USING GPS TO OBSERVE CRUSTAL LOADING SIGNALS IN THE TIBXS REGION

- Analyze dNEU GPS position time series residuals
  - use latest IGS solutions for a global set of 706 stations
  - compare with 28 stations in Tibet-Xinjiang-Siberia region
- Quantify error budget using models for crustal loads
- Discuss sources for unmodeled contributions
  - especially non-load annual effects

Jim Ray, NOAA/National Geodetic Survey

Xavier Collilieux & Paul Rebischung, IGN/LAREG

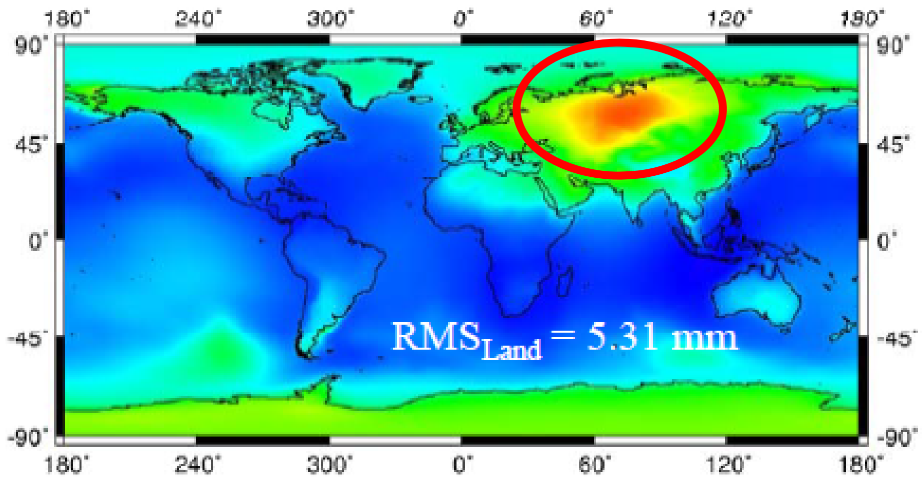
Tonie van Dam, University of Luxembourg

Zuheir Altamimi, IGN/LAREG

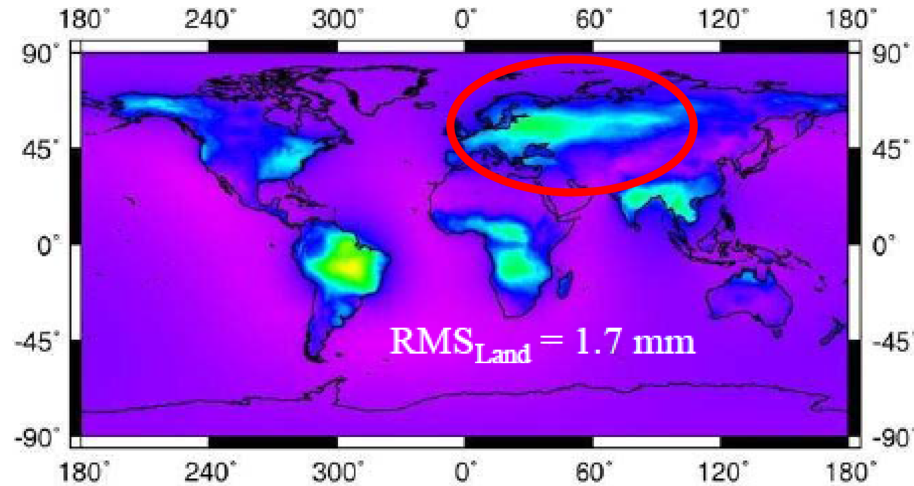
4th International TibXS Workshop, YiNing, China, 28 July - 1 August 2013

Modeled Vertical Loading Deformation Signals

Atmospheric Pressure (ECMWF-MOG2D)

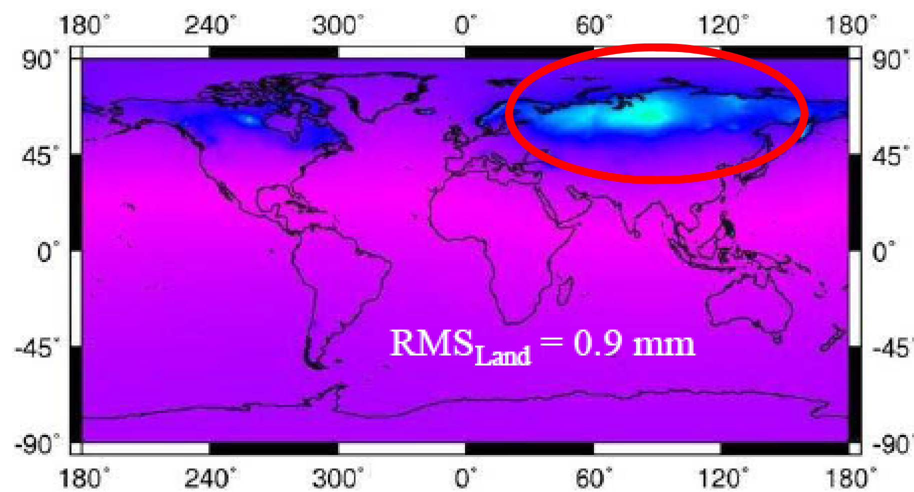


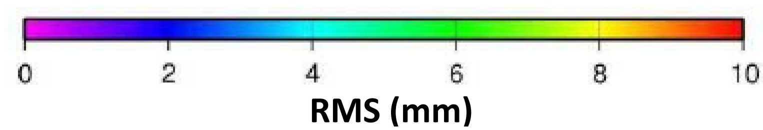
Soil Moisture (GLDAS)



- Crustal loading is large across central Asia for all major fluid sources
- Height variations can reach 1 cm
  - at annual periods, mostly
- Signatures should be clear in IGS station position time series

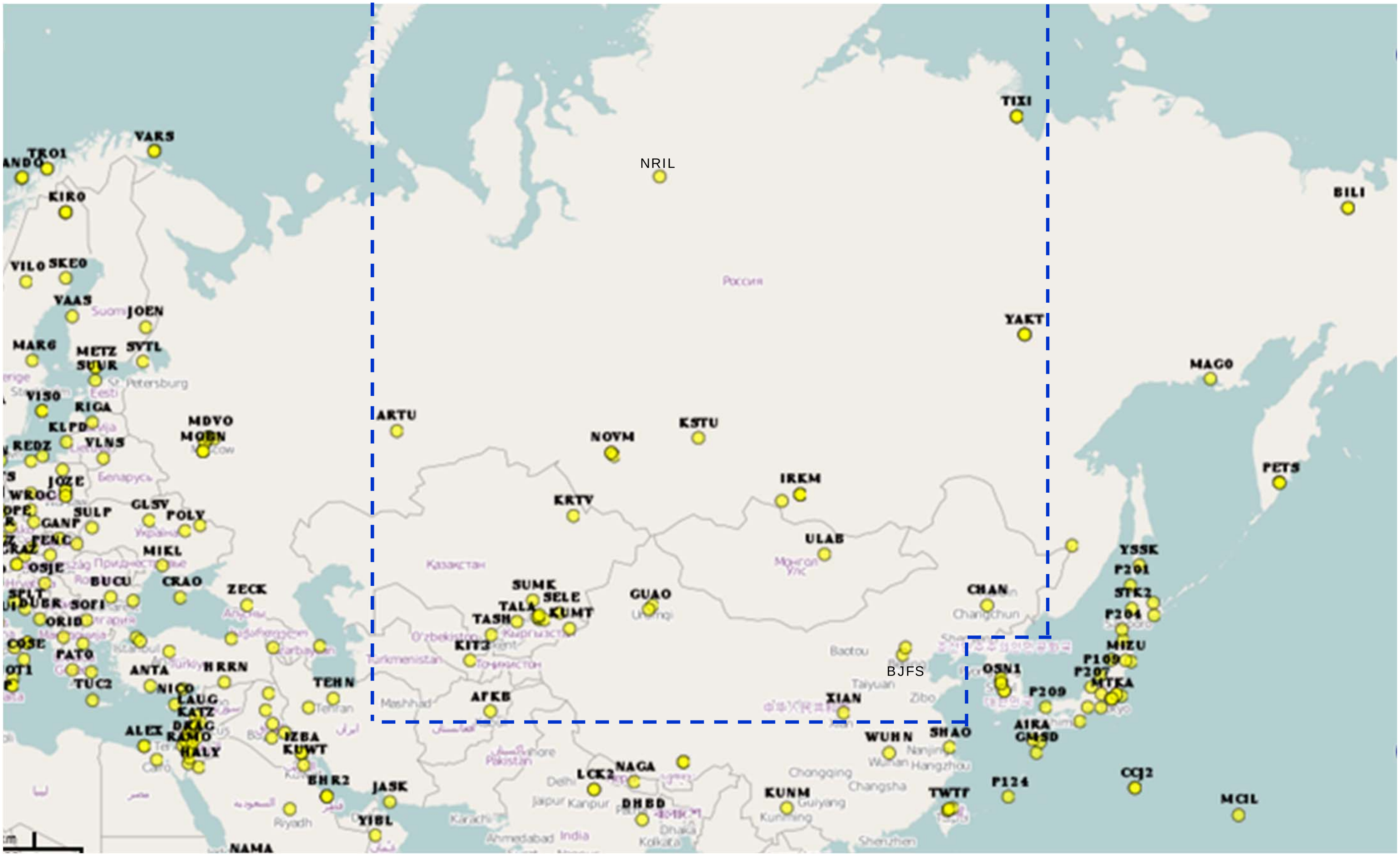
Snow (GLDAS)





(All plots from P. Gegout et al., EGU 2009)

IGS Stations in Tibet-Xinjiang-Siberia Region



- 28 stations in TibXS region with >100 weeks of IGS Repro1 results

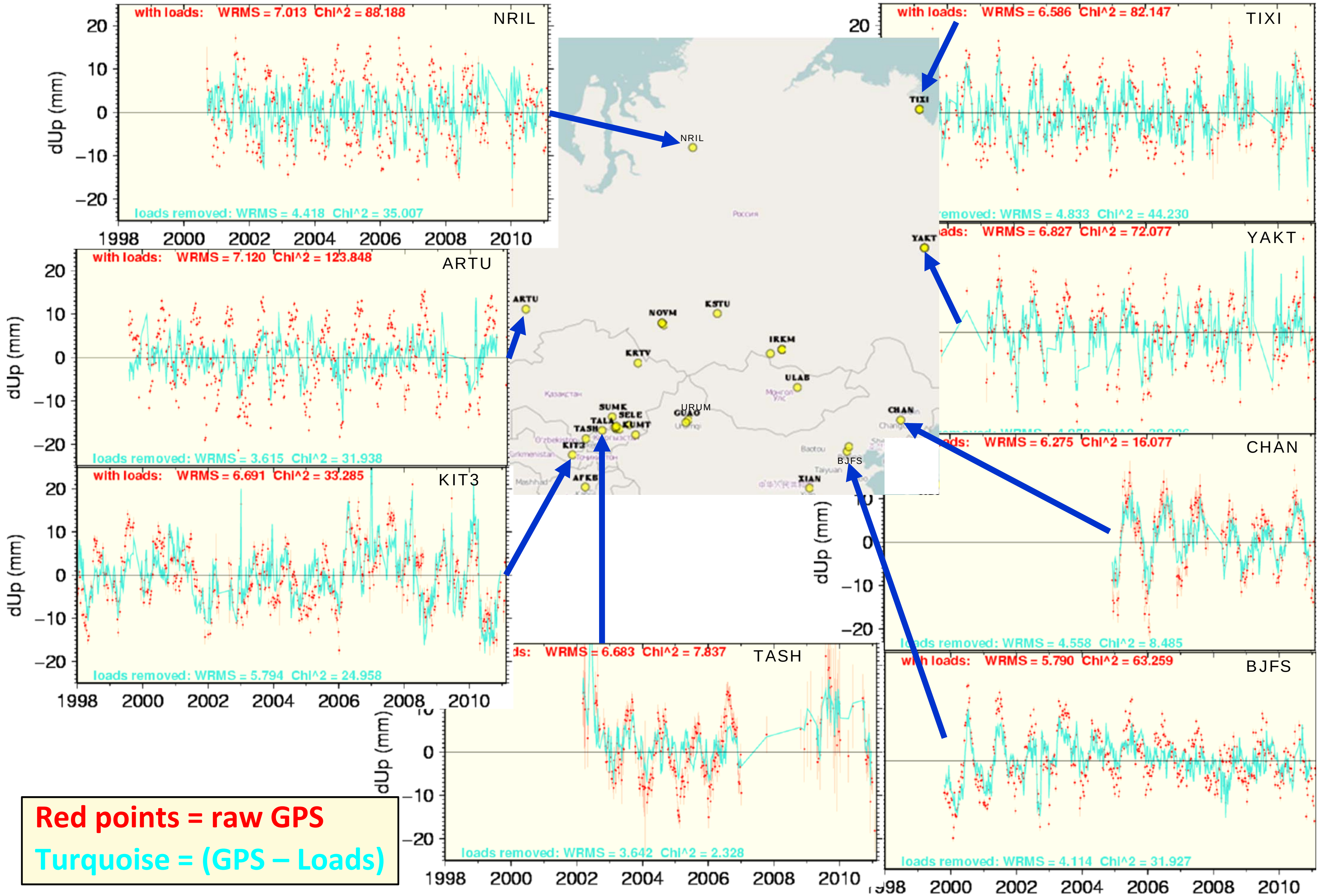
Data Sets to Compare

- GPS station position time series from IGS 1st reprocessing
  - analysis consistent with IERS 2010 Conventions (more or less)
  - combined weekly frame results from up to 11 Analysis Centers
  - 706 globally distributed stations, each with >100 weeks
  - data from 1998.00 to 2011.29
  - Helmert alignment (no scale) w.r.t. cumulative solution uses a well-distributed subnetwork to minimize aliasing of local load signals
  - care taken to find position/velocity discontinuities

- Mass load displacement time series for the same stations
  - 6-hr NCEP atmosphere
  - 12-hr ECCO non-tidal ocean
  - monthly GLDAS surface ice/water, cubic detrended to remove model drift
  - all computed in CF frame
  - sum is linearly detrended & averaged to middle of each GPS week
  - data from 1998.0 to 2011.0

- Study dN, dE, dU non-linear weekly residuals (1998.0 – 2011.0)
  - bias errors not considered here !

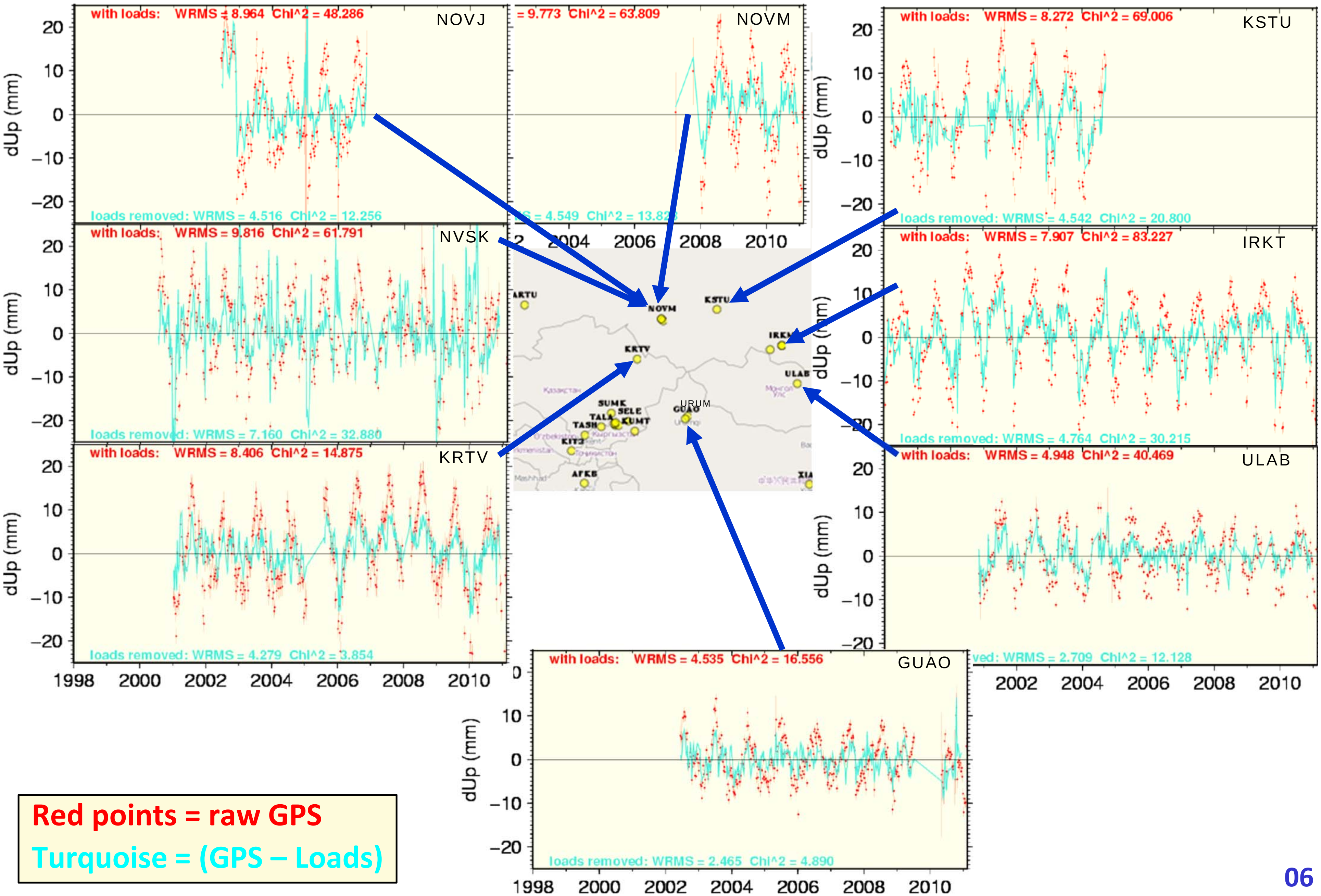
GPS dUp Time Series in TibXS Region (1/3)



Red points = raw GPS

Turquoise = (GPS – Loads)

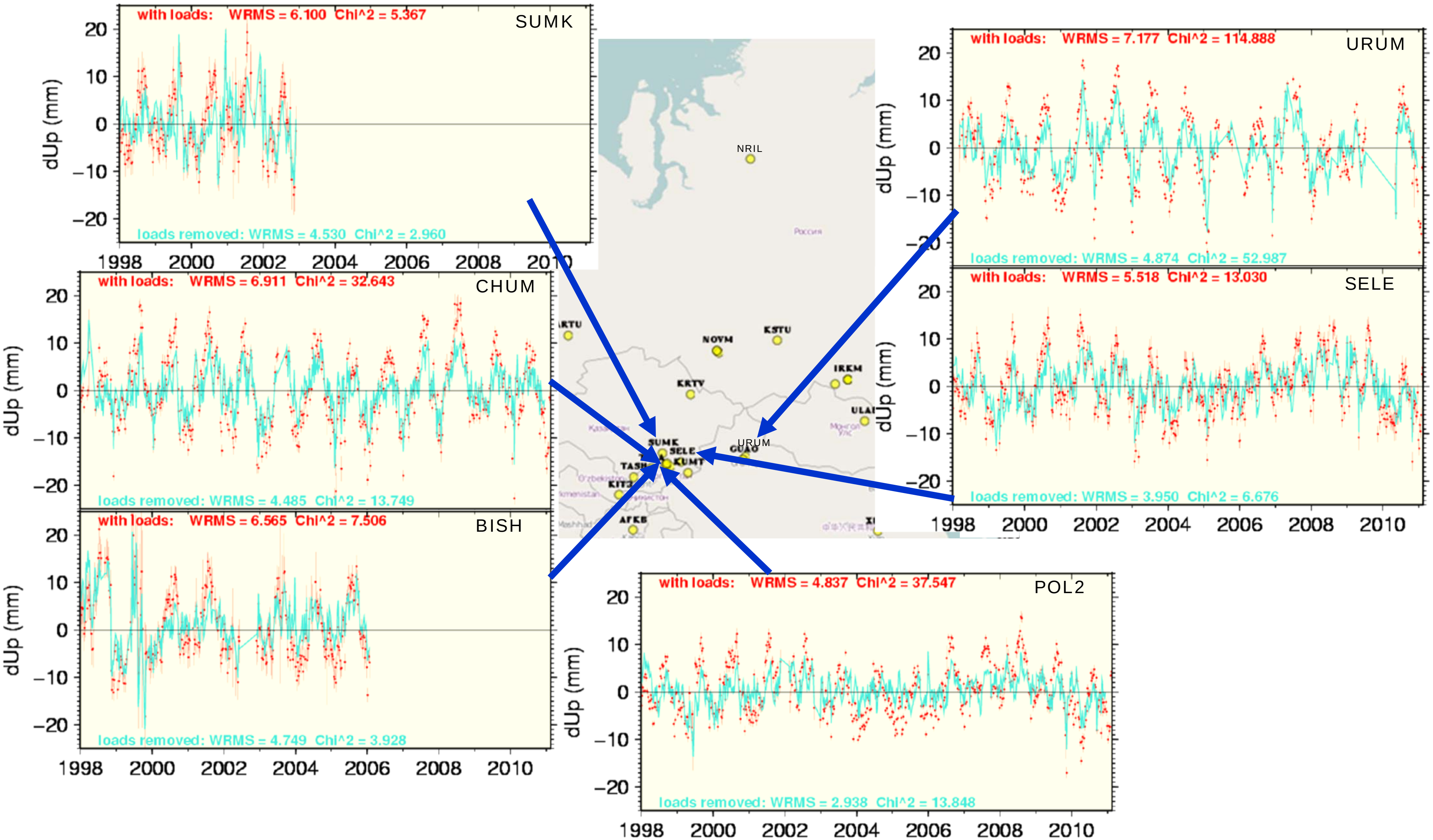
GPS dUp Time Series in TibXS Region (2/3)



Red points = raw GPS

Turquoise = (GPS – Loads)

GPS dUp Time Series in TibXS Region (3/3)



Red points = raw GPS
Turquoise = (GPS – Loads)

(GPS – Load) Comparison – WRMS Statistics

WRMS Changes					
	median GPS WRMS (mm)	median Load RMS (mm)	median (GPS – Load) WRMS (mm)	median WRMS reduction (%)	% of stations with lower WRMS
Global Network (706 stations)					
dN	1.4	0.5	1.3	3.8	72.0
dE	1.45	0.4	1.4	1.6	62.9
dU	4.6	2.6	3.8	15.2	87.4

- **Load corrections are globally effective to reduce WRMS**
  - **most stations show reduced WRMS scatter after load corrections**
  - **especially for dU**
  - **but most residual variation still remains after load corrections**
  - **especially for dN & dE**

(GPS – Load) Comparison – WRMS Statistics

WRMS Changes					
	median GPS WRMS (mm)	median Load RMS (mm)	median (GPS – Load) WRMS (mm)	median WRMS reduction (%)	% of stations with lower WRMS
Global Network (706 stations)					
dN	1.4	0.5	1.3	3.8	72.0
dE	1.45	0.4	1.4	1.6	62.9
dU	4.6	2.6	3.8	15.2	87.4
TibXS Network (28 stations)					
dN	1.9	0.8	1.6	10.9	78.6
dE	1.5	0.6	1.5	2.4	57.1
dU	6.75	4.4	4.5	33.6	100.0

- **Load corrections are globally effective to reduce WRMS**
  - **esp for dU – but most residual variation remains, esp for dN & dE**

- **Loads are larger & therefore corrections more effective in TibXS**
  - **esp for dU – but smaller % improved for dE**

(GPS – Load) Comparison – Annual Amp Statistics

Annual Amplitude Changes					
	median GPS annual (mm)	median Load annual (mm)	median (GPS – Load) annual (mm)	median annual (cor/no corr) ratio	% of stations with lower annual amp
Global Network (706 stations)					
dN	0.9	0.45	0.65	0.78	70.7
dE	0.8	0.4	0.7	0.92	59.3
dU	3.6	2.4	1.7	0.52	87.1

- **Load corrections similarly effective globally to reduce annual amps**
  - **most stations show reduced annual signals after load corrections**
  - **dU amplitude reduced by half**
  - **but most annual variation remains for dN & dE**

(GPS – Load) Comparison – Annual Amp Statistics

Annual Amplitude Changes					
	median GPS annual (mm)	median Load annual (mm)	median (GPS – Load) annual (mm)	median annual (cor/no corr) ratio	% of stations with lower annual amp
Global Network (706 stations)					
dN	0.9	0.45	0.65	0.78	70.7
dE	0.8	0.4	0.7	0.92	59.3
dU	3.6	2.4	1.7	0.52	87.1
TibXS Network (28 stations)					
dN	1.5	0.8	0.9	0.57	82.1
dE	1.0	0.6	0.9	0.97	53.6
dU	7.2	4.4	2.3	0.29	100.0

- Load corrections similarly effective globally to reduce annual amps
  - dU amp reduced by half – but most annual variation remains for dN & dE
- Loads are larger & therefore corrections more effective in TibXS
  - esp for dU – but less slightly effective for dE

A Generalized Model of Position WRMS

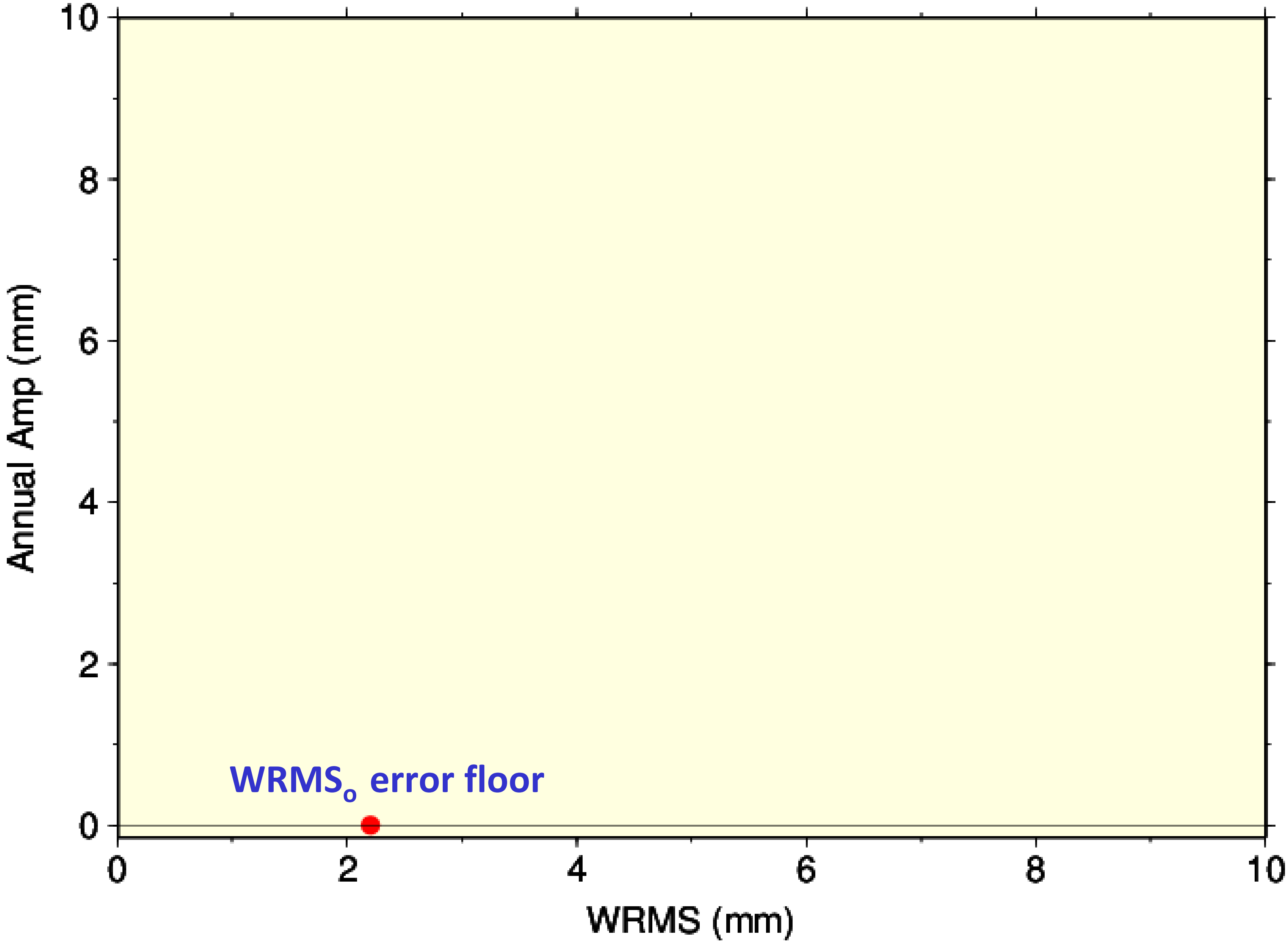
$$WRMS^2 = WRMS_o^2 + (A_i * AnnAmp_i)^2 + WRMS_i^2$$

- **$WRMS_o^2$ = globally averaged error floor, including:**
  - basement electronic & thermal noise
  - *a priori* modeling errors (tides & basic geophysics)
  - other large-scale random analysis errors (e.g., orbits)

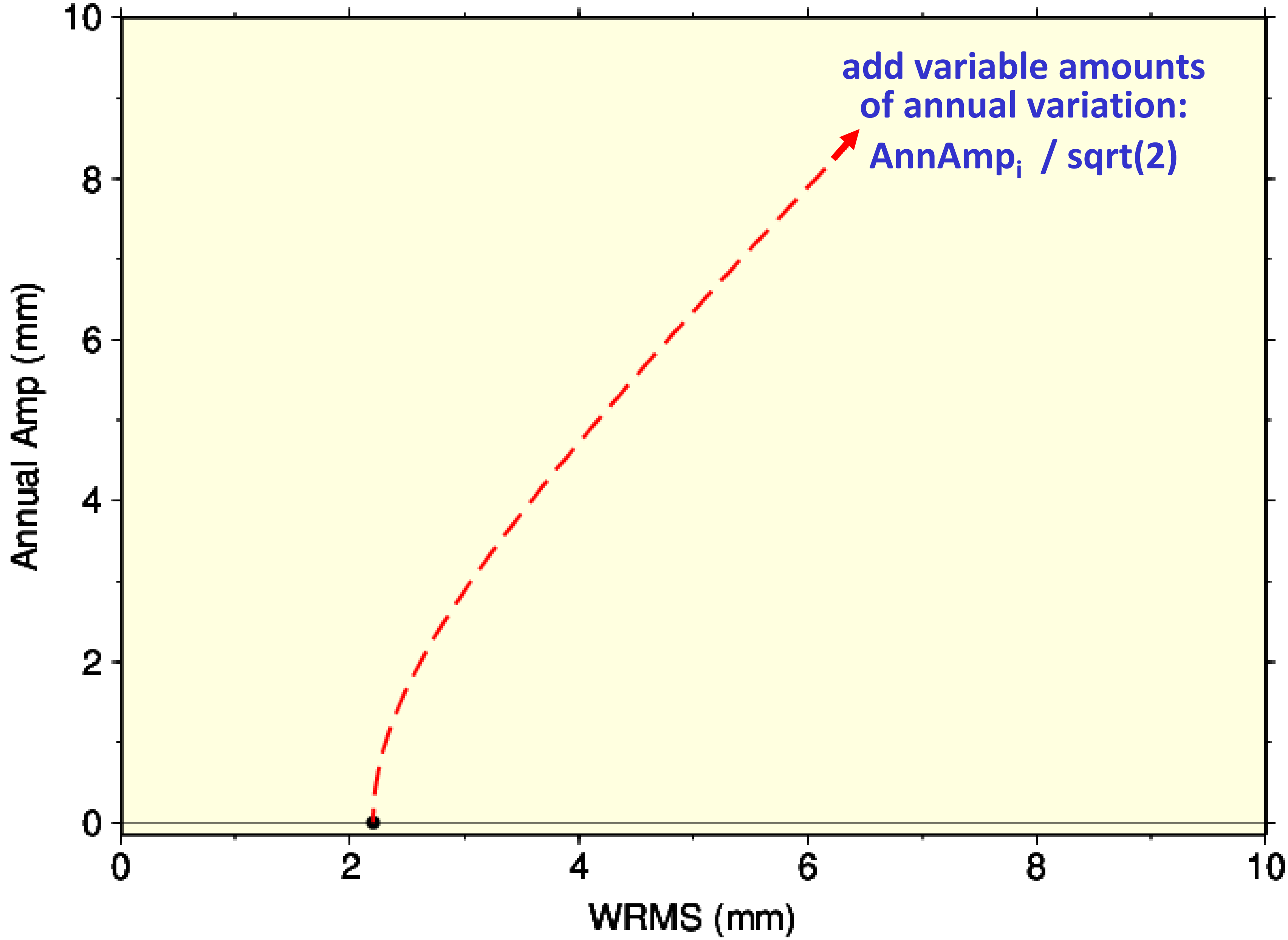
- **$AnnAmp_i$ = mean annual amplitude**
  - $A_i = 1 / \mathrm{sqrt}(2) = 0.7071$ or $A_i^2 = 0.5$ → for stationary sinusoid
  - $A_i^2 > 0.5$ → for non-stationary seasonal variations
  - includes loads + all other annual effects (e.g., technique errors)

- **$WRMS_i^2$ = local site-specific errors (<u>non-annual part only</u>), e.g.:**
  - multipath + monument noise
  - antenna mis-calibration + GNSS hardware effects
  - thermal expansion of antenna installation & bedrock
  - tropo mis-modeling + orbit errors
  - non-annual loads (& residual load model errors, if corrected)
  - inter-AC analysis & station usage differences + RF realization

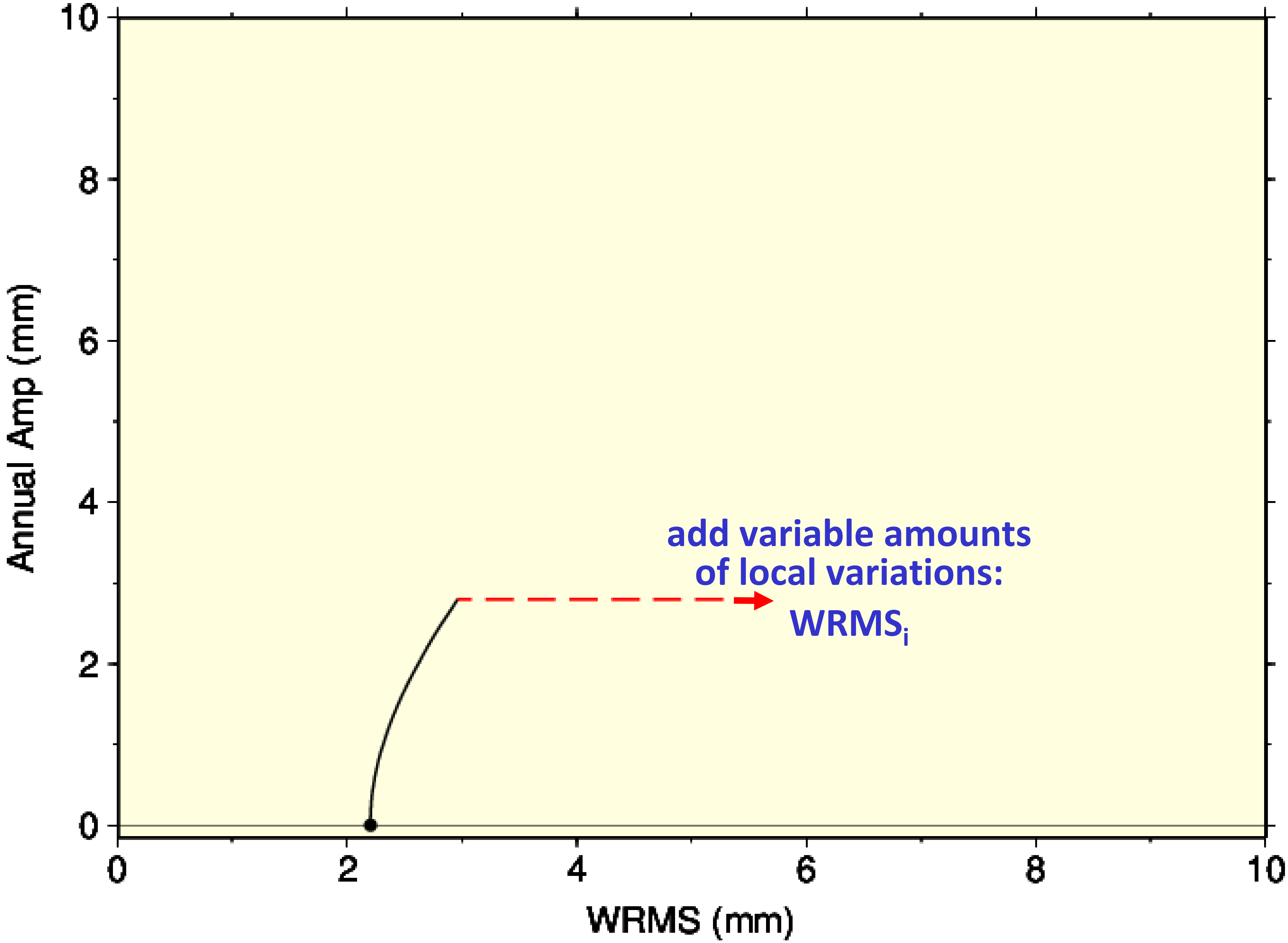
Model of Position WRMS – Global Error Floor



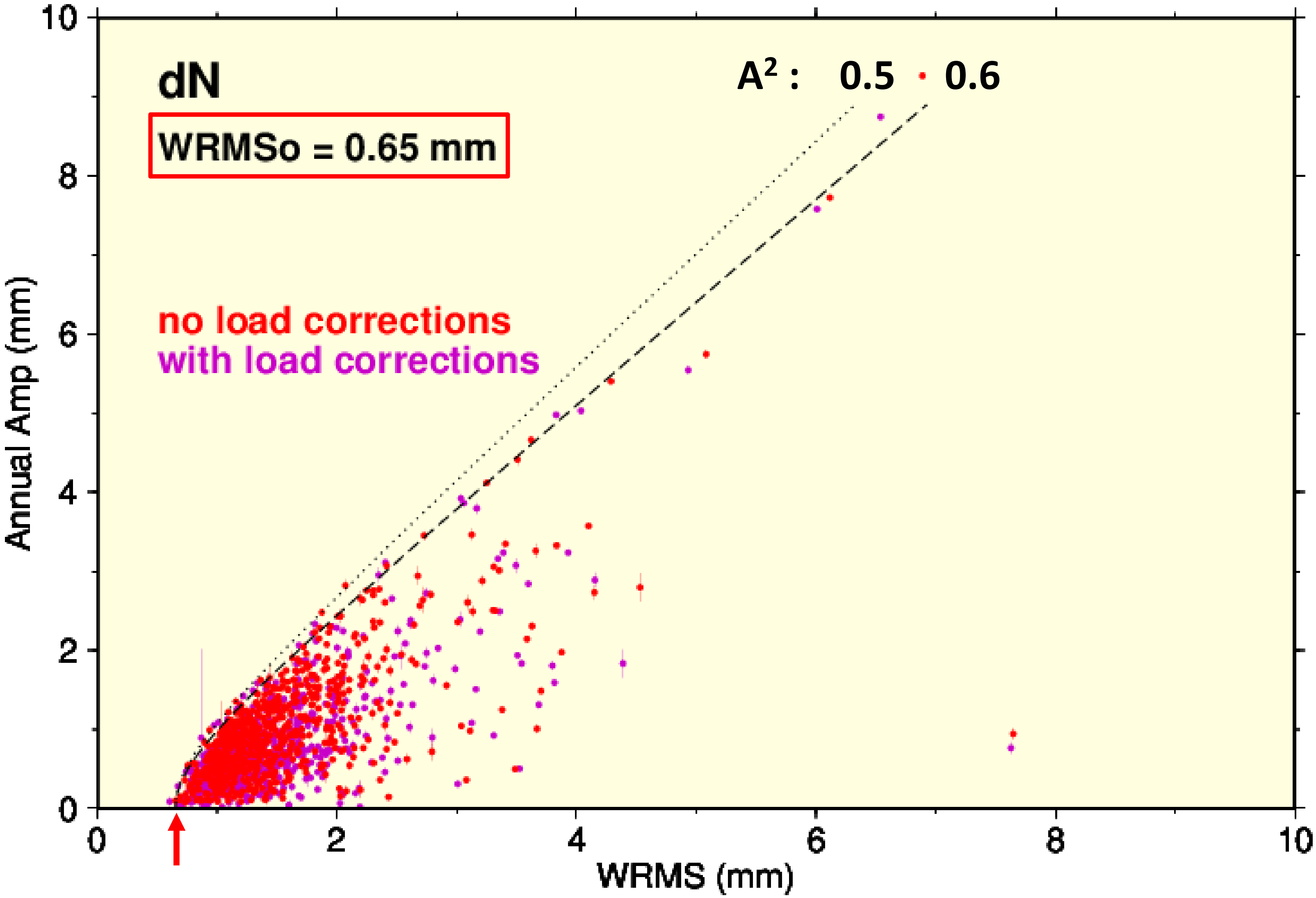
Model of Position WRMS – Annual Components



Model of Position WRMS – Local Errors

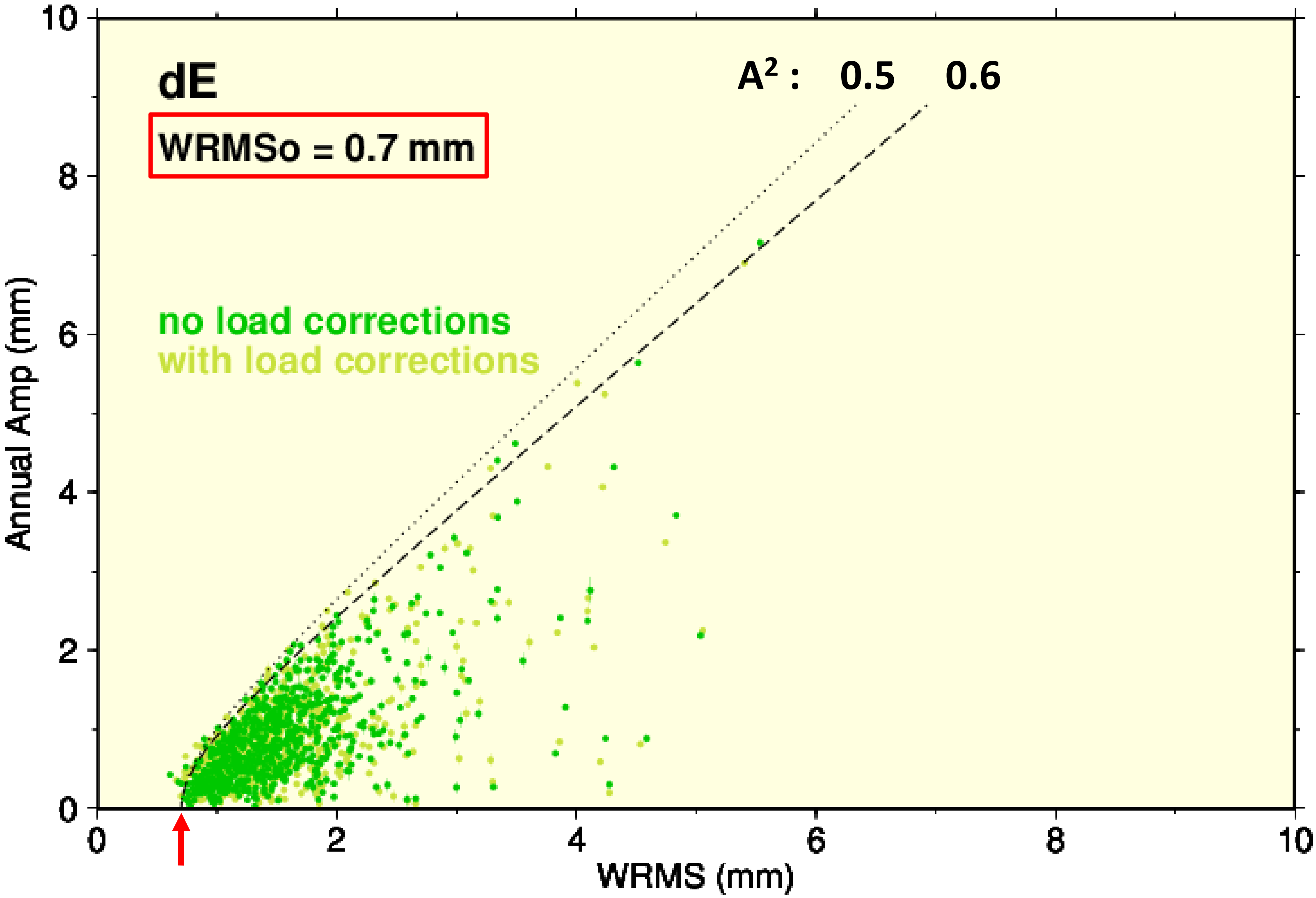


IGS Results – dN With/Without Loads



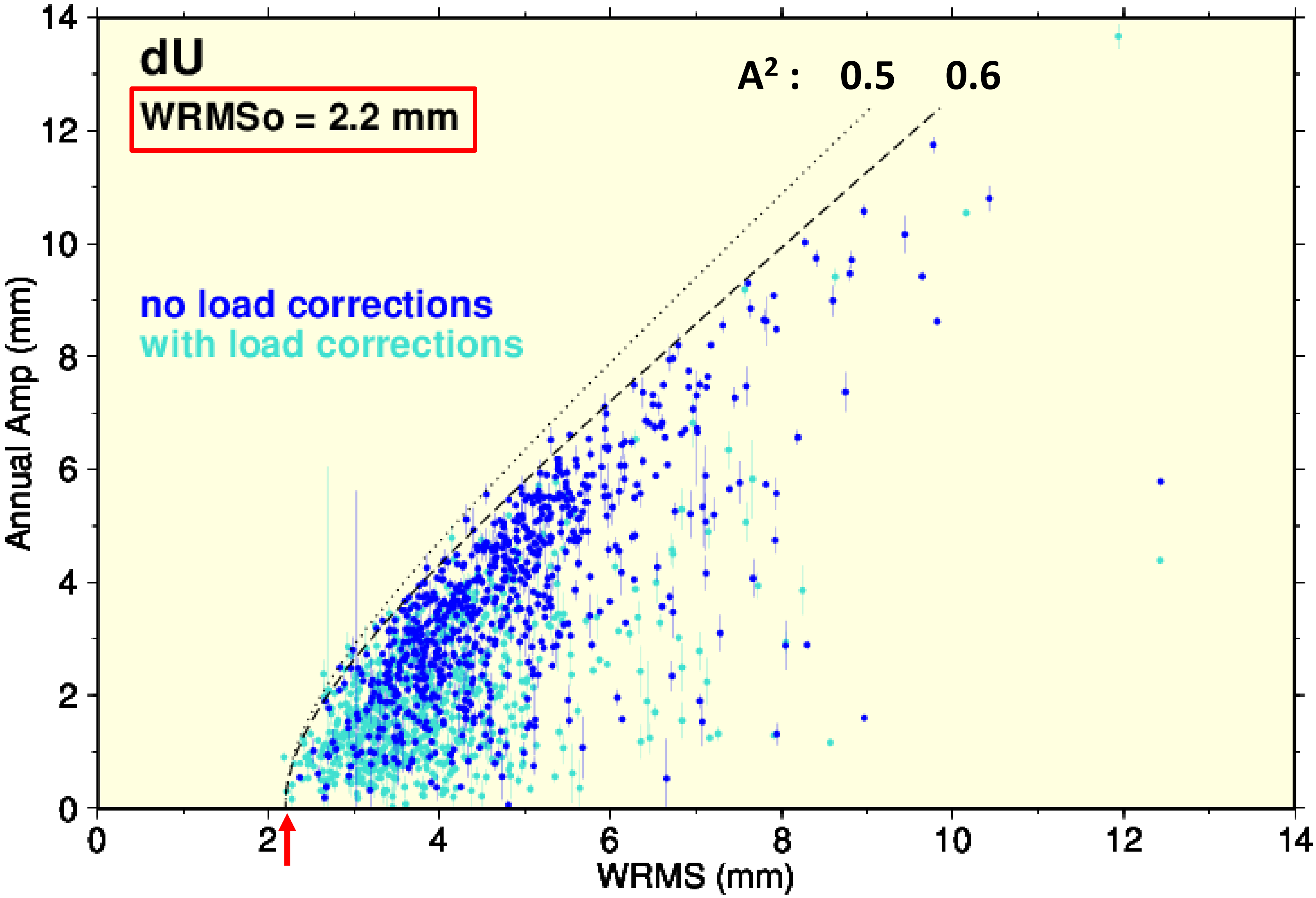
- **Load corrections have no impact on dN noise floor assessment**
  - **local site & non-load errors overwhelmingly dominate**

IGS Results – dE With/Without Loads



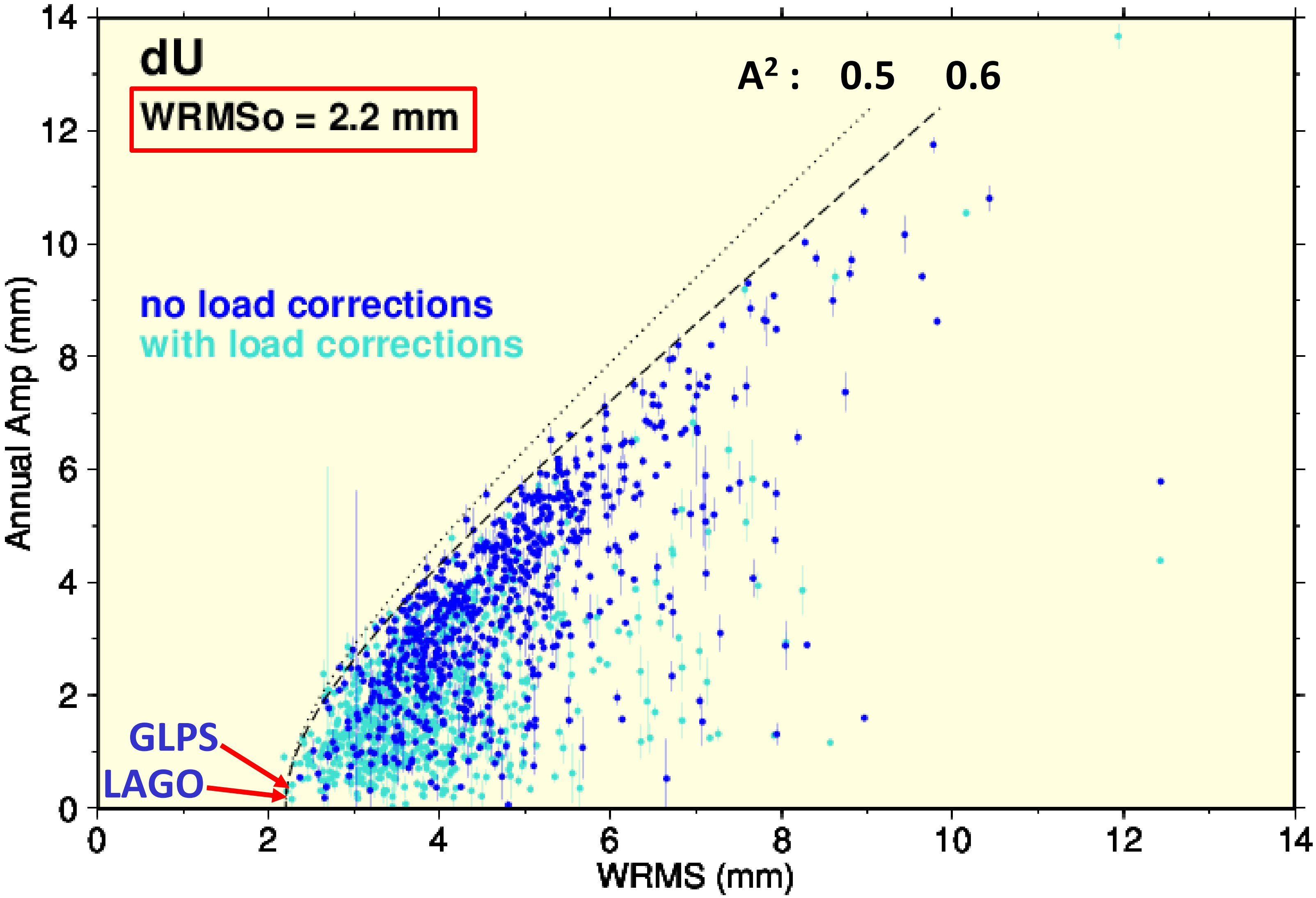
- **Load corrections have no impact on dE noise floor assessment**
  - **local site & non-load errors overwhelmingly dominate**

IGS Results – dU With/Without Loads



- **Load corrections move results much closer to dU noise floor**
  - **but local site & non-load errors still dominate**

IGS Results – dU With/Without Loads



- "Best" 2 stations in dU (WRMS = 2.2 mm) are:
  - LAGO (S. coast, Portugal) & GLPS (island, Pacific Ocean)
  - loading effects moderated by nearby oceans due to inverted barometer

Evaluation of Error Sources: Error Floor

$$WRMS^2 = \boxed{WRMS_o^2} + (A_i * AnnAmp_i)^2 + WRMS_i^2$$

- $WRMS_o^2$ = globally averaged error floor, including:
  - basement electronic & thermal (receiver) noise
  - *a priori* modeling errors (tides & basic geophysics)
  - other large-scale random analysis errors (e.g., orbits)

- Estimate thermal noise from differences between station pairs with shared antennas (19 globally)

- Infer modeling + analysis error floors by quadratic differencing

Decomposition of Weekly WRMS Error Floor

	thermal noise (via 19 global pairs with shared antennas)	inferred models + analysis error floor	observed total $WRMS_o$ (mm)
dN	0.4	0.5	0.65
dE	0.4	0.6	0.7
dU	1.3	1.7	2.2

Evaluation of Error Sources: Annual Signals

$$WRMS^2 = WRMS_o^2 + \boxed{(A_i * AnnAmp_i)^2} + WRMS_i^2$$

- $AnnAmp_i$ = mean annual amplitude
  - includes loads + all other annual effects (e.g., technique errors)
  - $A_i^2 \approx 0.6$ → from empirical IGS results
- Most horizontal annual motions probably not caused by loads
  - technique errors are probably most important sources
- dU load modeling seems fairly reliable (see next slide)
  - but non-load & technique errors are also significant for dU

Decomposition of Annual Signals (global medians)

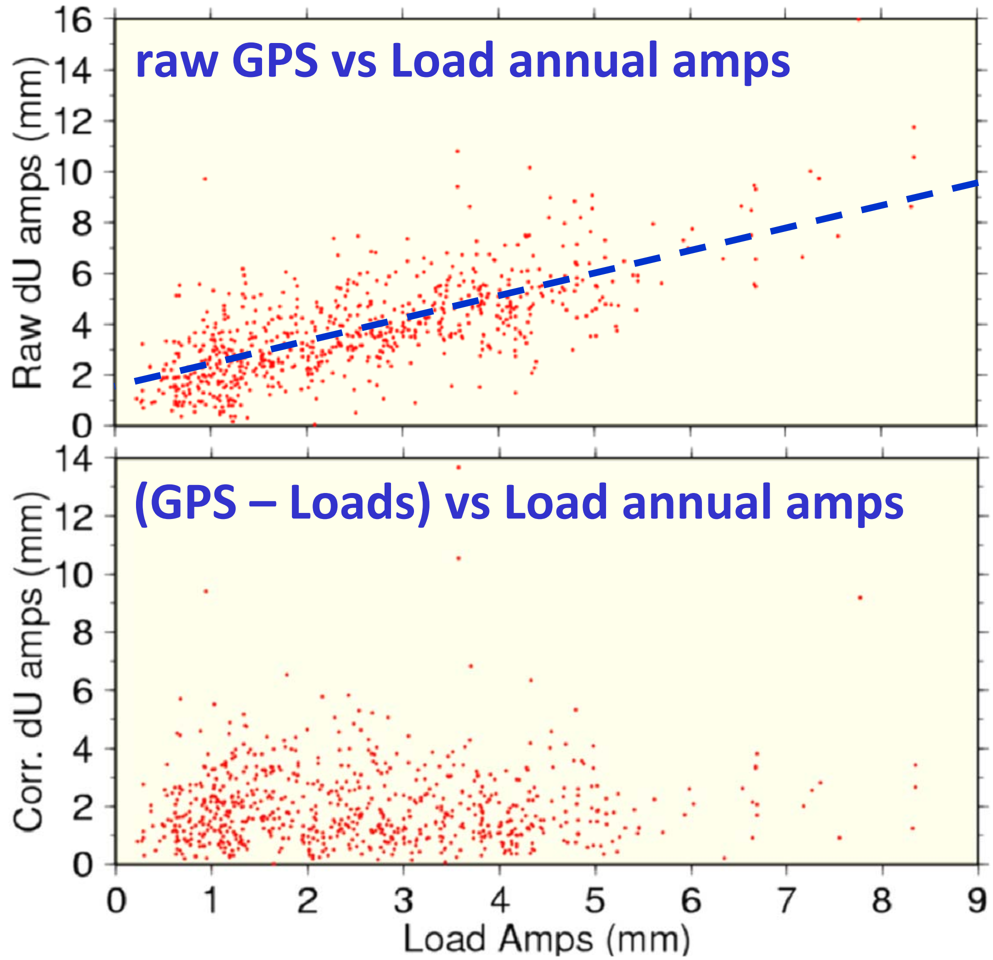
	median load annual amp (mm)	median non-load annual amp (mm)	observed median GPS raw annual amp (mm)
dN	0.45	0.65	0.9
dE	0.4	0.7	0.8
dU	2.4	1.7	3.6

Effectiveness of dU Annual Load Models

- **dU load corrections appear rather effective at annual periods**
  - **e.g., no scale defect seen**
  - **but residual non-load annual signals also clearly remain**

- **dN, dE load corrections have essentially no effect**
  - **non-load sources dominate annual signals**

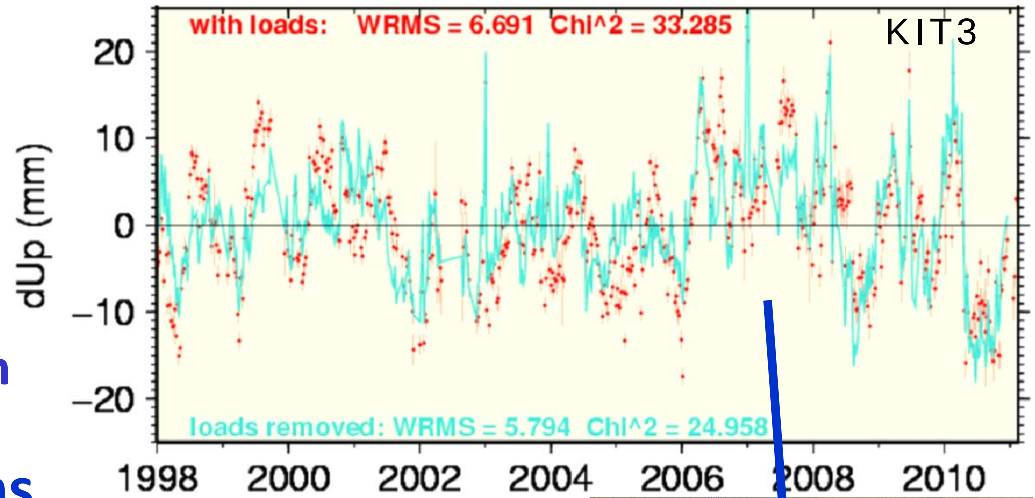
- **Need to identify sources for non-load annual signals**
  - **see following slides**

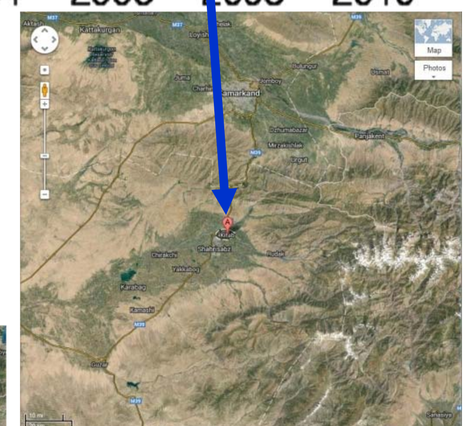


- **But no doubt that model load must have some errors too**
  - **probably largest errors from land water & ice/snow hydrology**
  - **e.g., inter-annual hydrology variations (see next slide)**

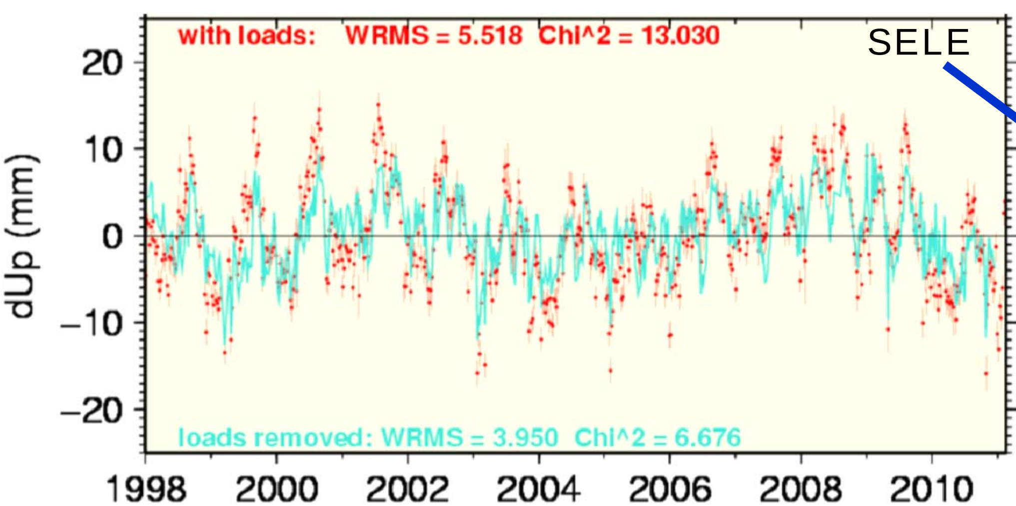
Some Inter-Annual Signals Possibly Mismodeled

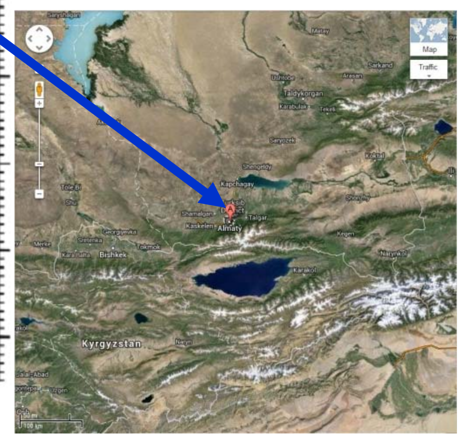
- **KIT3 (Kitab, Uzbekistan) & SELE (Almaty, Kazakhstan) both show significant inter-annual dU variations**
  - load corrections partially effective
  - but inter-annual signals remain





- **Both stations also sit in basins in mountainous regions**
  - unmodeled water/snow load signals appear plausible





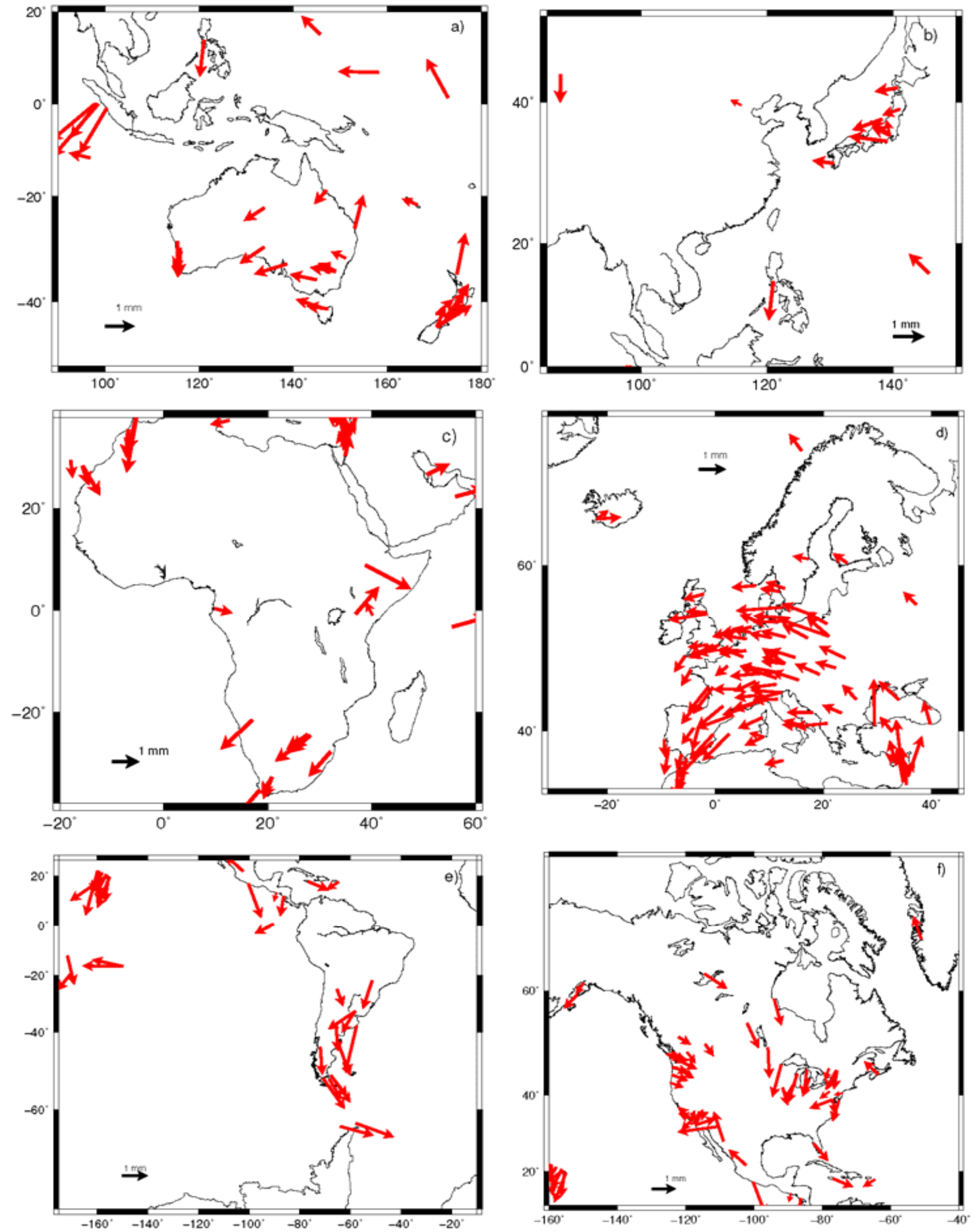
Non-load Annual Signals: 1. Draconitic Errors

- **Draconitic year = 351.2 d**
  - or frequency = 1.04 cpy
  - 1st & 2nd harmonics overlay seasonal signals

- **Strong spatial correlations in IGS position time series**
  - fit (1.0 + 2.0 + 3.12 + 4.16) cpy
  - plot significant dU 4th harmonics (ϕ clockwise from N wrt 2000)
  - very striking in most regions
  - also seen in dN distribution
  - esp coherent in Europe
  - Amiri-Simkooei (2013) found mean 1st harmonic amps of: 1.4 (dN), 1.3 (dE), 2.8 (dU) mm

- **Implies orbit-related source**
  - also seen in all other products

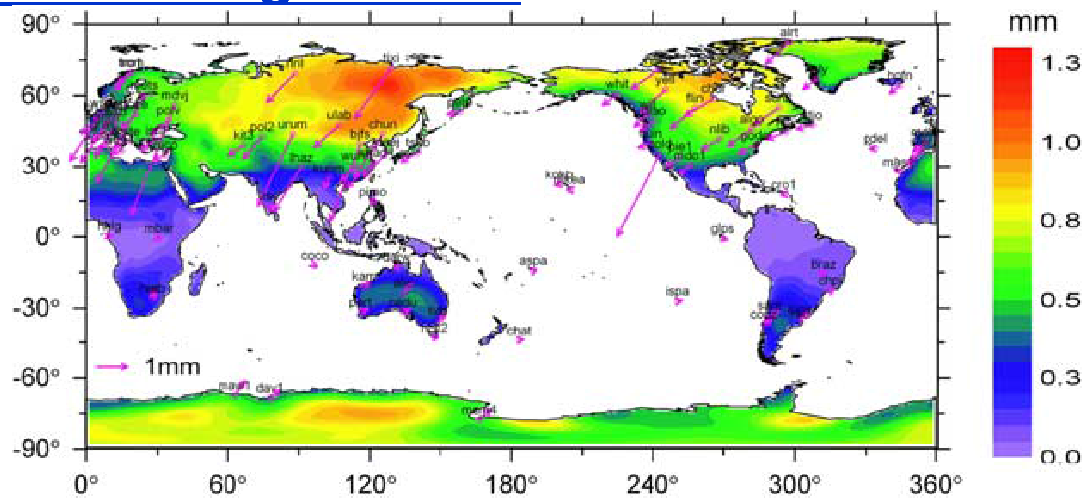
Distribution of dU 4th Draconitic Signals

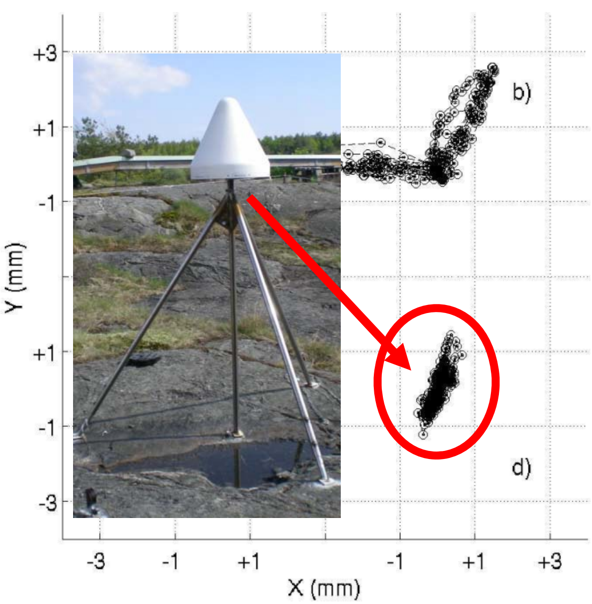


Non-load Annual Signals: 2. Temperature Cycle

- **Thermal dU expansion of antenna monument structures**
  - ΔU (mm) $\approx$ 0.015 * (Hgt/m) * (ΔT/°C)
  - for Hgt = 3 m + annual ΔT = 30 °C ⇒ annual ΔU (mm) = 1.35 mm
  - so annual ΔT cycle probably significant for most stations outside tropics

- **Thermal dU expansion of surrounding bedrock**
  - H. Yan et al. (GRL, 2009) predict max annual amps ~1.3 mm in NE Asia





- **Horizontal tilting of antenna structures**
  - S. Bergstrand et al. (2013) measured diurnal tilting of ±1 mm for shallow drill-braced monument
  - tilting for other types usually larger
  - probably explains most dN/dE annual signals for stations outside tropics

Non-load Annual Signals: 3. IERS Models

- **Unmodeled ocean pole tide deformation**
  - to account for centrifugal effect of polar motion variations on oceans
  - amps reach ~ 0.5, 0.5, 1.8 mm in dN, dE, dU, mostly near annual & Chandler (433 d) periods
  - IERS model in Conventions 2010, but not yet implemented

- **Aliases of errors in subdaily EOP tide model**
  - K1, P1, T2 lines alias to annual periods
  - coupling through resonant 12-hr GPS orbits leads to draconitic errors
  - magnitude of position effects not yet quantified

- **Seasonal variations of low-degree geopotential terms**
  - frame origin might shift by ~1 mm, mainly in Z component
  - WRMS orbit differences might reach few-mm level

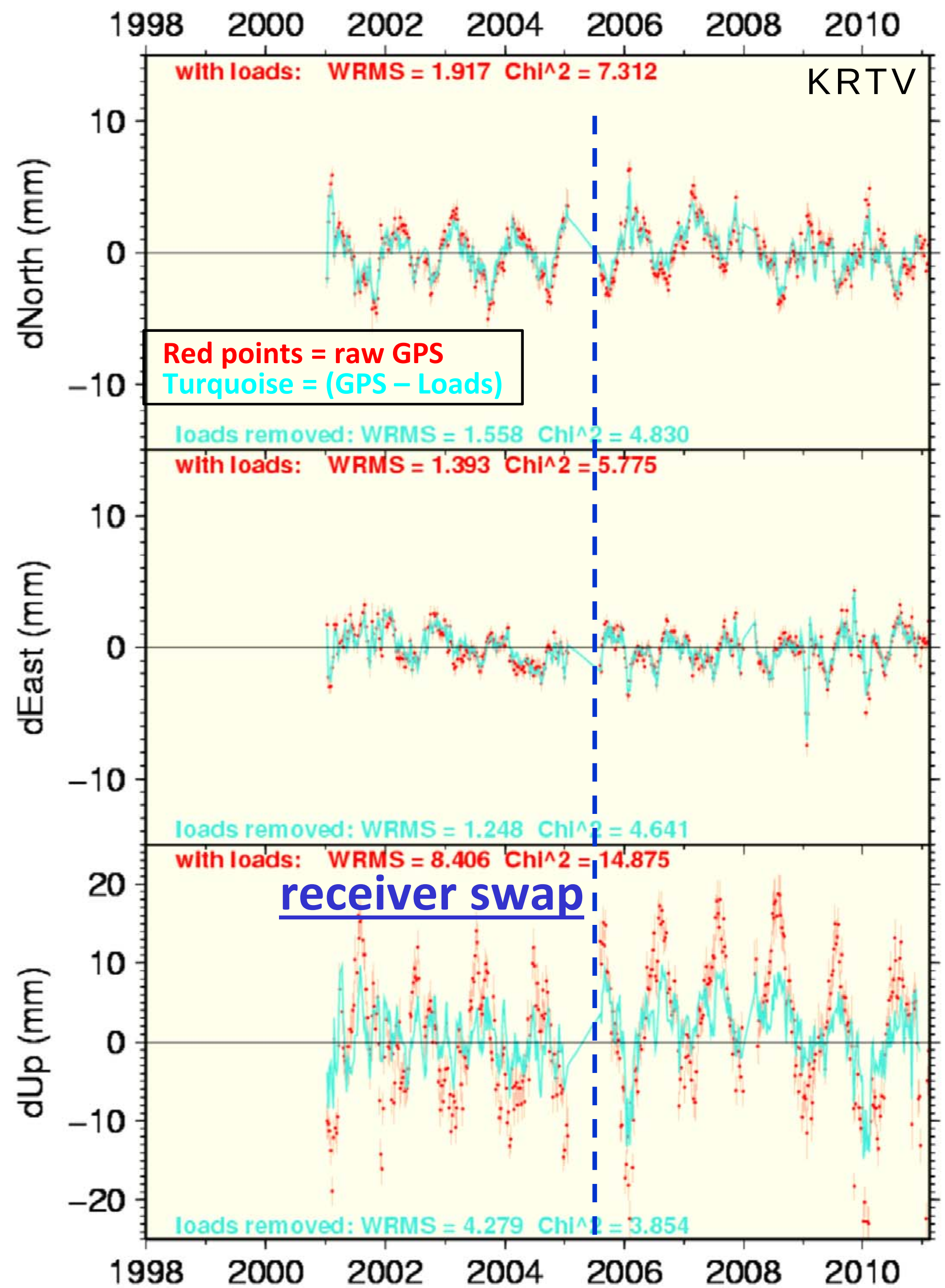
- **Unmodeled S1/S2 atmosphere pressure loading**
  - dU amps reach 1.5 mm in tropics with 12/24 hr periods
  - but should mostly average out for daily data processing

Non-load Annual Signals: 4. Antenna-Related Effects

- **Local multipath errors**
  - especially due to near-field reflectors & environment changes
  - GPS ground tracks repeat with K1 (sidereal) period
  - can alias to GPS draconitic year (352 d) for daily processing
- **Snow, ice cover, rain on or near antennas**
  - can add annual signals to data quality & sky visibility
  - most serious for stations at higher latitudes
- **Antenna calibration errors**
  - similar alias effects possible, as with local multipath

Non-load Annual Signals: 5. Receiver Hardware

- **Receiver artifacts sometimes seen**
- **e.g., receiver changed: AOA Rogue SNR-8000 → Trimble 4000SSI on 2005-08-02**
  - dU annual amp clearly increased after receiver swap
  - non-load annual amp also increased afterwards
  - no obvious impact for dN, dE
- **Such effects can occur due to improved/degraded sky coverage, SNR change, etc**
- **While not unique, such receiver effects are not very common**



Non-load Annual Signals: 6. Other Effects

- **Troposphere delay mismodeling**
  - due to errors in *a priori* dry zenith delay & dry/wet mapping functions
  - also errors in treatment of troposphere horizontal gradients
  - continuous progress being made
  - but ultimate solution of accurate, independent line-of-sight delays remains remote

- **Aliasing in long-term time series stacking**
  - local position variations (including load effects) can alias into Helmert frame parameters to derive long-term positions & residuals
  - methods used to minimize effects but residual errors still not eliminated

- **Processing differences among Analysis Centers (ACs)**
  - clear differences between ACs are sometimes seen for the same stations
  - effects include different draconitics but also more random variations
  - causes are unknown & probably diverse

Summary of Weekly GPS Position Errors

IGS Error Budget for Weekly Integrations							
	$WRMS_o$ (mm)			median Annual Amps (mm)		median site $WRMS_i$ (mm)	median total WRMS (mm)
	thermal (via pairs)	models + analysis	total	loads	total		
dN	0.4	0.5	0.65	0.45	0.9	1.0	1.4
dE	0.4	0.6	0.7	0.4	0.8	1.1	1.45
dU	1.3	1.7	2.2	2.4	3.6	2.9	4.6

- **Noise floor $WRMS_o$ & local site errors $WRMS_i$ dominate over loads**
  - especially for dN & dE components
  - unless load models missing about half of total signal
- **Local site $WRMS_i$ inferred by quadratic differencing**
  - residual load model errors largest at inland stations
  - plus, high-frequency contributions from all other sources listed
- **Loads larger in TibXS region & corrections more effective for dU**
- **Significant technique improvements still needed in many areas**

Thank You !