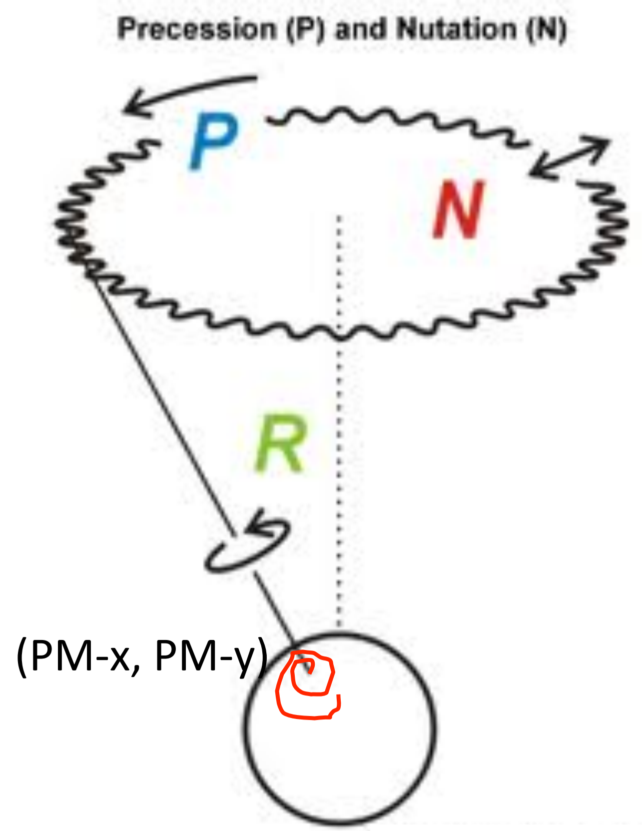
Special thanks to Zuheir Altamimi (IGN) for CATREF support

Earth Orientation Parameters (EOPs)

- EOPs are the angles used to relate points in the Terrestrial & Celestial Reference Systems:

[GCRS] = **P** · **N**(ψ, ε) · **R**(UT1) · **W**(xp, yp) · **[ITRS]**

  - **P**recession-**N**utation describes the motion of the Earth's rotation axis in inertial space
  - **R**otation about axis given by UT1 angle
  - **W**obble of pole in TRS given by terrestrial coordinates of polar motion (**PM-x, PM-y**)



- But ITRS differs from ITRF in scale & origin:
  - **[ITRS]** = S · **[ITRF** – O_G]
  - S = 1 + (0.6969… ppb) accounts for TCG (ITRS) versus TT (ITRF) time scales
  - $O_G(t)$ = geocenter motion offset between ITRS (CM) & ITRF (CF)

EOPs & TRF Alignment

- Analysis Center (AC) & Technique solutions (daily/weekly) for global terrestrial coordinates & polar motion aligned to a common reference frame (e.g., ITRF) using Helmert relation:

$$[\mathbf{ITRF}] = [\mathbf{TRF}_{AC}] + \mathbf{T} + \mathbf{D}\cdot[\mathbf{TRF}_{AC}] + \mathbf{R}\cdot[\mathbf{TRF}_{AC}]$$

  - where T, D, R are origin, scale, rotation corrections, respectively
  - consistency requires corresponding polar motion corrections:

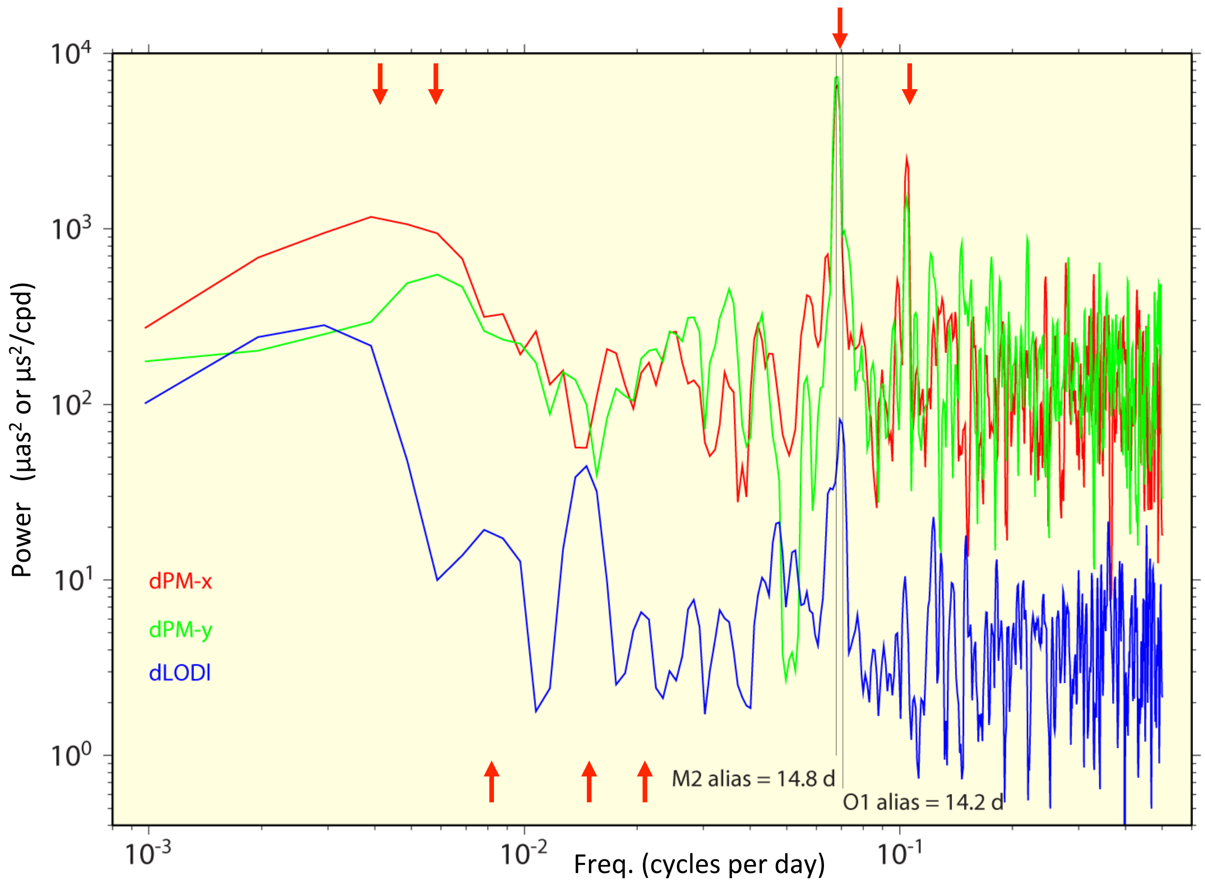
$$xp(ITRF) = xp(AC) + R_2$$
$$yp(ITRF) = yp(AC) + R_1$$

- Correlations between R_i (rotations) & T_j (apparent geocenter offsets) can bias PM values if networks are not globally uniform
  - SLR observes annual geocenter amps of ~3 mm in X,Y & ~6 mm in Z
  - for induced PM errs <5 µas, correlations must be <5% & <2.5%
  - in practice, this is not feasible, not even for IGS GNSS network
  - current impact is at ~30 µas level for IGS *[Ray et al., IAG REFAG2014]*

Top Non-Frame Error: Subdaily Tide Model Aliases

- IERS model for subdaily (12/24 hr) EOP tides has errors of ~20%
  - mostly resonate into subdaily orbit solar radiation pressure parameters
  - but some >1 d errors alias into EOP estimates
  - causes errors at discrete lines: ~**14 d**, ~**9 d**, **annual**, **semiannual**, & **odd draconitics** (for LOD)

- Spectra of simulated subdaily EOP tide model alias errors
  - *Griffiths & Ray [2013]*

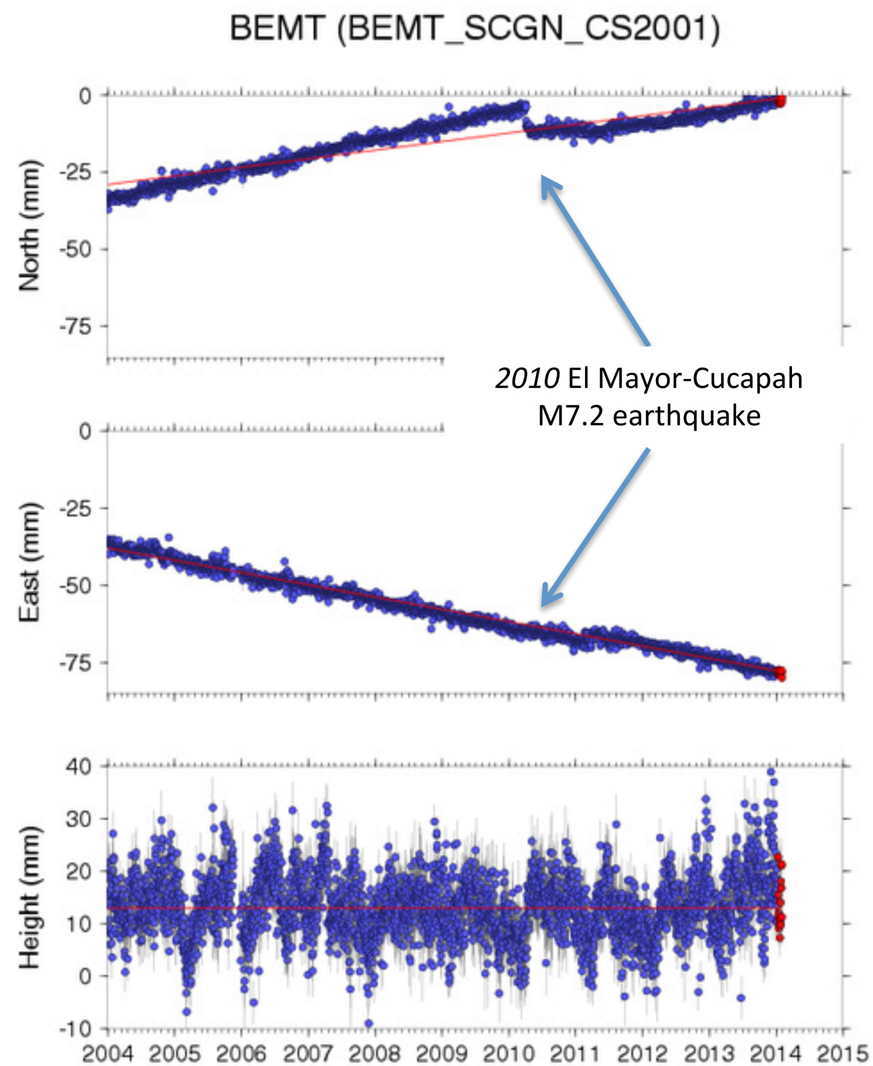


Sources of TRF-related Effects on Rotations

- Rotational offsets via Helmert NNR constraints
  - due to non-uniform networks & some poorly determined stations
- Origin offsets via Helmert NNT constraints
  - due to non-uniform networks that induce Ti vs Rj correlations
  - probably main source of PM error *[Ray et al., IAG REFAG2014]*
    - NNR-only vs. NNR+NNT at AC level: TRF-related PM errors at ~30 µas level
- Scale offsets
  - probably not significant but not studied yet
- Load displacements of TRF positions
  - leads to modest inconsistency with EOP excitation theory
  - needs to be corrected for best geodesy vs geophysics agreement
  - effects on reference frame under study by IAG Joint WG 1.3
- **Position/velocity discontinuities**
  - accumulated effect weakens station velocities and internal TRF stability
  - **magnitude of effect positional offsets studied here**

Offsets in GNSS Time Series (1/3)

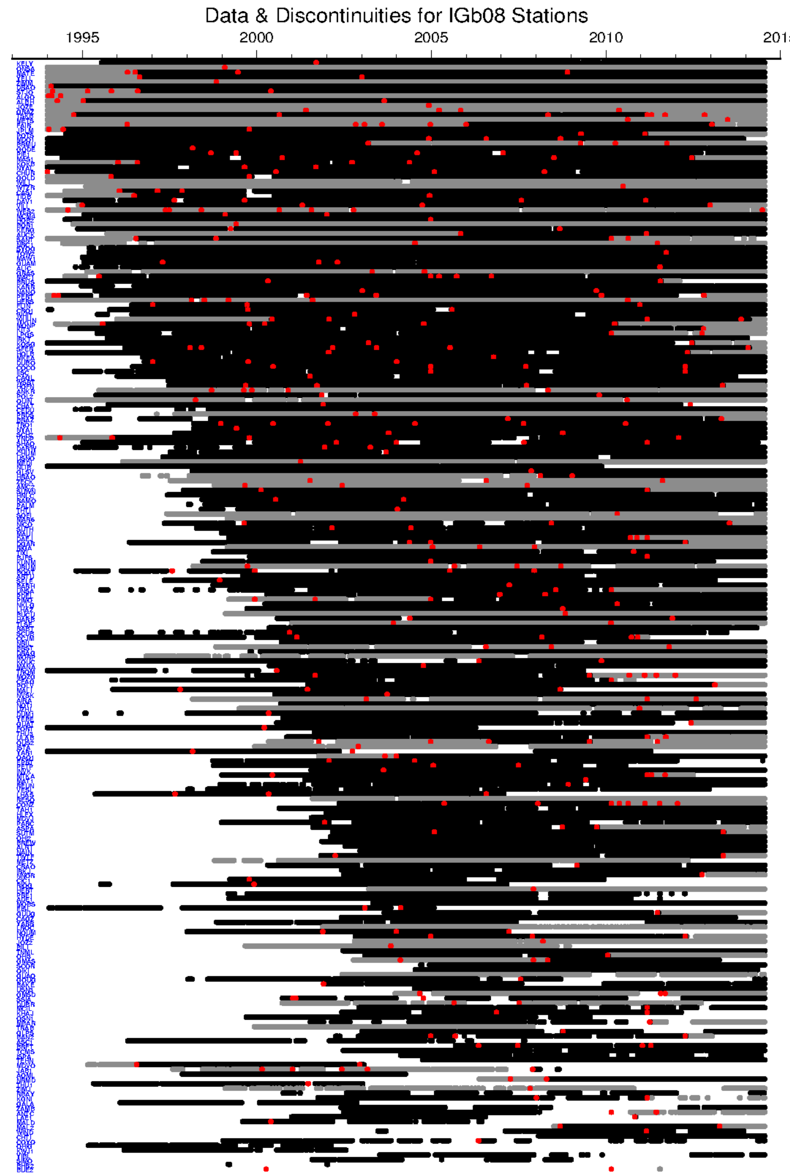
- Position offsets occur in station time series for several reasons
- Most offsets are caused by station equipment (antenna & receiver) changes
- The most dramatic offsets are caused by earthquakes
  - time series plots to the right show offsets for a station near a predominantly N-S trending strike-slip earthquake rupture in Baja, California
- Other offsets are caused by:
  - anthropogenic changes near stations
  - unknown/undocumented events



Plot courtesy of unavco.org

Offsets in GNSS Time Series (2/3)

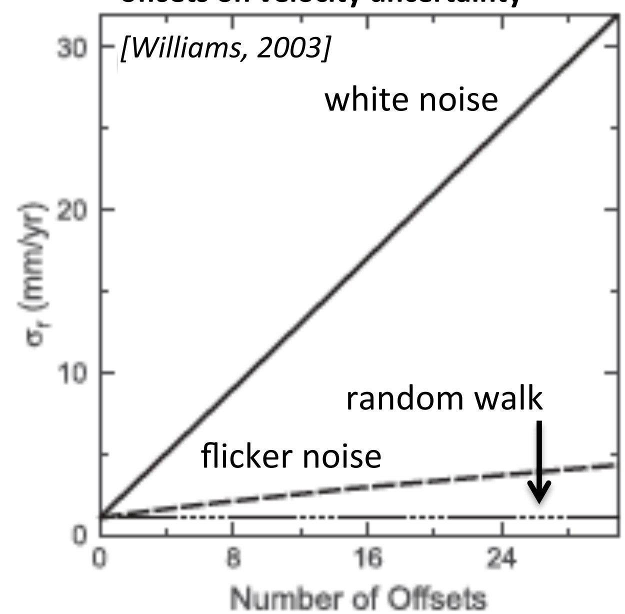
- Offsets occur often for most reference frame stations
- Figure to right shows occurrences for IGS reference frame stations:
  - each row of black/gray dots represents data for an individual station
    - black dot indicates IGb08 core station with valid reference coordinates
    - gray dot means no valid reference coordinate
  - red dots mark positional discontinuities
  - **average data span 8.2 ± 6.1 yrs**
  - **average uninterrupted data span ~3 yrs**
- IGS average # offsets per station:
  - **core network: ~0.6 offsets per station**
  - **full network: ~0.9 offsets per station**



Offsets in GNSS Time Series (3/3)

- Instances of unreported offsets and those with unknown origin are found manually and/or using ad hoc detection algorithms
  - i.e., DOGEx (http://acc.igs.org/trf/pos-discont-DOGEx_IUGG11.pdf)
- In a frame realization, all offset displacements are:
  - estimated empirically
    - accuracy depends on duration of data span and systematic & power-law errors in time series
  - correlated with EOPs and TRF parameters
- Velocity uncertainty mainly impacted by:
  - known/estimated offsets in presence of white and flicker noise
    - $time^{-1/2}$ dependence for evenly spaced offsets
  - undetected/residual offsets (smaller impact)
    - introduce random level shifts in time series, which are pseudo-random walk in nature
    - impacts velocity uncertainty by up to 0.4 mm/√yr

Effect of number of evenly spaced offsets on velocity uncertainty

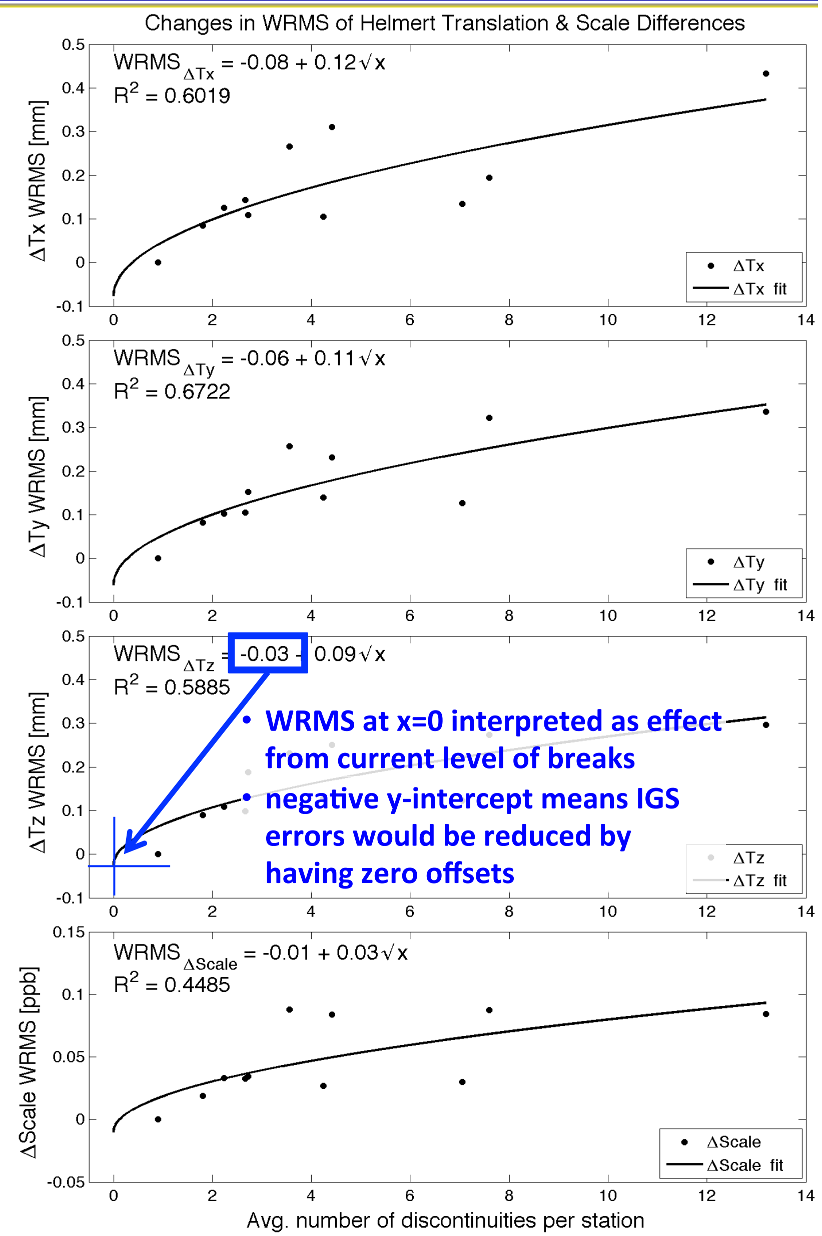


Approach for Assessing Effects of GNSS Offsets

- Induce TRF instabilities
  - use existing IGS weekly SINEX files (ftp://cddis.gsfc.nasa.gov/gps/products/)
  - establish baseline solution equivalent to IGS cumulative
    - using CATREF software *[e.g., Altamimi et al., 2011]* from IGN
  - iteratively insert offset parameters at the midpoint of each data segment, and
  - restack using no-net-[**T**,**D**,**R**] constraints w.r.t. intrinsic datum, solving for:
    - regularized station positions [up to ~57,000 params]
    - secular velocities [up to ~57,000 params]
    - Earth orientation parameters [~37,500 params]
    - weekly Helmert alignment parameters [~6,500 params]
    - and the empirical shifts across all positional discontinuities
  - no new velocity discontinuities introduced in restacking
- Assess impact on frame stability by comparing each restacked cumulative solution to the baseline
  - polar motion changes can be used to infer global frame instabilities
  - station velocity changes reveal local instability effects

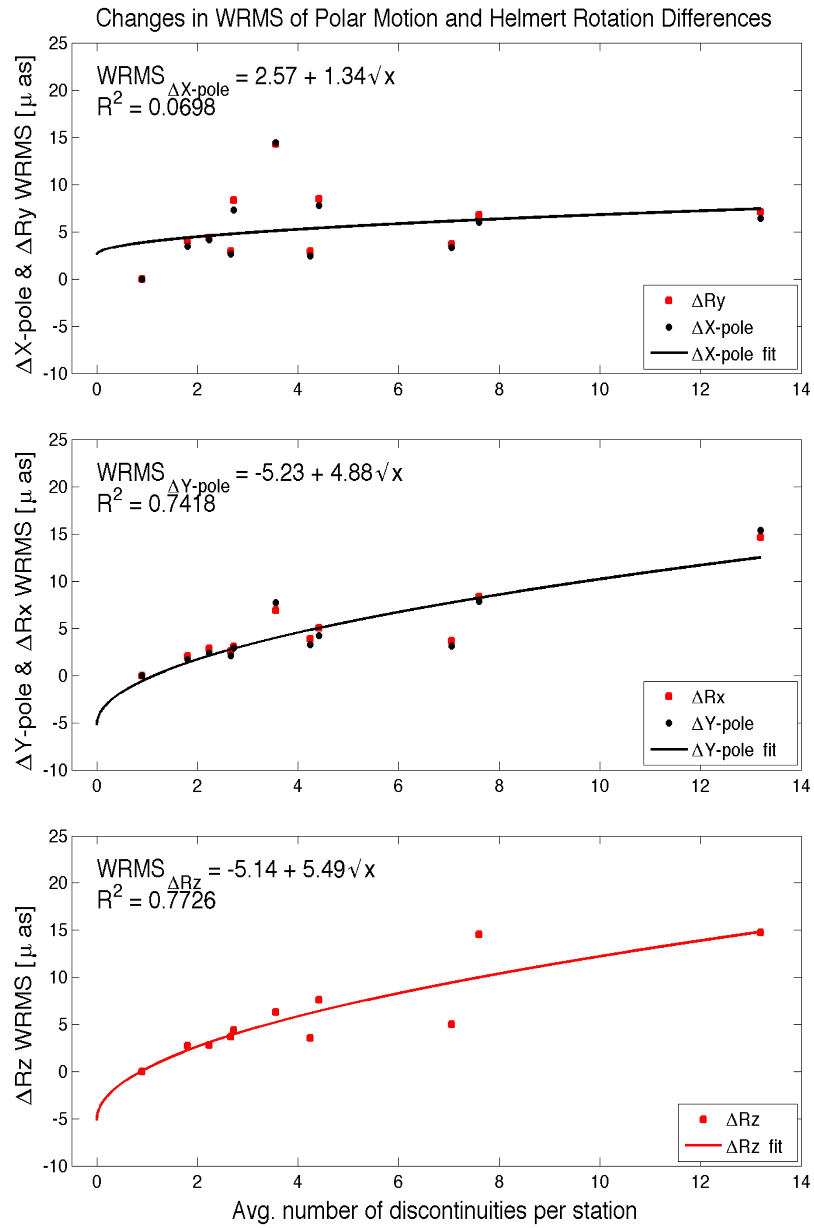
Impact on Helmert Translations and Scale

- WRMS of weekly Helmert translation and scale differences computed w.r.t. baseline solution for each iteration
- Fit √-function w.r.t. avg. #disc/station
- Helmert translation and scale response consistent with √-dependence, but…
- Translation and scale errors due to current number of offsets are insignificant:
  - Tx: 0.08 ± 0.07 mm
  - Ty: 0.06 ± 0.06 mm
  - Tz: 0.03 ± 0.06 mm
  - Scale: 0.01 ± 0.02 ppb
- Thus, the impact on IGS frame origin and scale from existing position offsets is negligible



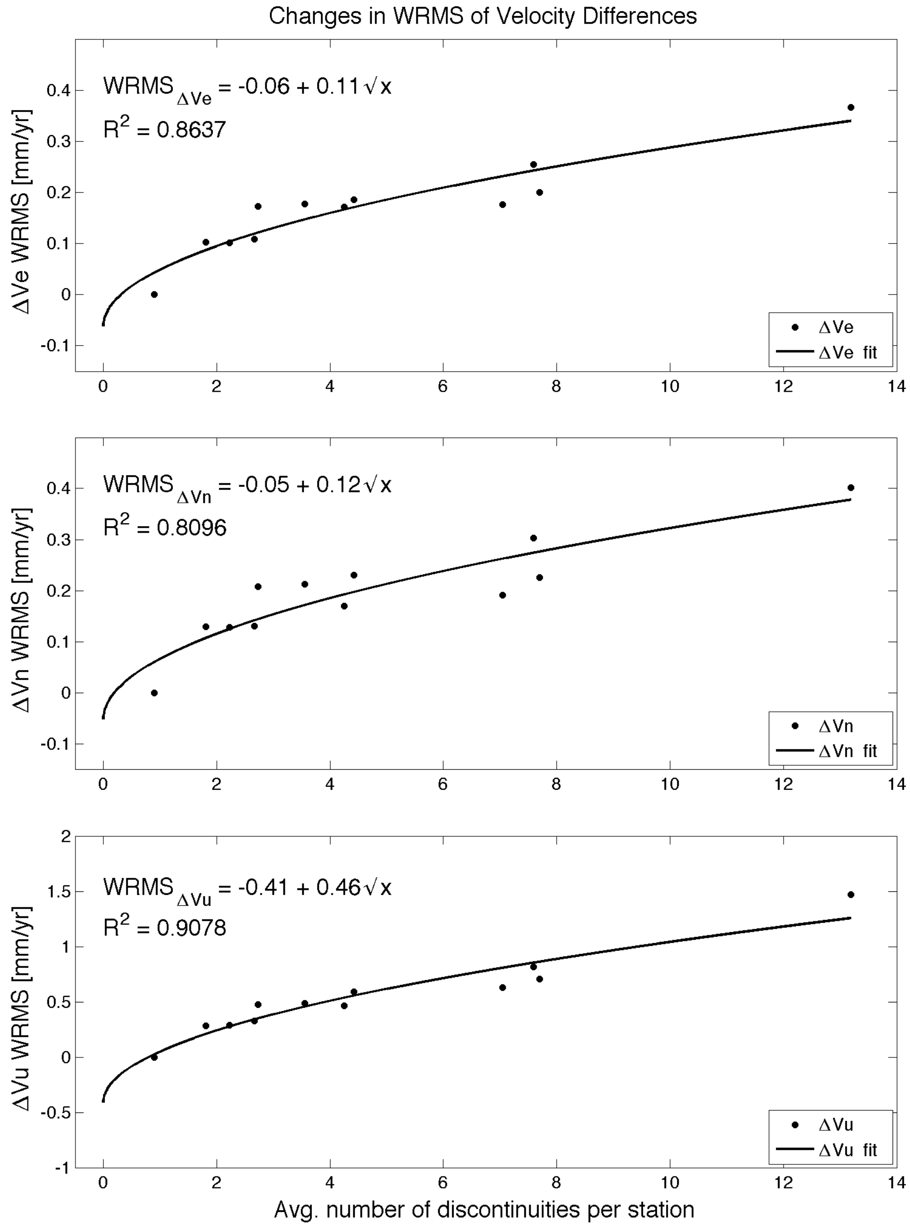
Impact on PM and Helmert Rotations

- Likewise, compute WRMS of weekly PM & Helmert rotation differences, and fit a √-function to each series of WRMS changes
- Overall difference in PM-x and PM-y responses likely related to land-water distribution w.r.t. X & Y axes
  - more land mass (i.e., stations) along/near the Y-Z plane than along the X-Z
  - RX rotations (= PM-y) likely less affected by station distribution than RY (= PM-x)
- Current IGS PM and frame rotation errors now small, but significant for Y-pole & RZ:
  - -2.57 ± 3.48 μas (RY/X-pole – insignificant)
  - 5.23 ± 2.05 μas (RX/Y-pole – significant)
  - 5.14 ± 2.12 μas (RZ – significant)



Impact on Station Velocities

- Repeat the procedure for station velocity differences
- IGS velocities affected, with significant excess errors already:
  - Ve: 0.06 ± 0.03 mm/yr
  - Vn: 0.05 ± 0.04 mm/yr
  - Vu: 0.41 ± 0.10 mm/yr
- Compare w/ IGS avg. formal errors
  - $\bar{\sigma}_{Ve}$ = 0.14 mm/yr
  - $\bar{\sigma}_{Vn}$ = 0.14 mm/yr
  - $\bar{\sigma}_{Vu}$ = **0.26 mm/yr**
- Results consistent with random walk effect observed for offsets estimated in presence of white & flicker noise *[Williams, 2003]*



Discussion of Results

- GGOS aims for ITRF accuracy and stability to be better than 1 mm and 0.1 mm/yr, respectively
  - refers to mean errors over network, not at individual stations
- IGS frame rotational stability currently limited by no-net rotation alignment approach *[Ray et al., IAG REFAG2014]*
  - use of SLR seasonal geocenter motion model in IGS analysis approach could help?
  - or perhaps use NNR+NNT alignment approach – further studies needed
- Our results suggest existing IGS discontinuities induce PM-y errors that exceed the 0.1 mm level (=3.2 μas)
  - not a rate, but daily scatter in global frame stability
  - 5.32 μas of PM-y error is ~16 % of stated 1 mm accuracy goal
- And, IGS Up velocities already impacted on average up to ~0.41 mm/yr
  - existing discontinuities complicate usage of IGS network for altimetry calibration and local subsidence/uplift monitoring below 0.41 mm/yr level
  - for realistic velocity errors, analysts should account for the effect of position offsets for each station in addition to standard correlated noise adjustment

Summary

- IGS TRF rotation (thus PM) errors are likely mainly due to origin offsets via Helmert NNT constraints *[Ray et al., IAG REFAG2014]*
  - IGS PM accuracy probably ~30 mas due to errors in daily Helmert frame alignments to remove AC origin offsets
  - IGS formal errors at ~5 mas level
- This study focused on role of IGS positional discontinuities
  - induce TRF instabilities by adding offsets in IGS SINEX files, restacked with CATREF
  - velocity offsets not considered here so full effects could be larger
- Impact on IGS EOPs small, but significant for PM-y (~5.23 ± 2.05 mas)
  - difference in X-pole and Y-pole responses likely related to land-water distribution
- Empirical results suggest impact on IGS velocities already significant, especially for Vu at 0.41 ± 0.10 mm/yr
  - supported by global mean formal uncertainties for IGS velocities
- Implications for ITRF accuracy and stability, along with impacts on local ground motion monitoring

Questions?