

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

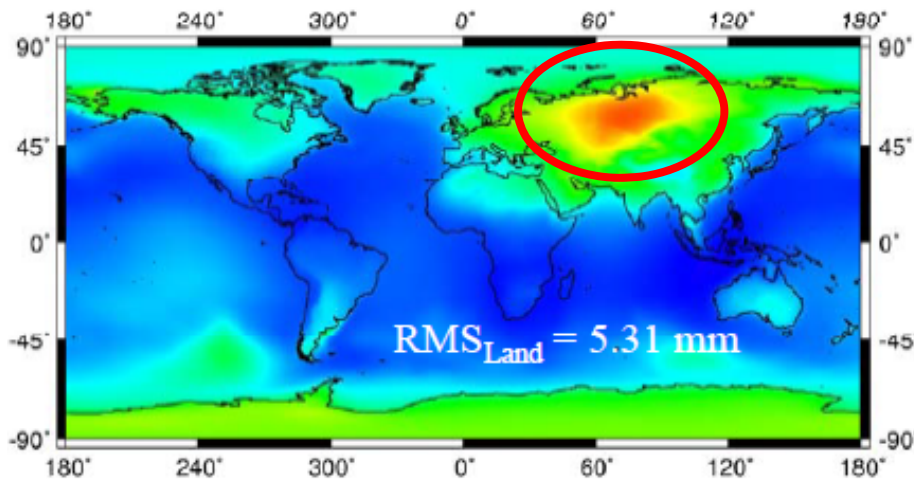
Xavier Collilieux & Paul Rebischung, IGN/LAREG

Tonie van Dam, University of Luxembourg

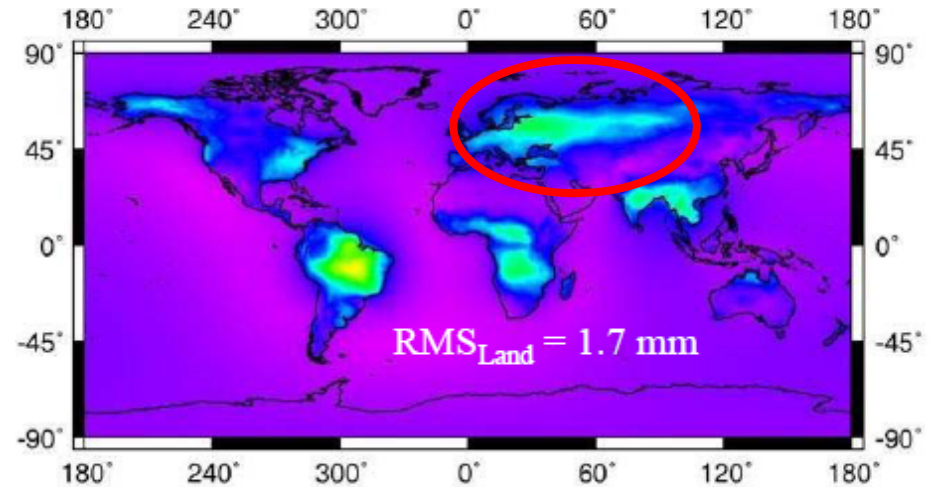
Zuheir Altamimi, IGN/LAREG

Modeled Vertical Loading Deformation Signals

Atmospheric Pressure (ECMWF-MOG2D)

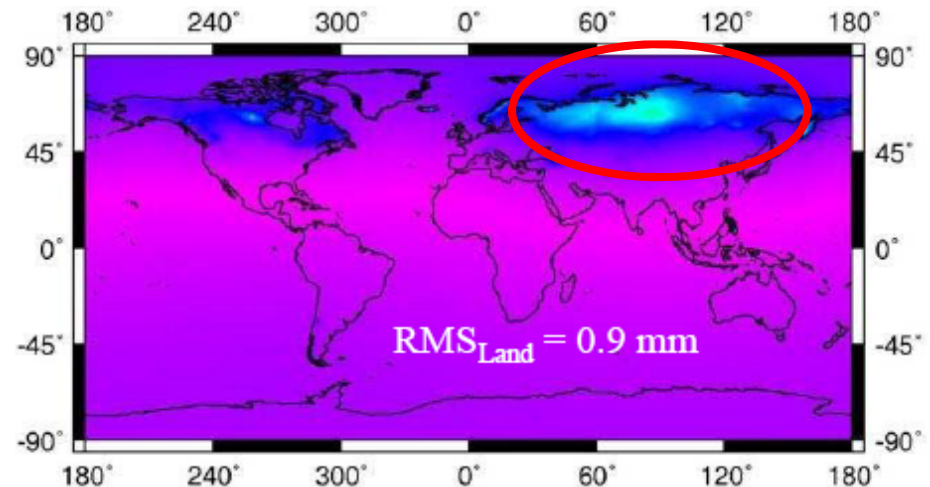


Soil Moisture (GLDAS)

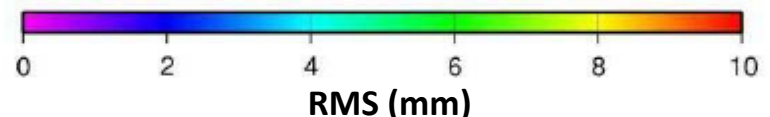


- Crustal loading is large across central Asia for all major fluid sources
- Height variations can reach 1 cm
 - at annual periods, mostly
- Signatures should be clear in IGS station position time series

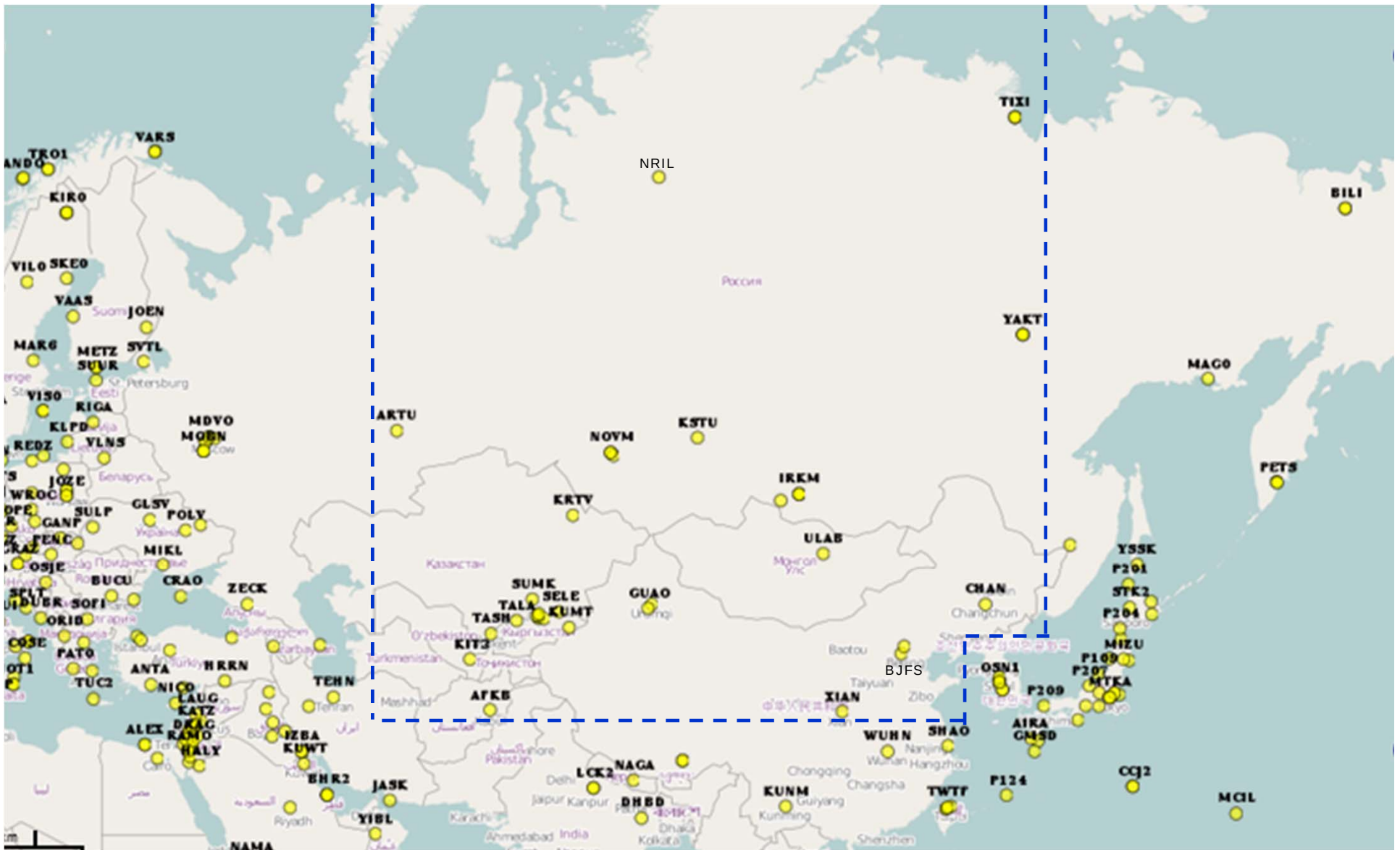
Snow (GLDAS)



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



IGS Stations in Tibet-Xinjiang-Siberia Region

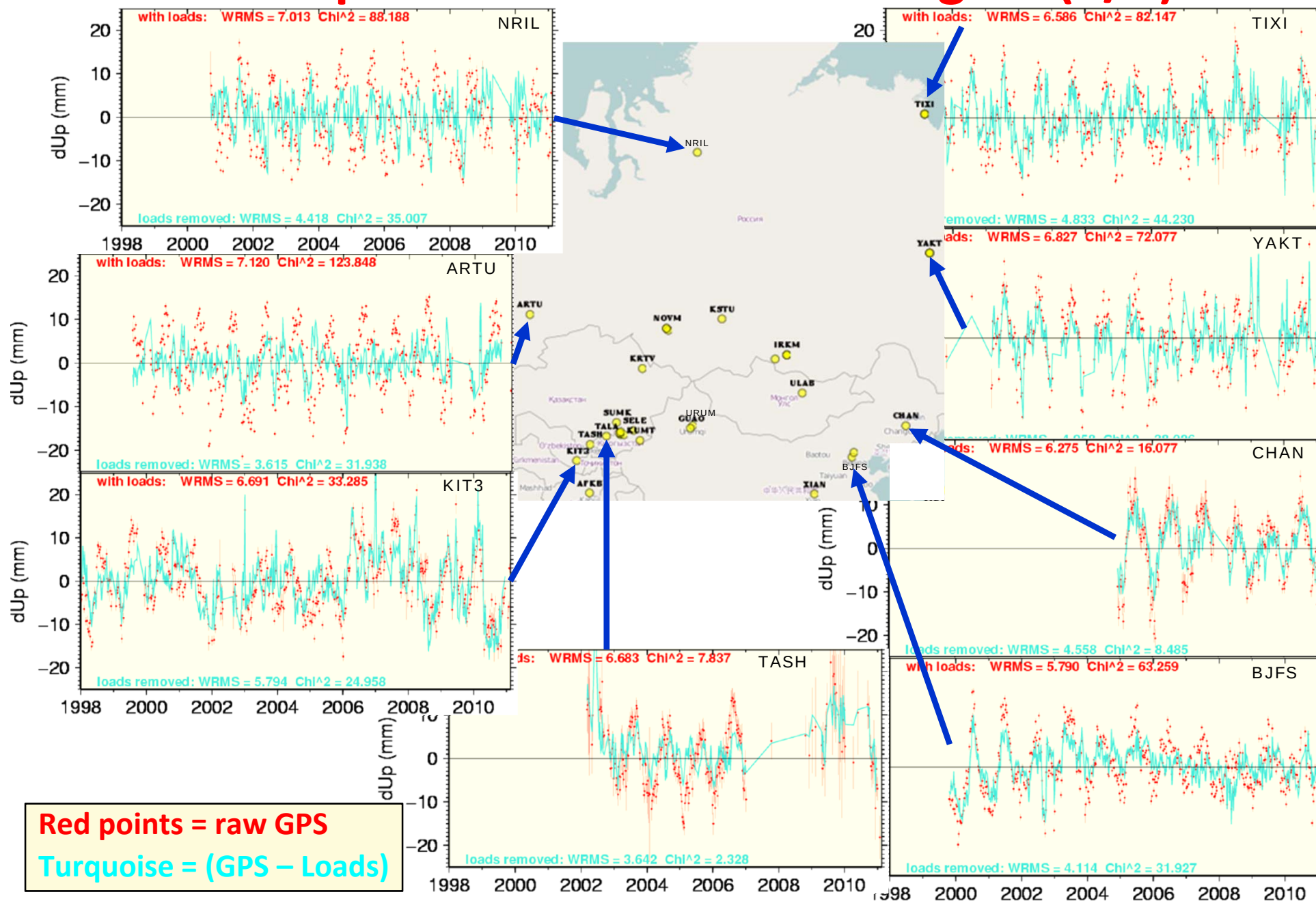


- 28 stations in TibXS region with >100 weeks of IGS Repro1 results

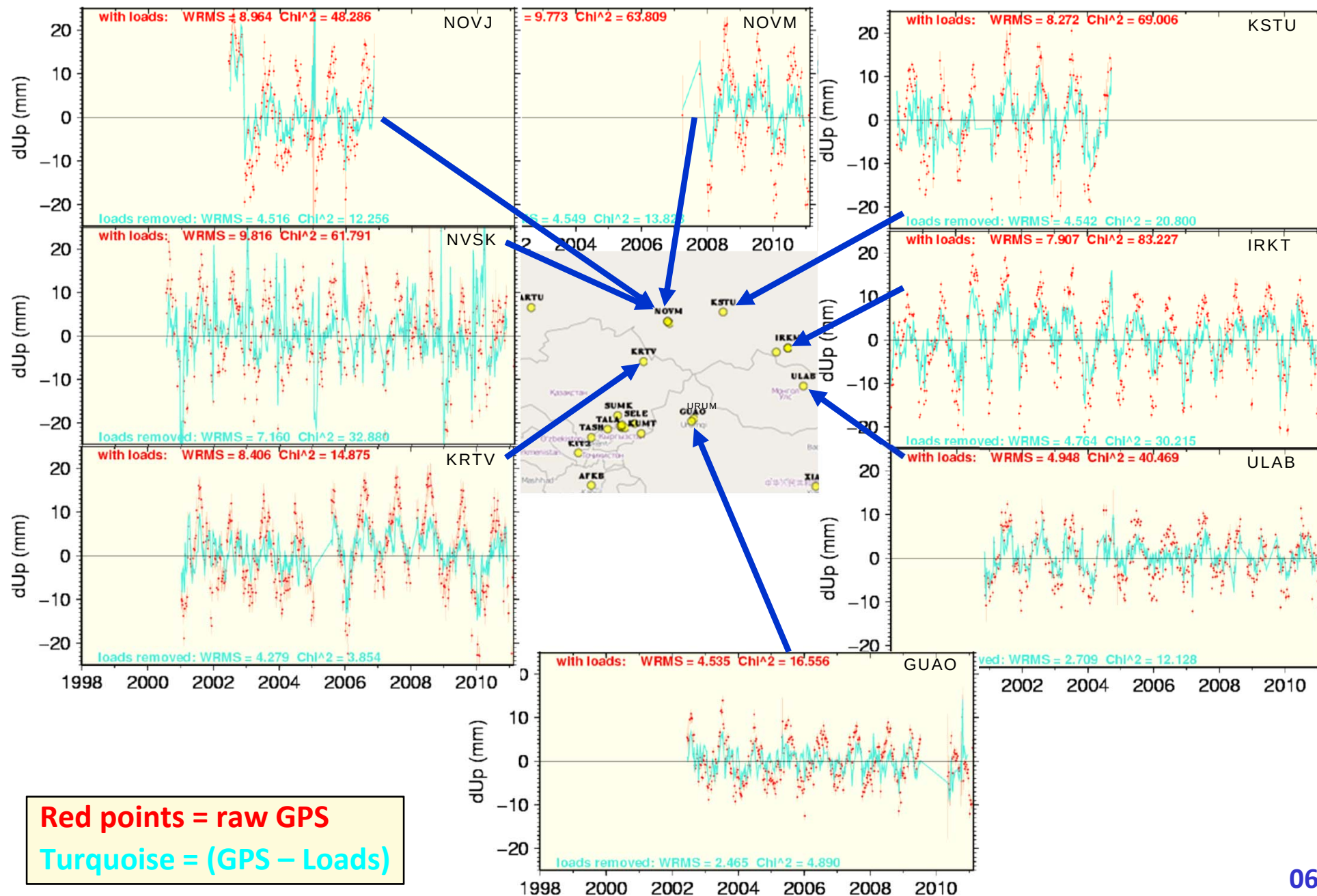
Data Sets to Compare

- **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 !

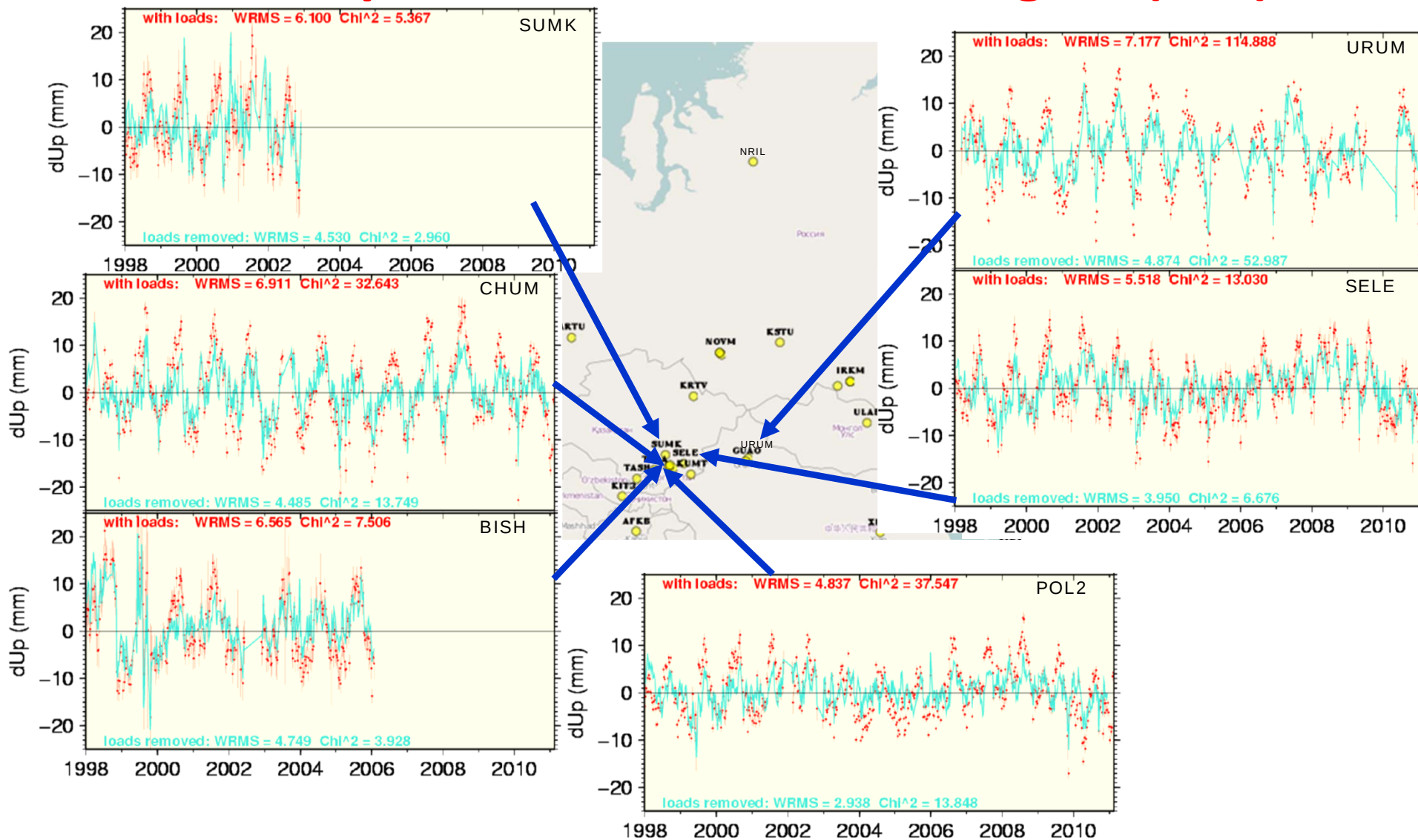
GPS dUp Time Series in TibXS Region (1/3)



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



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

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

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

- 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

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- Load corrections similarly effective globally to reduce annual amps
 - dU amp reduced by half – but most annual variation remains for dN & dE

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

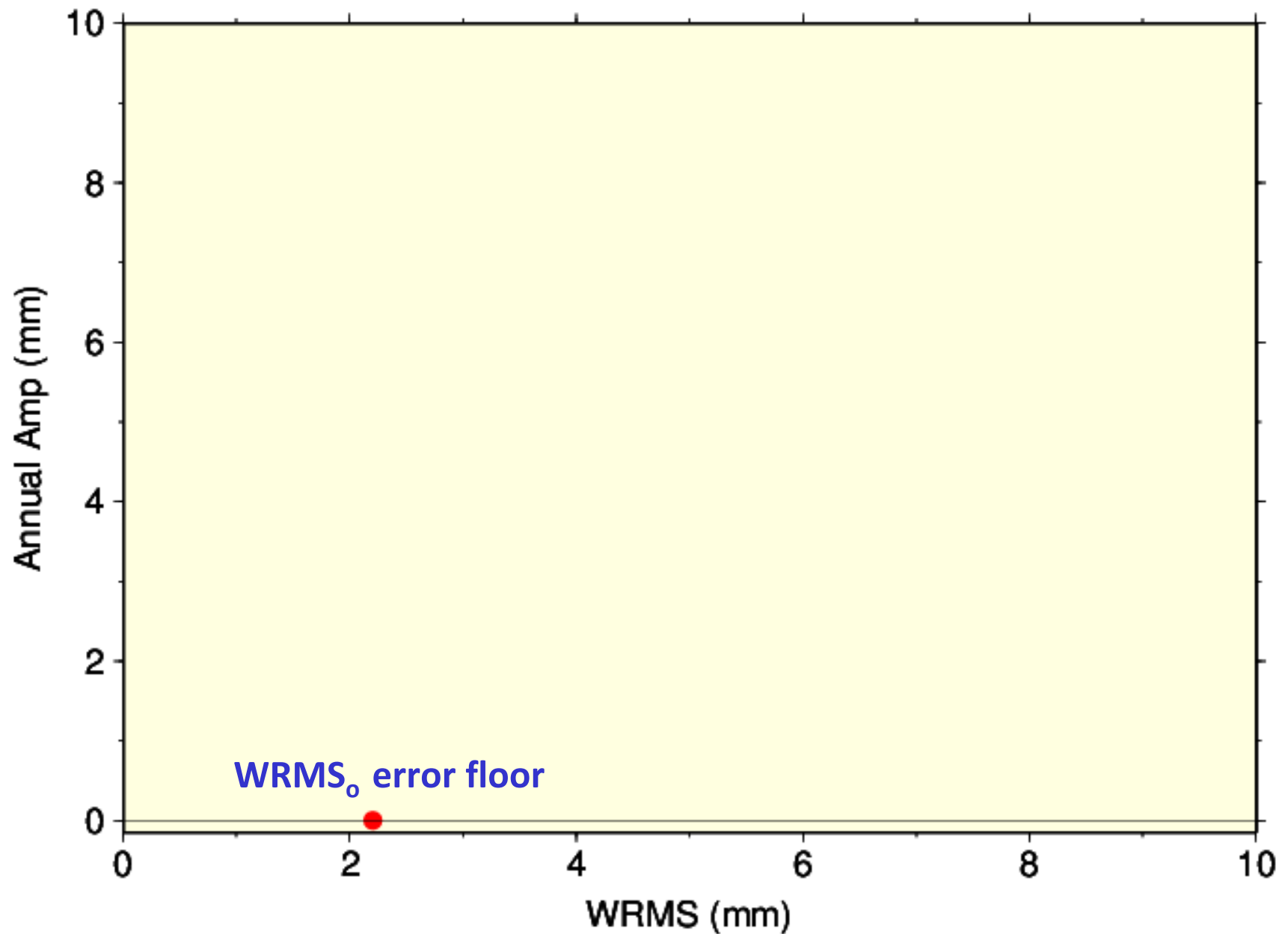
- Loads are larger & therefore corrections more effective in TibXS
 - esp for dU – but less slightly effective for dE

A Generalized Model of Position WRMS

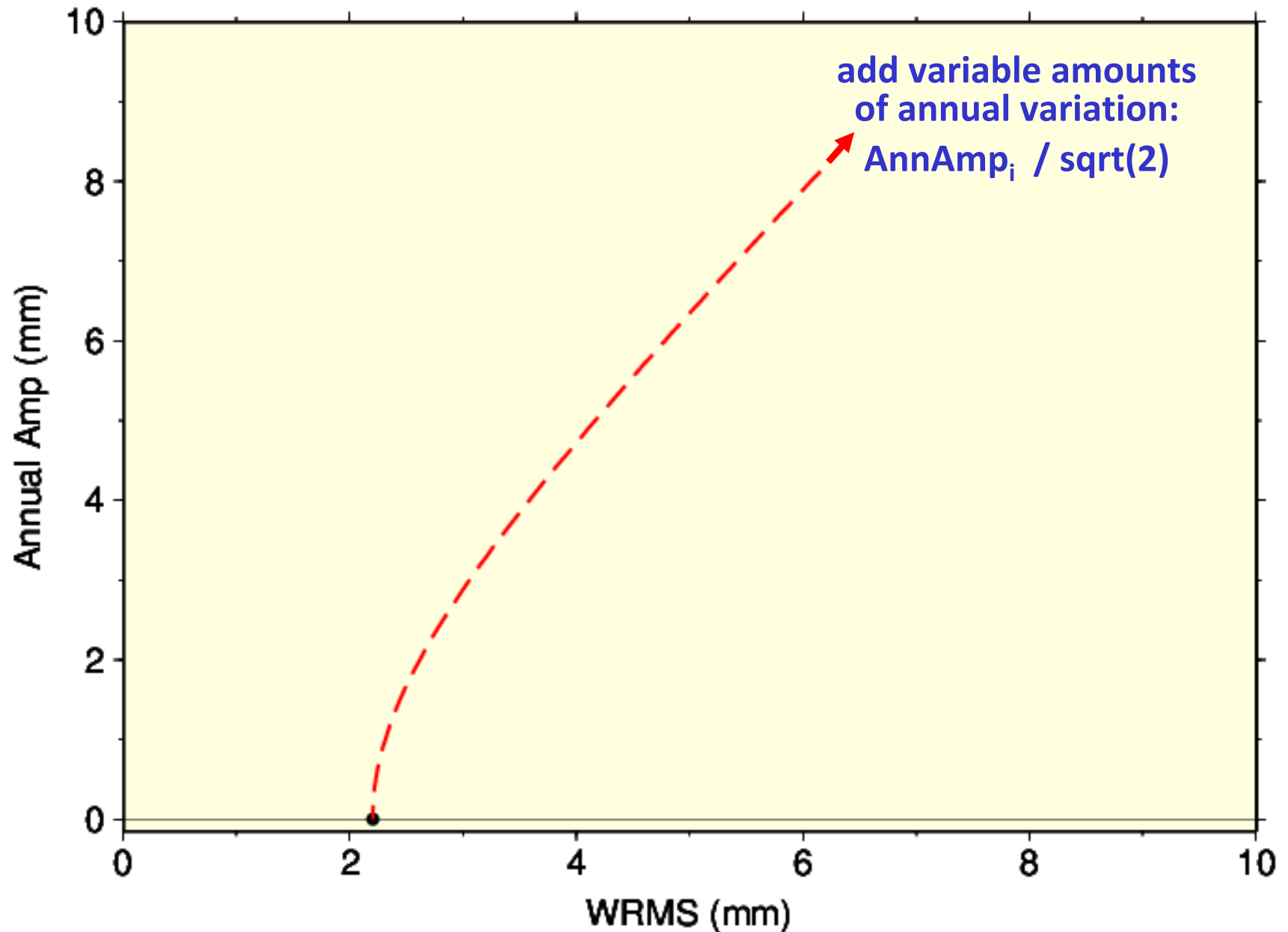
$$\text{WRMS}^2 = \text{WRMS}_o^2 + (A_i * \text{AnnAmp}_i)^2 + \text{WRMS}_i^2$$

- **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**
 - $A_i = 1 / \sqrt{2} = 0.7071$ or $A_i^2 = 0.5 \rightarrow$ for stationary sinusoid
 - $A_i^2 > 0.5 \rightarrow$ for non-stationary seasonal variations
 - includes loads + all other annual effects (e.g., technique errors)
- **WRMS_i^2 = local site-specific errors (non-annual part only), 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

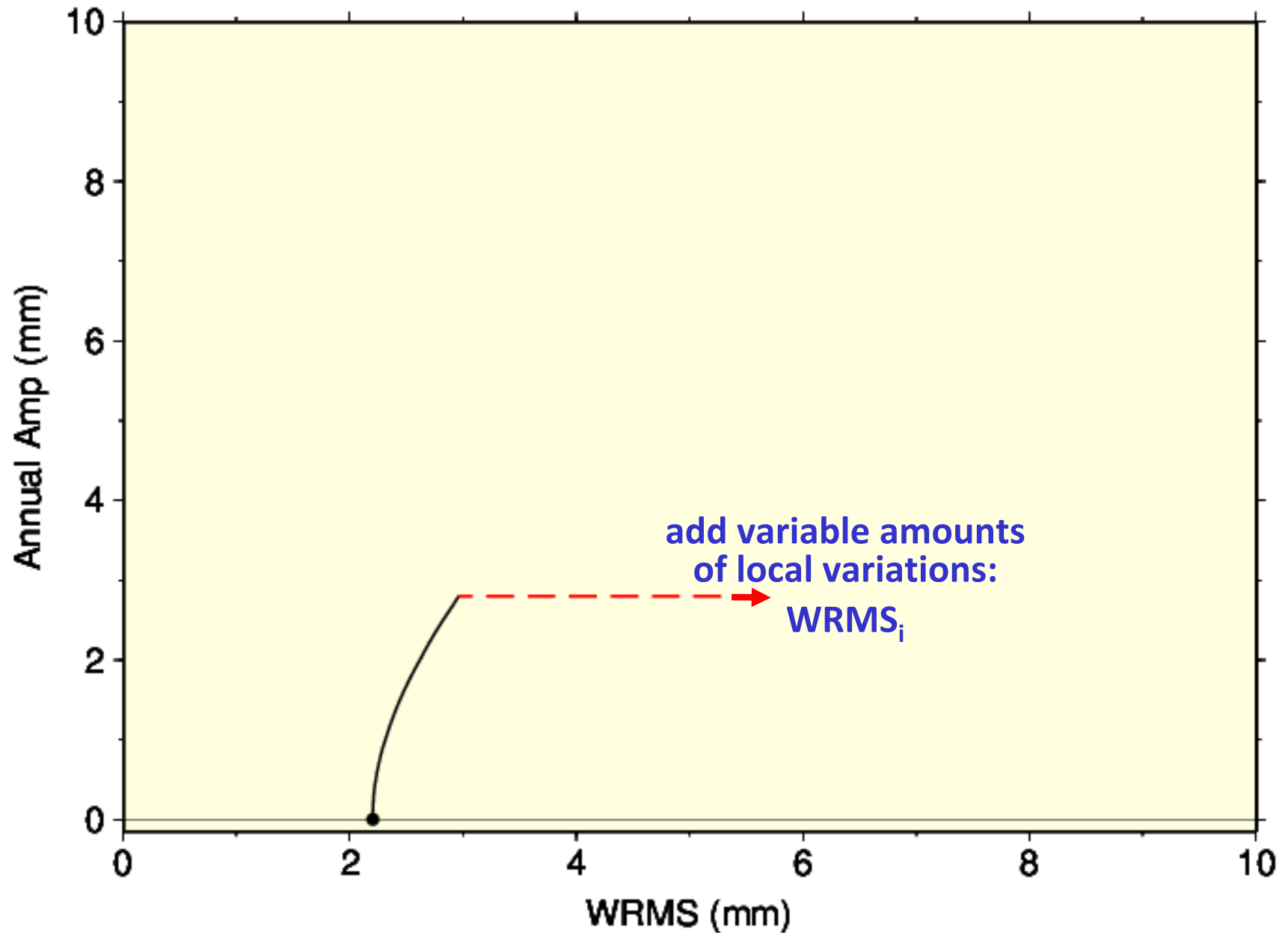
Model of Position WRMS – Global Error Floor



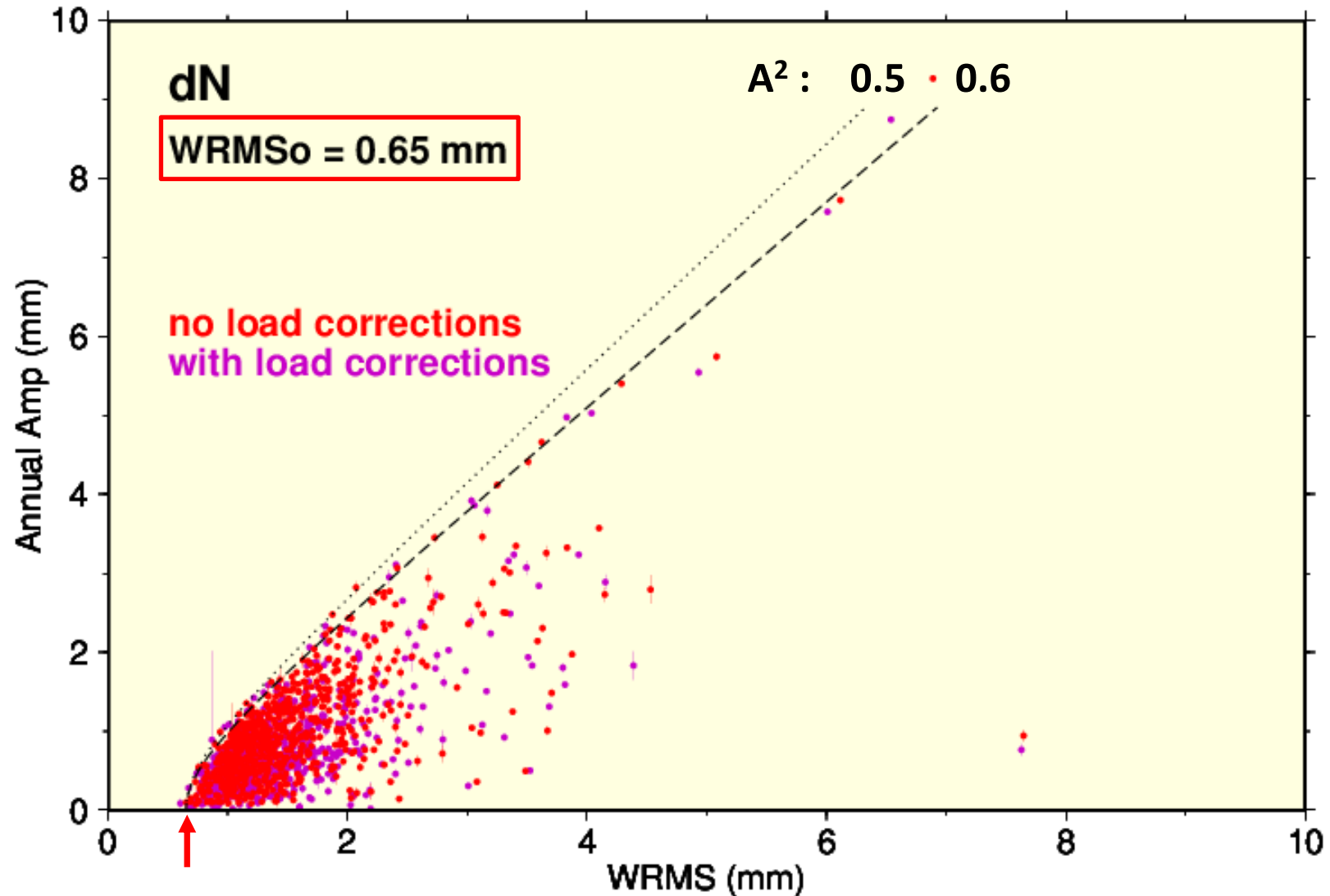
Model of Position WRMS – Annual Components



Model of Position WRMS – Local Errors

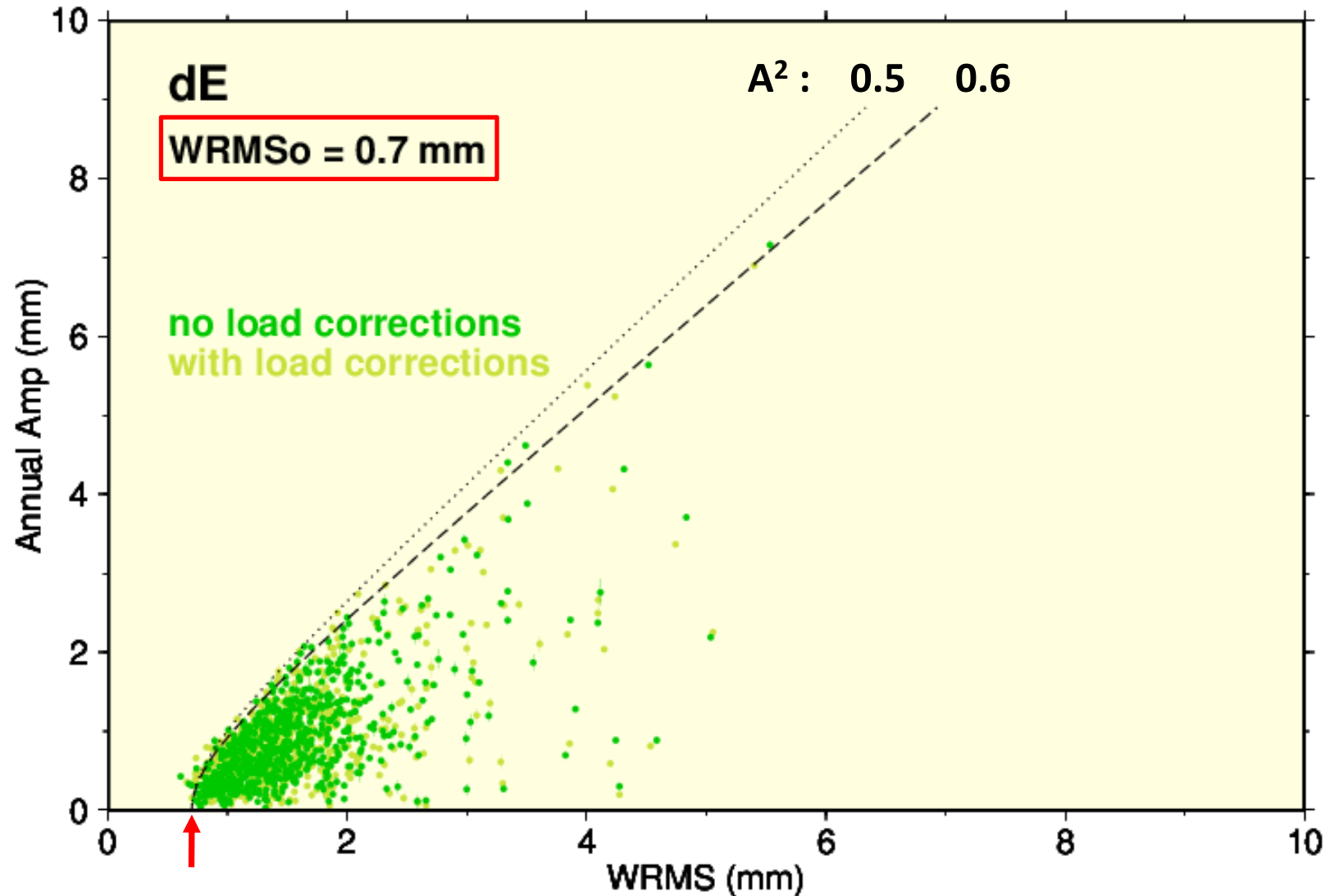


IGS Results – dN With/Without Loads



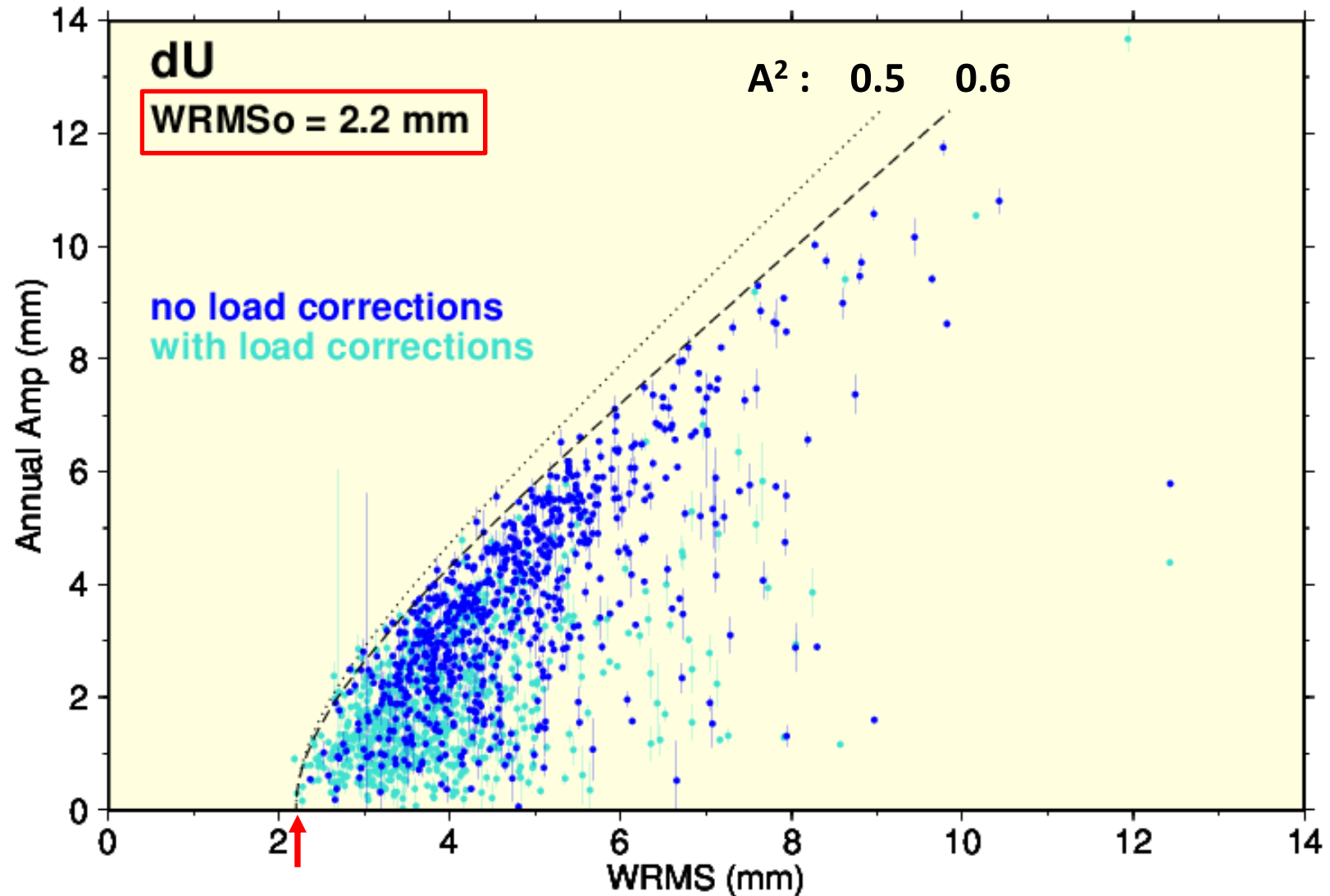
- Load corrections have no impact on dN noise floor assessment
 - local site & non-load errors overwhelmingly dominate

IGS Results – dE With/Without Loads



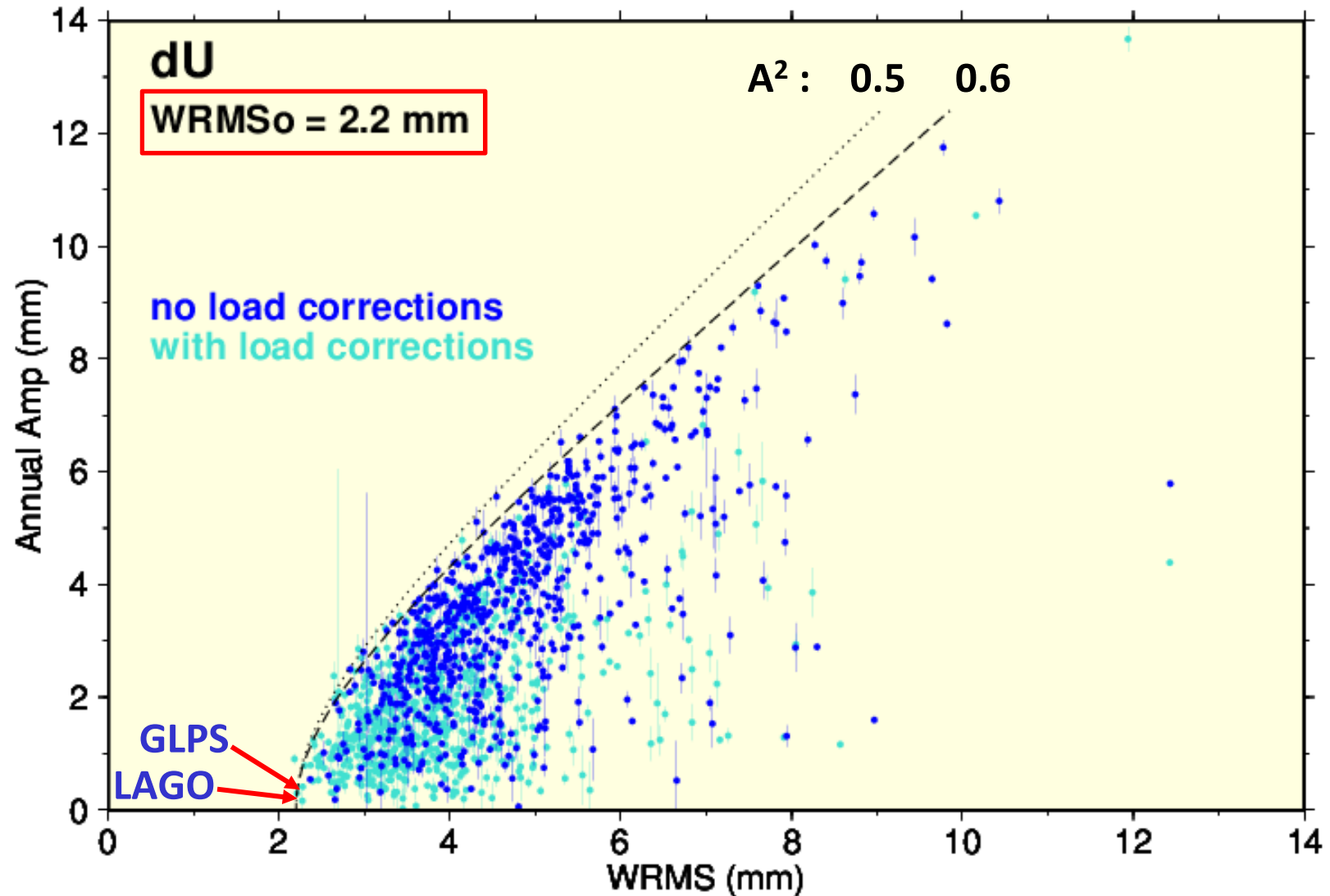
- Load corrections have no impact on dE noise floor assessment
 - local site & non-load errors overwhelmingly dominate

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

$$\text{WRMS}^2 = \boxed{\text{WRMS}_o^2} + (A_i * \text{AnnAmp}_i)^2 + \text{WRMS}_i^2$$

- **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

$$\text{WRMS}^2 = \text{WRMS}_o^2 + (A_i * \text{AnnAmp}_i)^2 + \text{WRMS}_i^2$$

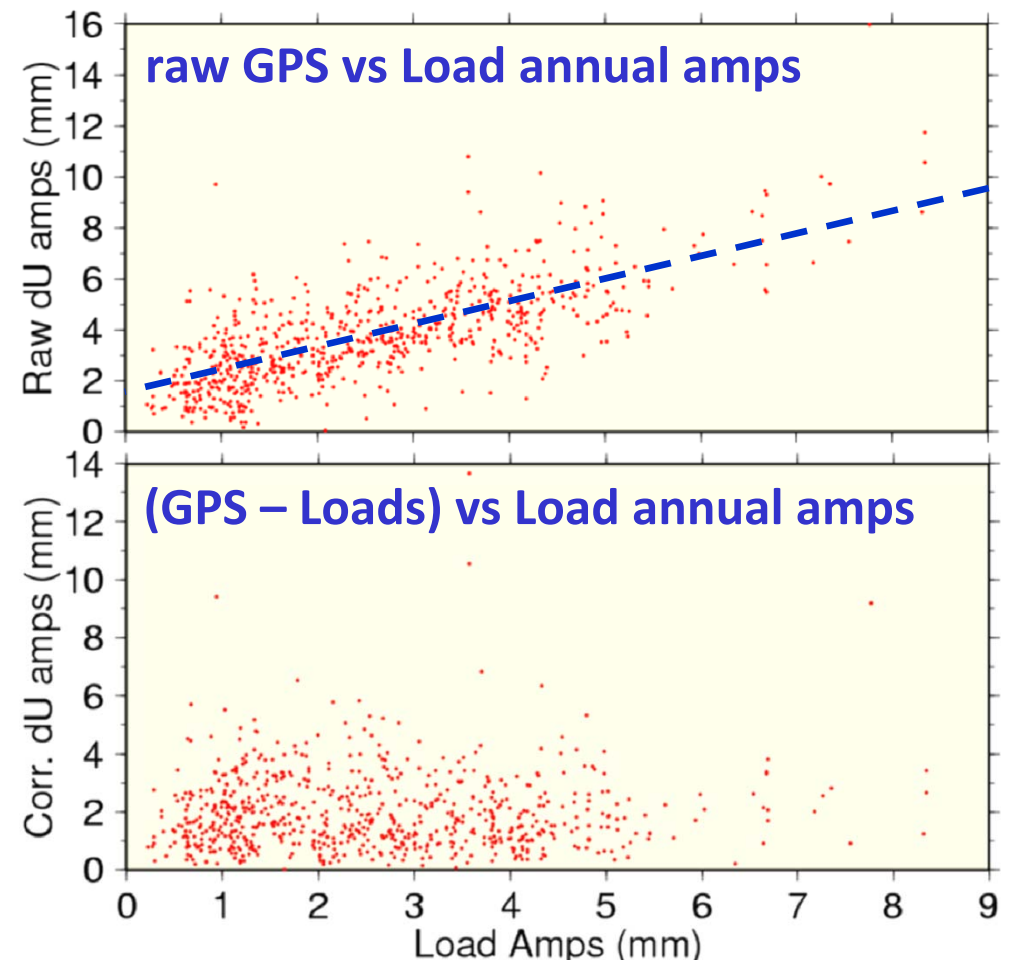
- **AnnAmp_i = mean annual amplitude**
 - includes loads + all other annual effects (e.g., technique errors)
 - $A_i^2 \approx 0.6 \rightarrow$ from empirical IGS results
- **Most horizontal annual motions probably not caused by loads**
 - technique errors are probably most important sources
- **dU load 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

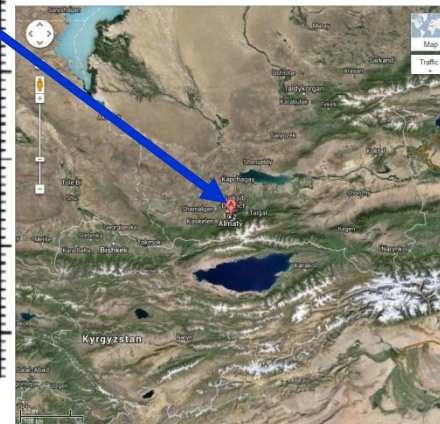
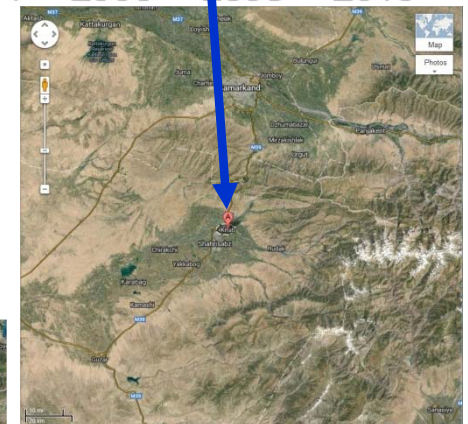
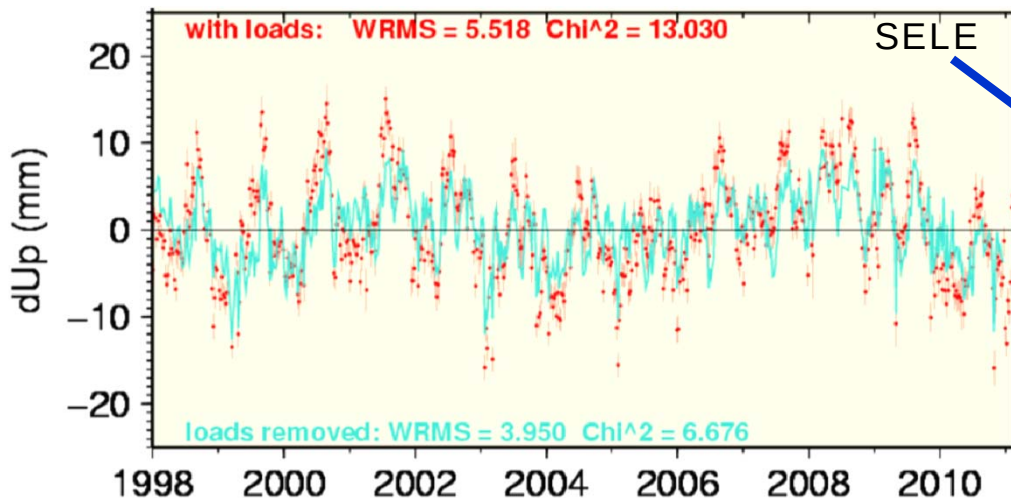
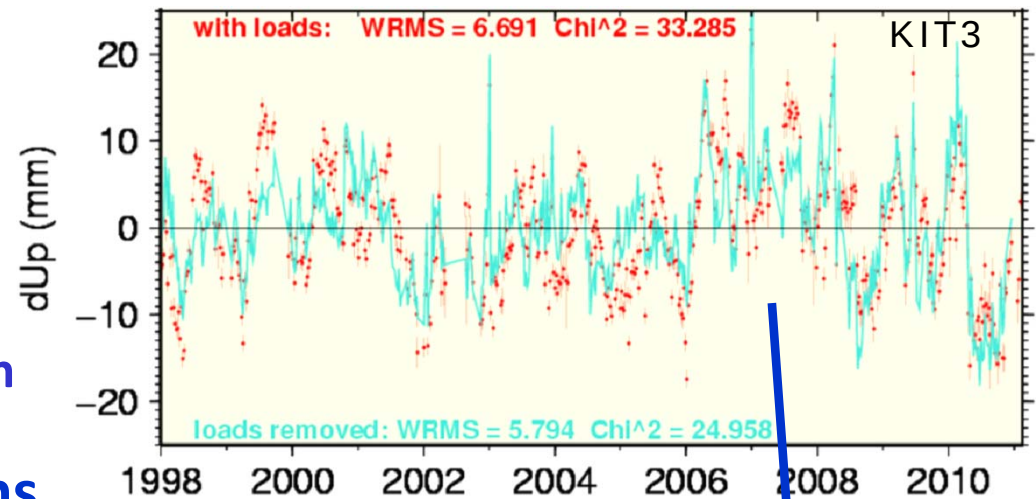
Effectiveness of dU Annual Load Models

- 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

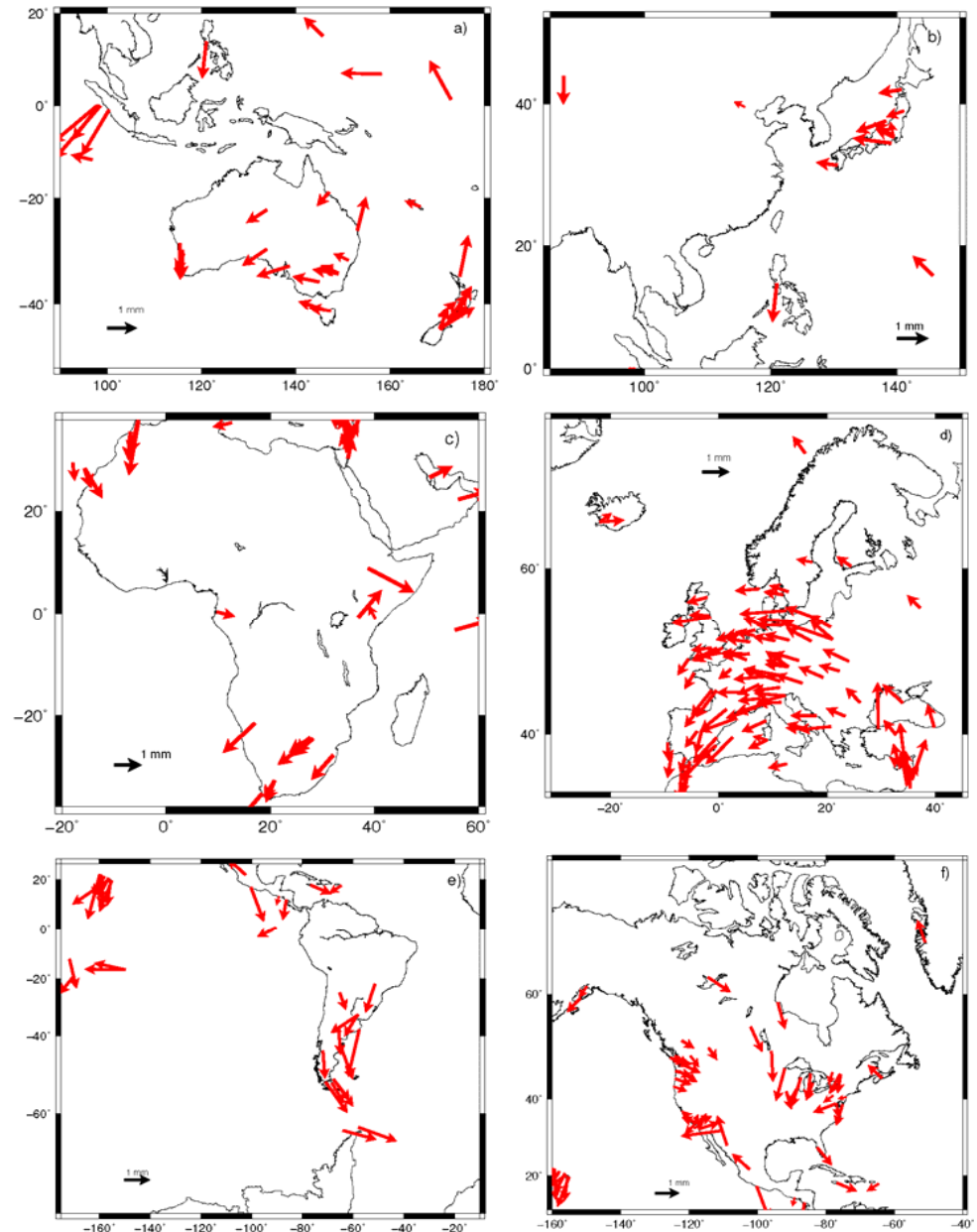
- KIT3 (Kitab, Uzbekistan) & SELE (Almaty, Kazakhstan) both show significant inter-annual dU variations
 - load corrections partially effective
 - but inter-annual signals remain
- Both stations also sit in basins in mountainous regions
 - unmodeled water/snow load signals appear plausible



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 $(1.0 + 2.0 + 3.12 + \textcolor{red}{4.16})$ 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

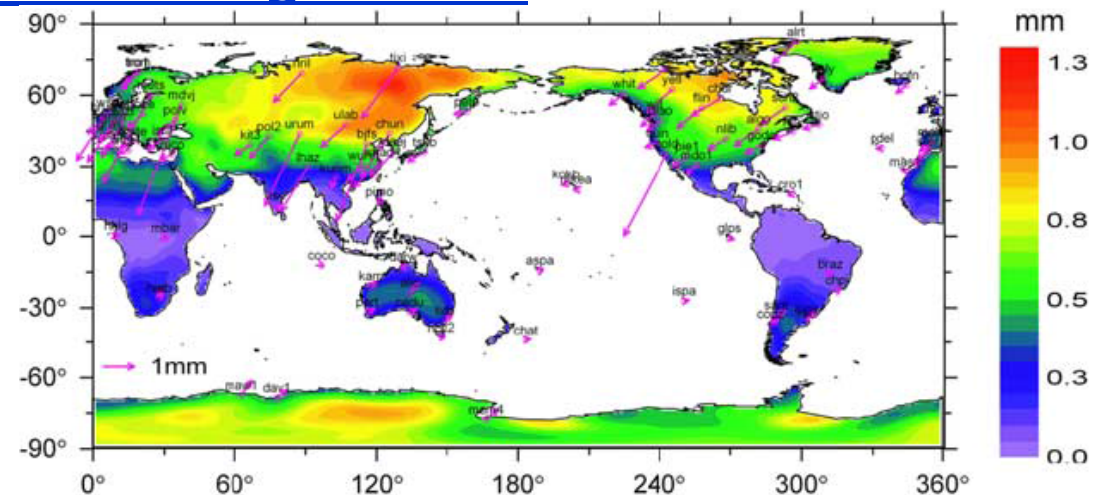
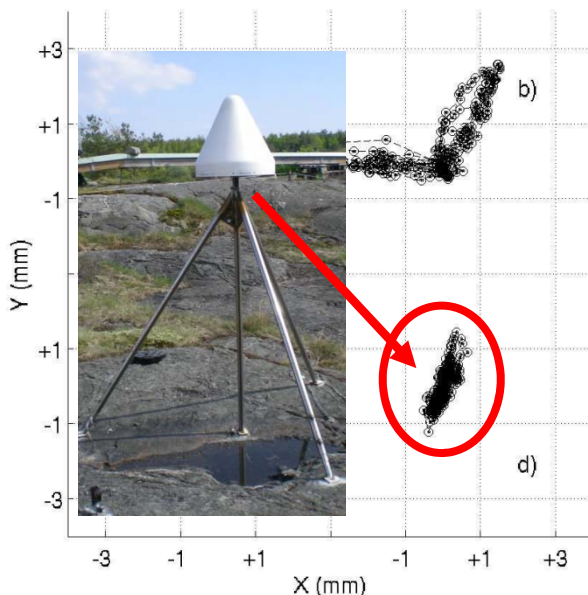


Non-load Annual Signals: 2. Temperature Cycle

- Thermal dU expansion of antenna monument structures
 - $\Delta U \text{ (mm)} \approx 0.015 * (\text{Hgt/m}) * (\Delta T/^{\circ}\text{C})$
 - for $\text{Hgt} = 3 \text{ m} + \text{annual } \Delta T = 30^{\circ}\text{C} \Rightarrow \text{annual } \Delta U \text{ (mm)} = 1.35 \text{ mm}$
 - 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 $\sim 1.3 \text{ mm}$ in NE Asia



- Horizontal tilting of antenna structures

- S. Bergstrand et al. (2013) measured diurnal tilting of $\pm 1 \text{ mm}$ 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

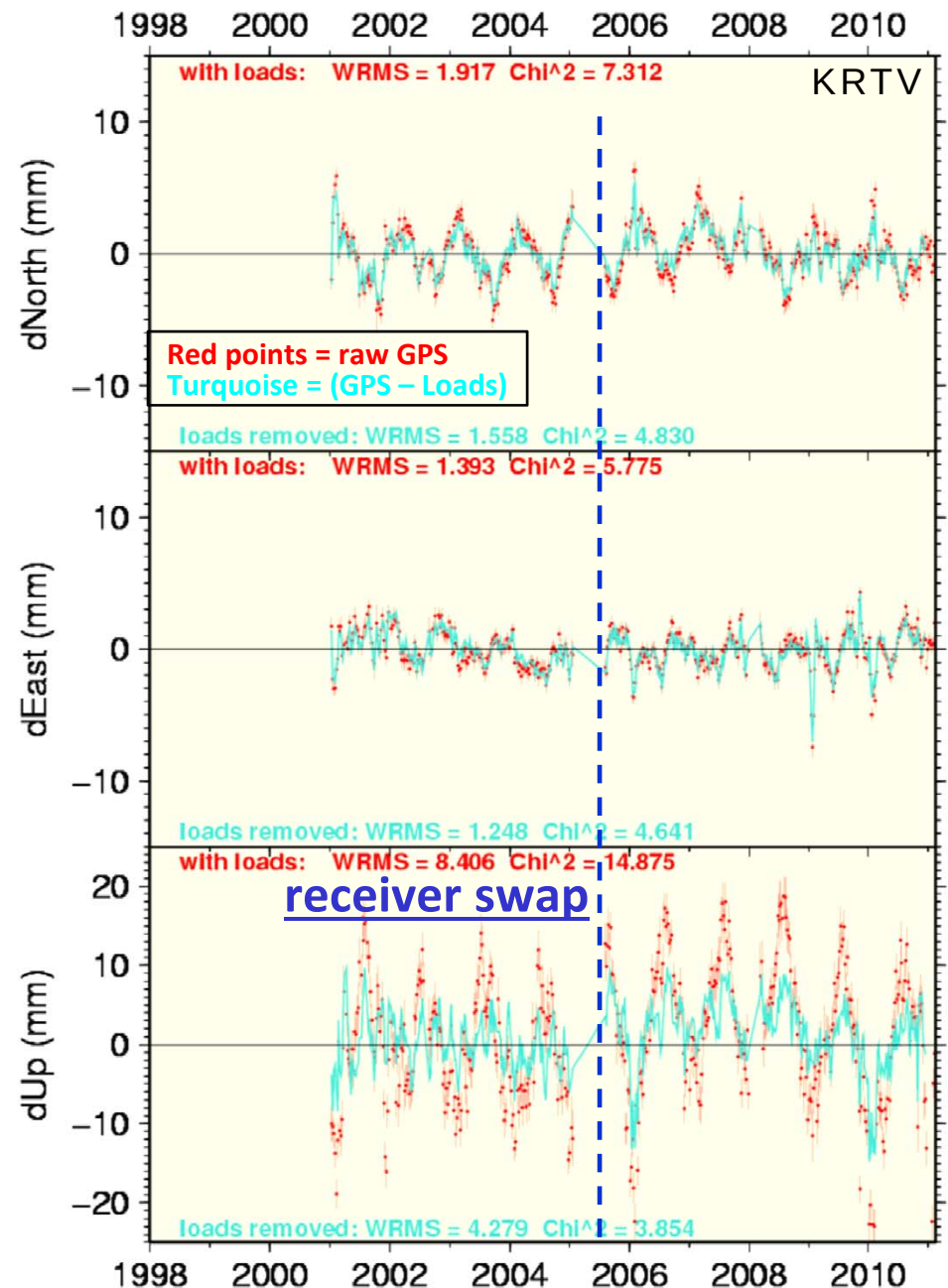
- **Unmodeled ocean pole tide deformation**
 - to account for centrifugal effect of polar motion variations on oceans
 - amps reach $\sim 0.5, 0.5, 1.8$ mm in dN, dE, dU, mostly near annual & Chandler (433 d) periods
 - IERS model in Conventions 2010, but not yet implemented
- **Aliases of errors in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