# Consistency of Crustal Loading Signals Derived from Models & GPS: Inferences for GPS Positioning Errors

- Quantify error budget for weekly dNEU GPS positions
  - use IGS solutions for a global set of 706 stations
- Include results from subset of 119 close station pairs
  - isolate electronic/thermal noise component
- Assess draconitic errors too
  - spatial distribution & station vs. satellite source


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# Input Data Sets to Compare

- **GPS station position time series from IGS reprocessing**
  - analysis consistent with IERS 2010 Conventions (more or less)
  - combined 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 LDAS 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 residuals (1998.0 – 2011.0)**
  - bias errors not considered here !

# (GPS – Load) Comparison Statistics

## WRMS Changes

| | median GPS WRMS (mm) | median Load RMS (mm) | median (GPS – Load) WRMS (mm) | median WRMS reduction (%) | % of stations with lower WRMS |
|---|---|---|---|---|---|
| **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 |

## Annual Amplitude Changes

| | median GPS annual (mm) | median Load annual (mm) | median (GPS – Load) annual (mm) | median annual (corr/no corr) ratio | % of stations with lower annual amp |
|---|---|---|---|---|---|
| **dN** | 0.9 | 0.45 | 0.65 | 0.8 | 70.7 |
| **dE** | 0.8 | 0.4 | 0.7 | 0.9 | 59.3 |
| **dU** | 3.6 | 2.4 | 1.7 | 0.5 | 87.1 |

- **Load corrections are effective to reduce WRMS & annual amps**
  - **for most stations, esp for dU – but less for dN & even less for dE**

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- Load corrections are effective to reduce WRMS & annual amp
- But most residual variation remains, esp in dN & dE

# A Generalized Model of Position WRMS

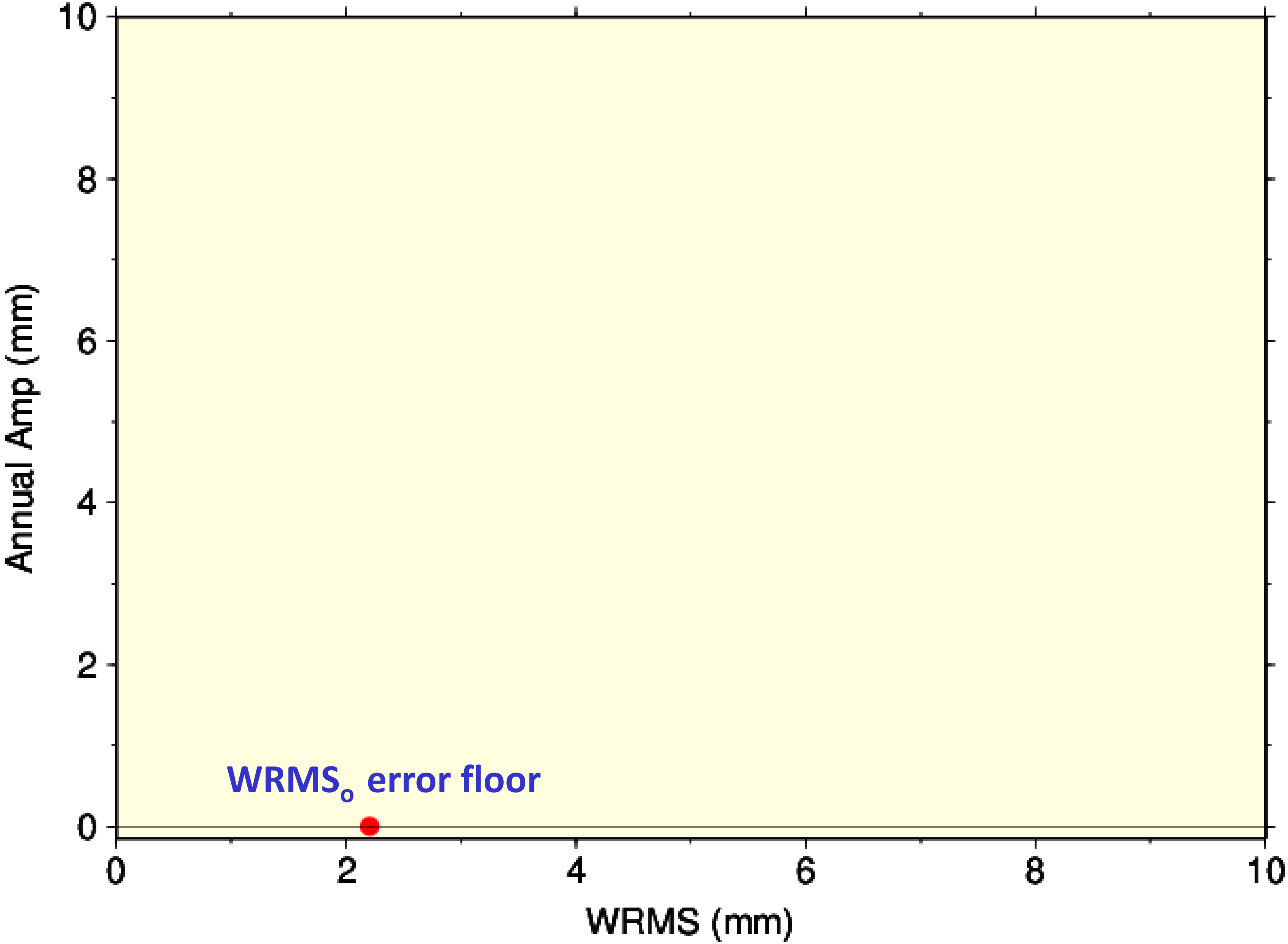
$$WRMS^2 = WRMS_o^2 + (A_i * AnnAmp_i)^2 + WRMS_i^2$$

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

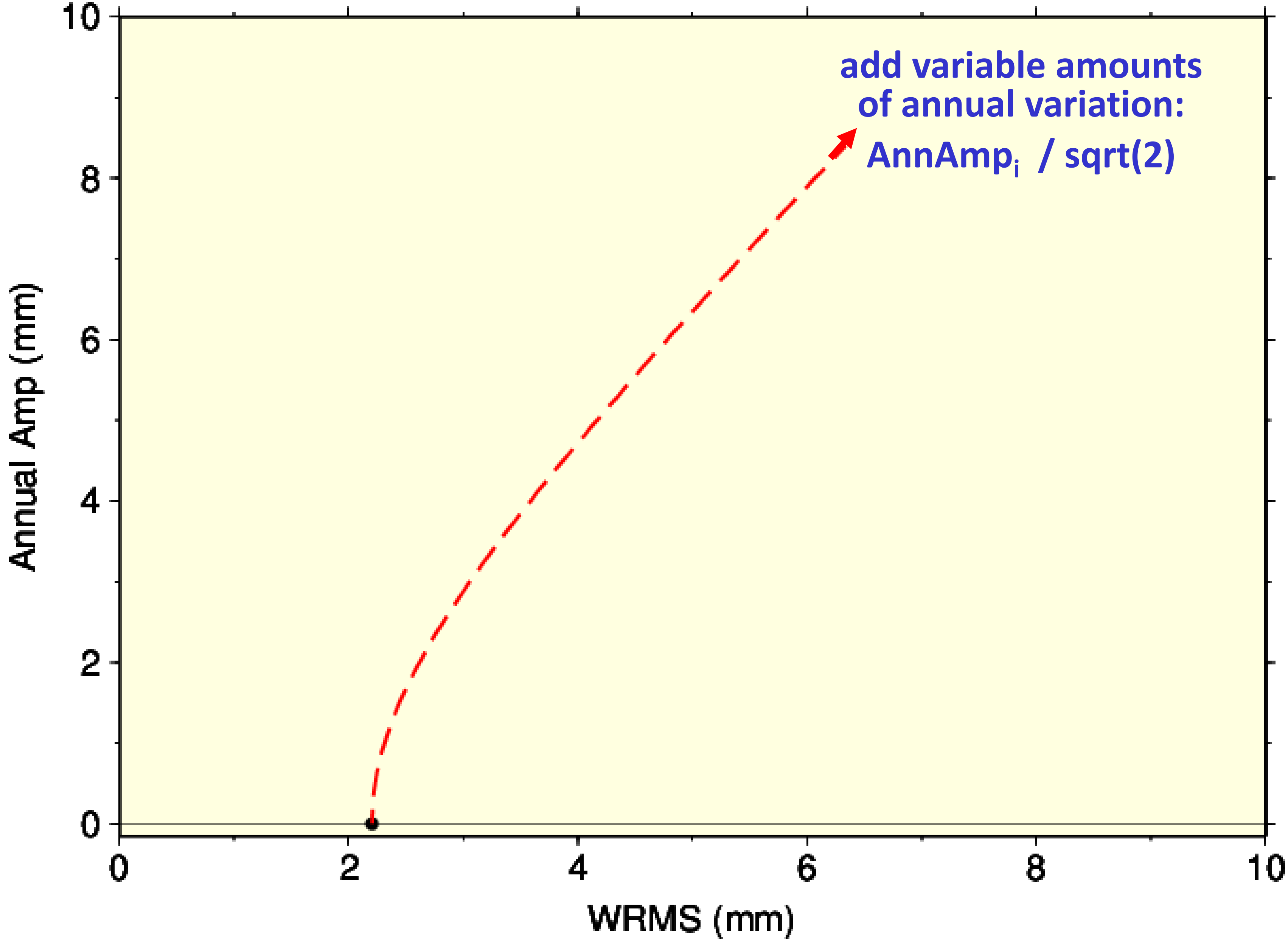
- **$AnnAmp_i$ = mean annual amplitude**
  - $A_i$ = 1 / sqrt(2) = 0.7071 or $A_i^2$ = 0.5 → for stationary sinusoid
  - $A_i^2 > 0.5$ → for non-stationary seasonal variations
  - includes loads + all other annual effects (e.g., technique errors)

- **$WRMS_i^2$ = local site-specific errors (non-annual part only):**
  - multipath & monument noise
  - antenna mis-calibration
  - thermal expansion of antenna installation & bedrock
  - tropo mis-modeling + geography-dependent orbit errors
  - non-annual loads (or residual load model errors, if corrected)
  - inter-AC analysis & station usage differences + RF realization

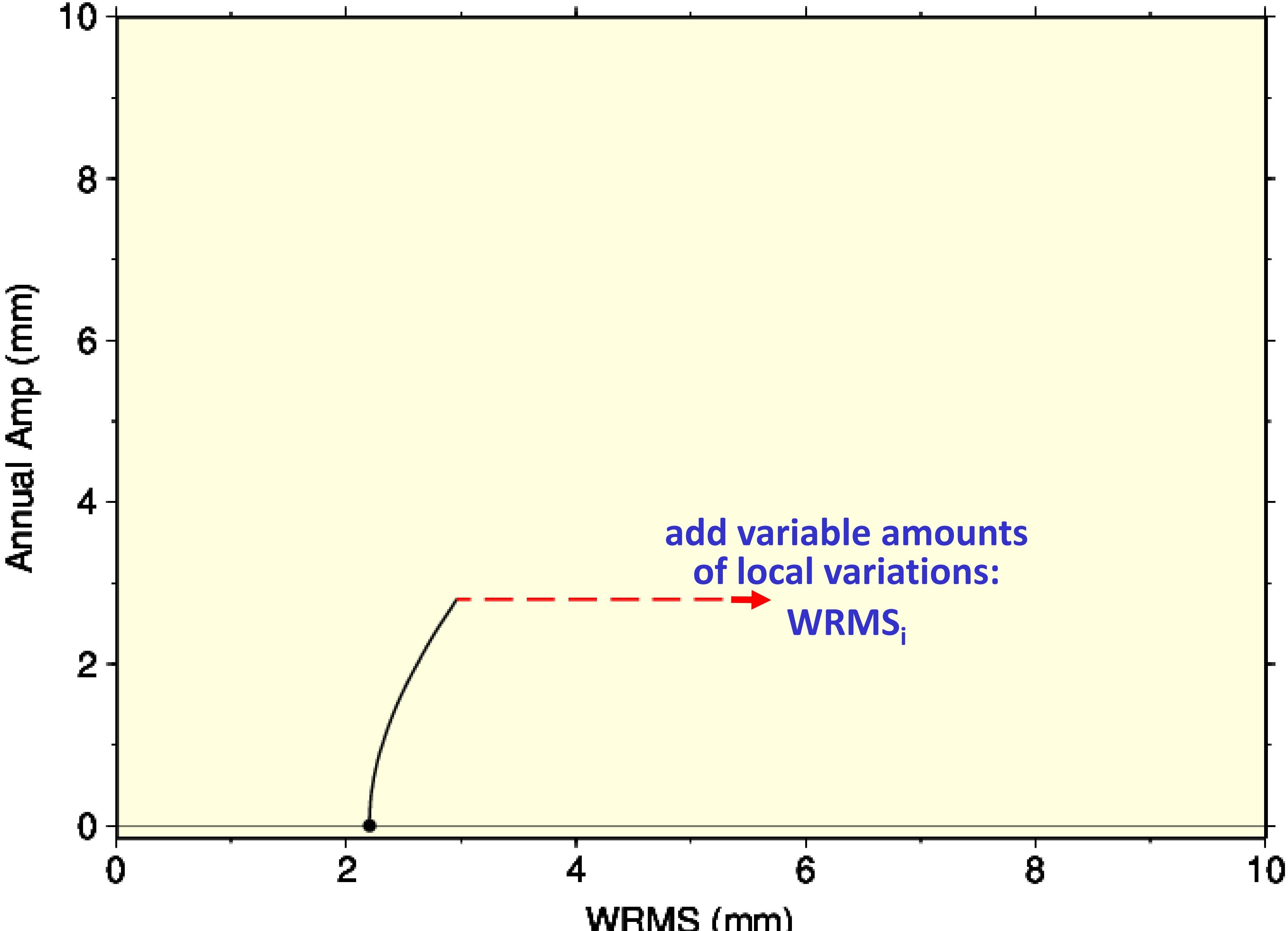
# Model of Position WRMS – Global Error Floor



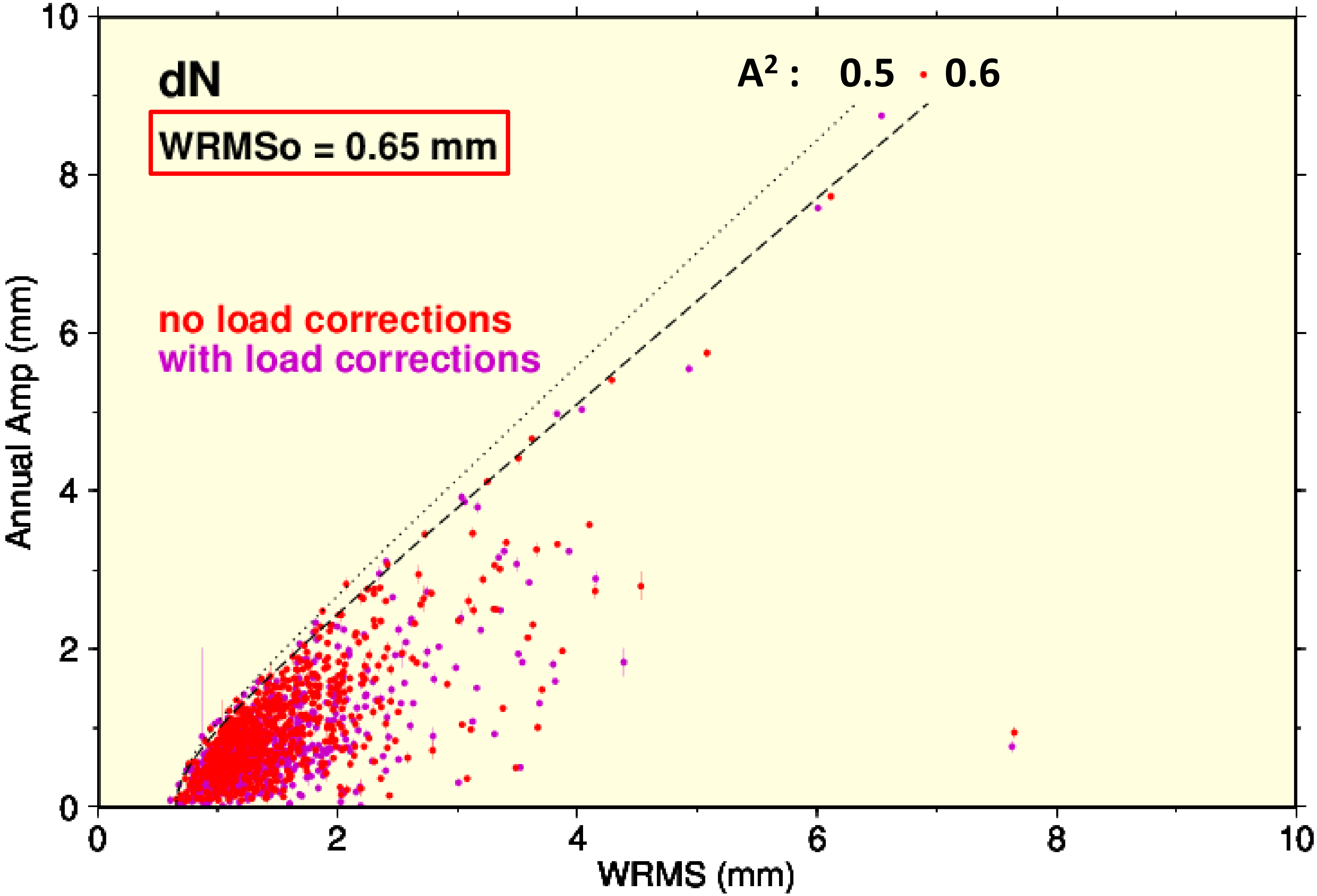
# Model of Position WRMS – Annual Components



# Model of Position WRMS – Local Errors

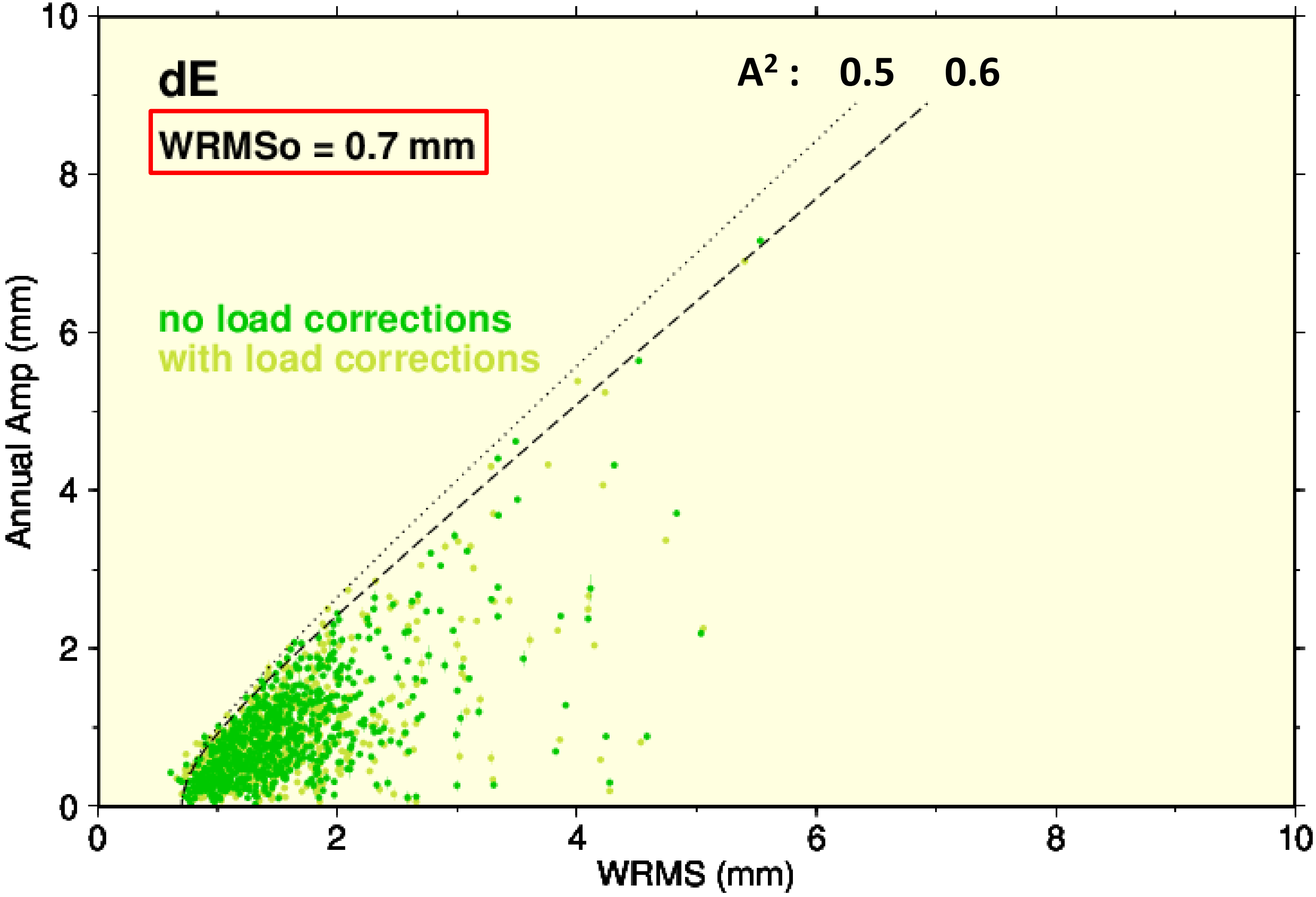


# IGS Results – dN With/Without Loads



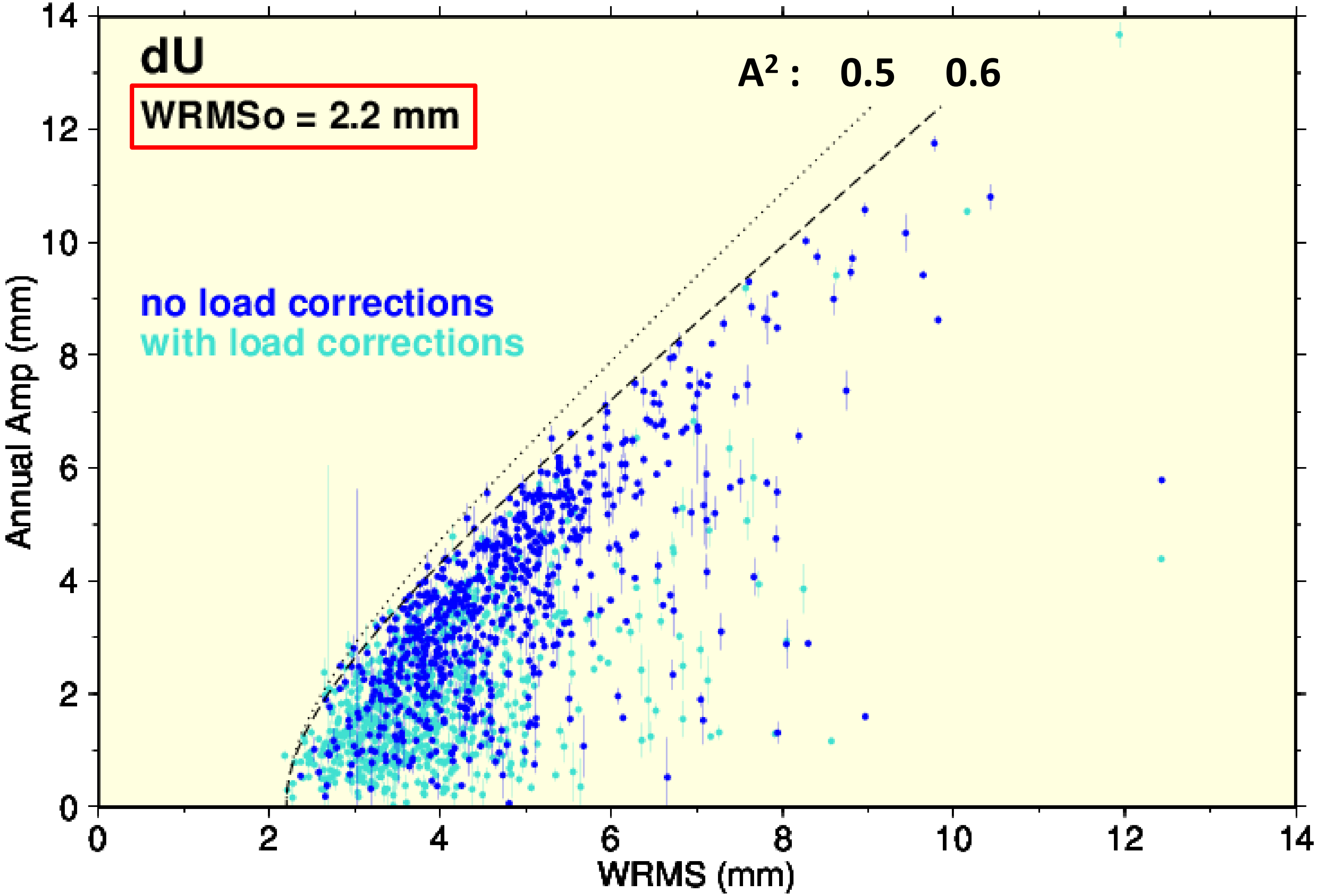

- **Load corrections have no impact on noise floor assessment**
  - **local site & non-load errors overwhelmingly dominate**

# IGS Results – dE With/Without Loads



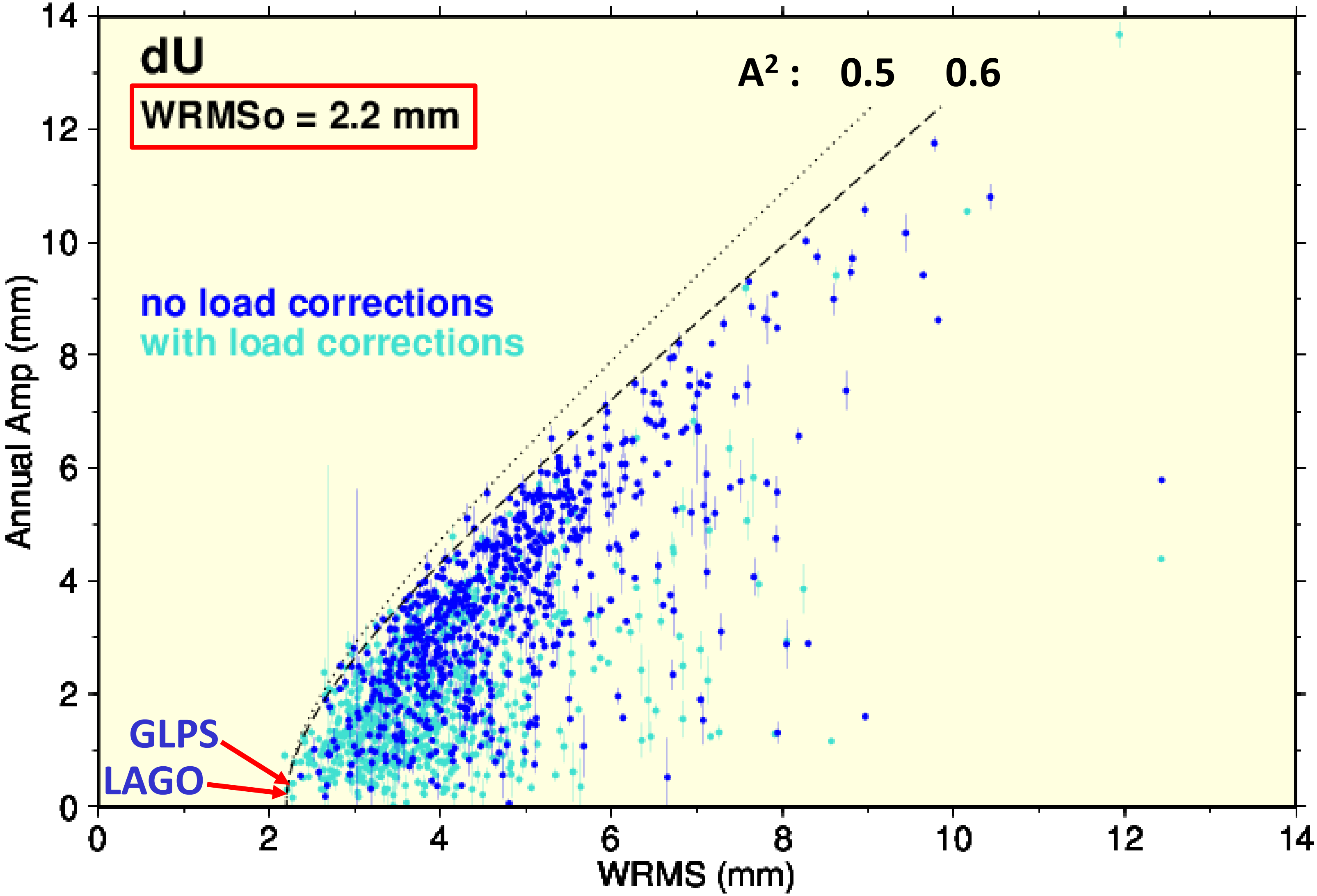

- **Load corrections have no impact on noise floor assessment**
  - **local site & non-load errors overwhelmingly dominate**

# IGS Results – dU With/Without Loads



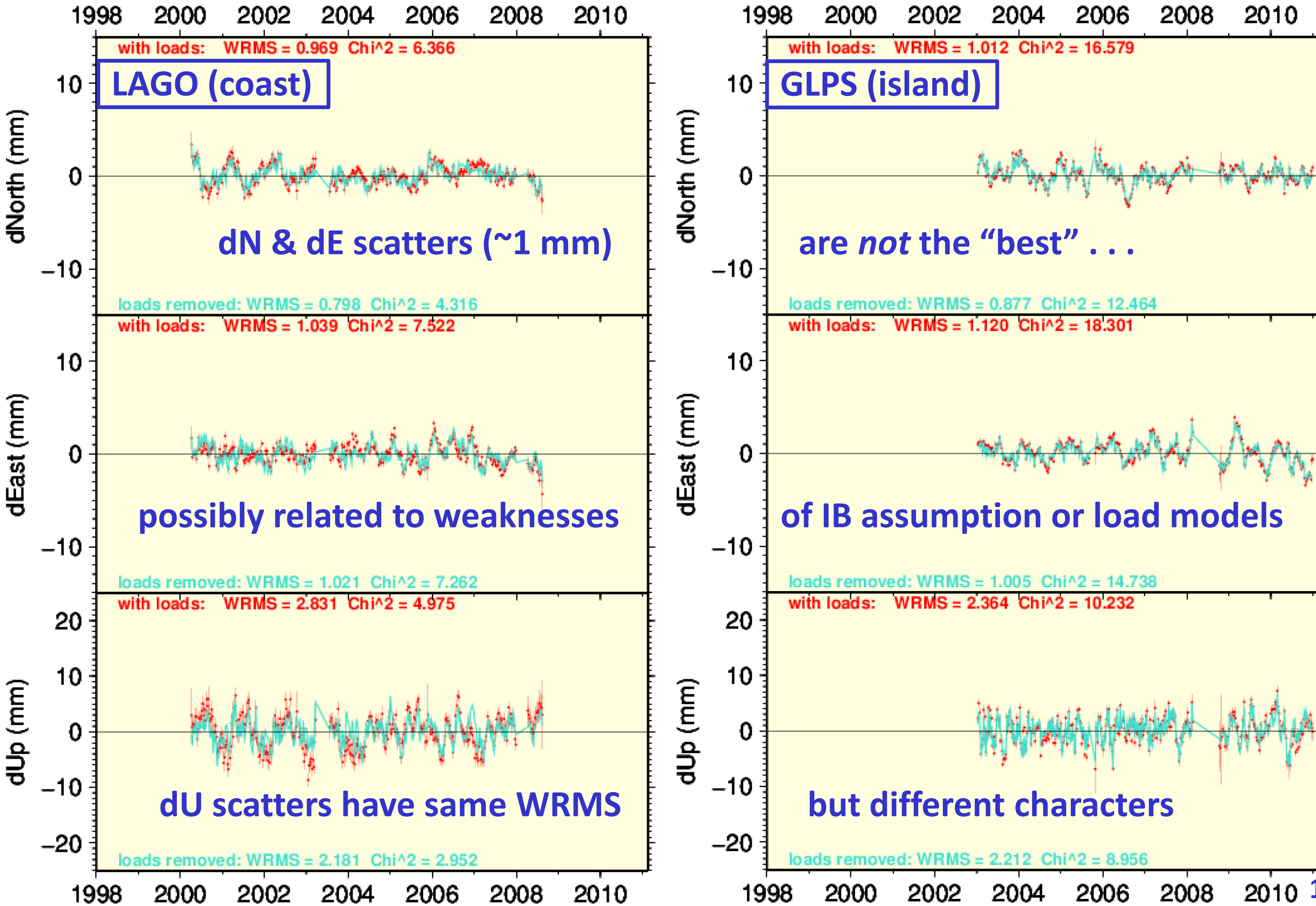

- Load corrections move results much closer to noise floor
  - but local site & non-load errors still dominate

# IGS Results – dU With/Without Loads




- "Best" 2 stations in dU (WRMS = 2.2 mm) are:
  - LAGO (S. coast, Portugal) & GLPS (island, Pacific Ocean)

# IGS Results – dU With/Without Loads



# Error Floors Inferred from Nearby Station Pairs

## Stations with Shared Antenna (19 pairs)

| | median WRMS (mm) | ……… wtd mean Amplitudes (mm) ……… | | |
|---|---|---|---|---|
| | | annual | semiannual | $4^{th}$ draconitic |
| **dN** | 0.4 | 0.08 | 0.06 | 0.03 |
| **dE** | 0.4 | 0.10 | 0.07 | 0.04 |
| **dU** | 1.3 | 0.20 | 0.24 | 0.18 |

## Stations Separated by 1 m – 25 km (100 pairs)

| | median WRMS (mm) | ……… wtd mean Amplitudes (mm) ……… | | |
|---|---|---|---|---|
| | | annual | semiannual | $4^{th}$ draconitic |
| **dN** | 0.8 | 0.37 | 0.12 | 0.09 |
| **dE** | 0.9 | 0.40 | 0.18 | 0.09 |
| **dU** | 2.1 | 0.81 | 0.45 | 0.25 |

- Single-station deconvolution from observed pair differences by 1/sqrt(2)

# Error Floors Inferred from Nearby Station Pairs

| Stations with Shared Antenna (19 pairs) | | |
|---|---|---|
| | median WRMS (mm) | |
| dN | 0.4 | estimates of electronic & thermal noise basement |
| dE | 0.4 | |
| dU | 1.3 | |

| Stations Separated by 1 m – 25 km (100 pairs) | | |
|---|---|---|
| | median WRMS (mm) | |
| dN | 0.8 | match prior global estimates of $WRMS_o$ error floor (0.65, 0.7, 2.2, respectively) |
| dE | 0.9 | |
| dU | 2.1 | |

- Good agreement of short-baseline & global $WRMS_o$ estimates implies that orbit errors are not significant part of error floor

# Decomposition 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 |

- **Infer site $WRMS_i^2$ using:**

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

$$\text{where } A^2 = 0.6$$

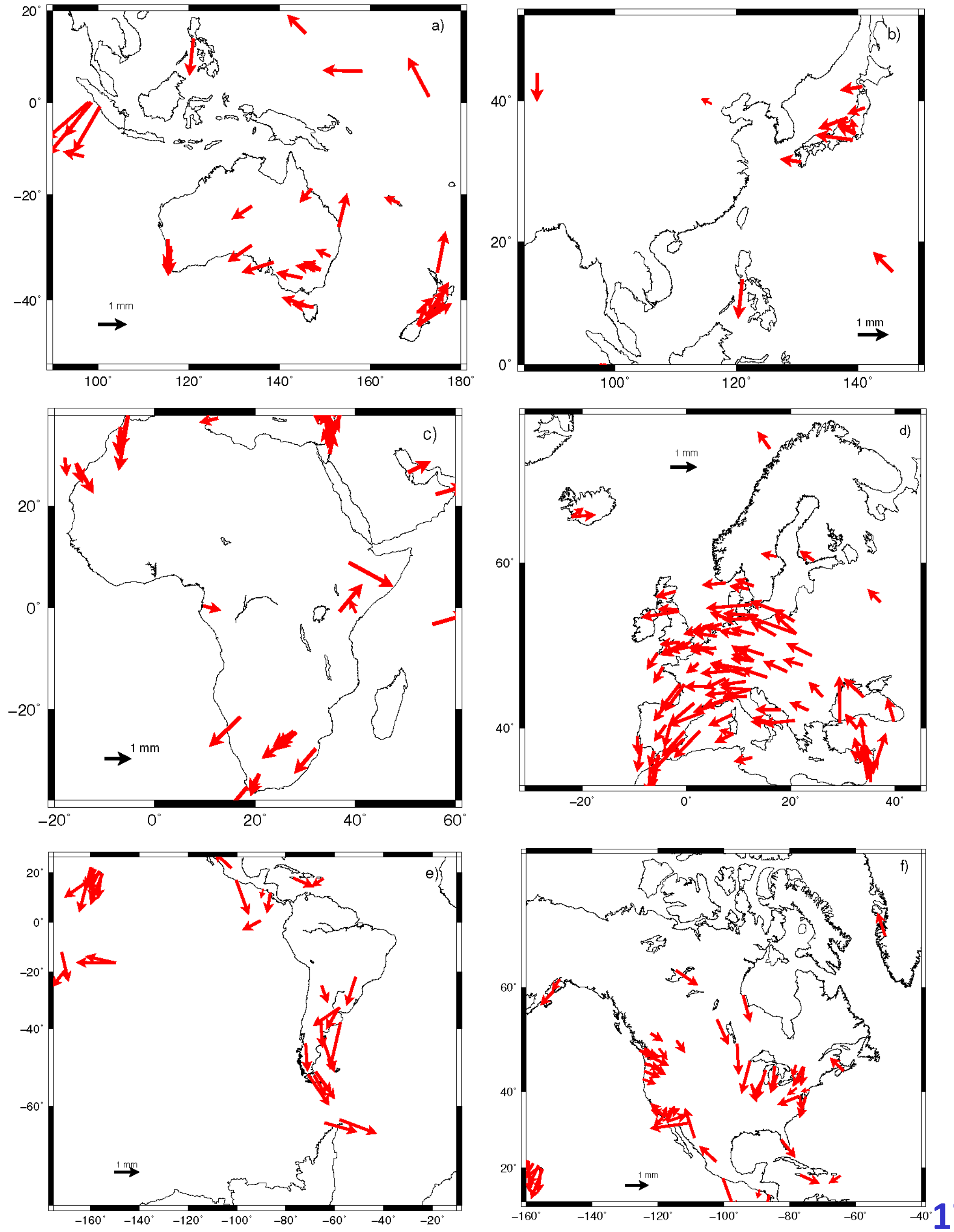
- **Noise floor $WRMS_o$ & local site errors $WRMS_i$ dominate over loads**
  - esp for N & E components
- **Non-load GPS annual errors are as large as annual load signals**
  - unless load models missing ~half of total signal

# Distribution of 4th GPS Draconitic in dU

- **Draconitic year = 351.2 d**
  - or frequency = 1.04 cpy
  - fit (1.0 + 2.0 + 3.12 + 4.16) cpy
  - phases clockwise from N w.r.t. 2000.0
  - plot significant 4th harmonics

- **Strong spatial correlations**
  - very striking in most regions
  - also seen in dN distribution
  - esp coherent in Europe
  - even for tiny dE signals

- **Implies orbit-related source**
  - at least for most of effect
  - smaller local contributions also likely based on close pairs



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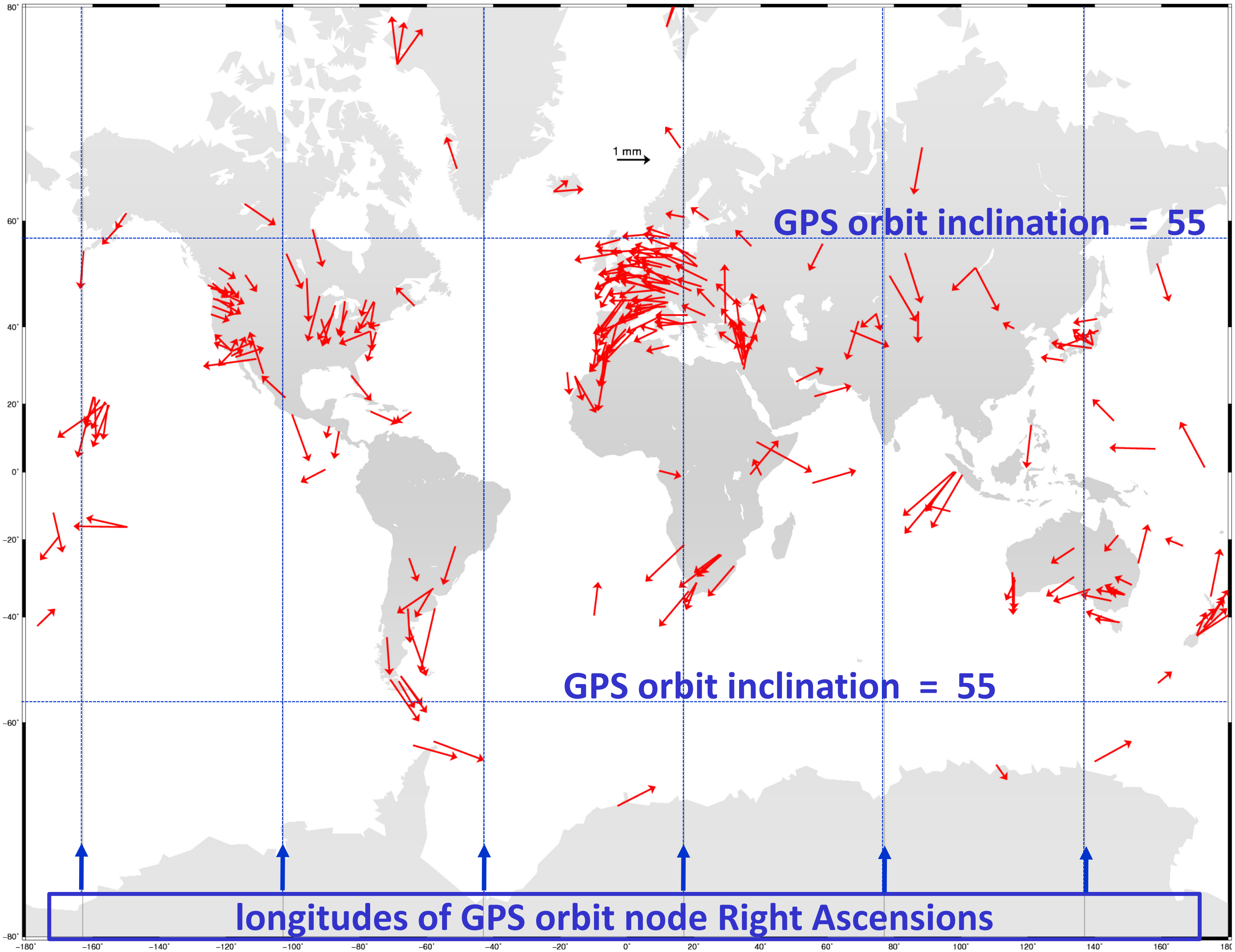
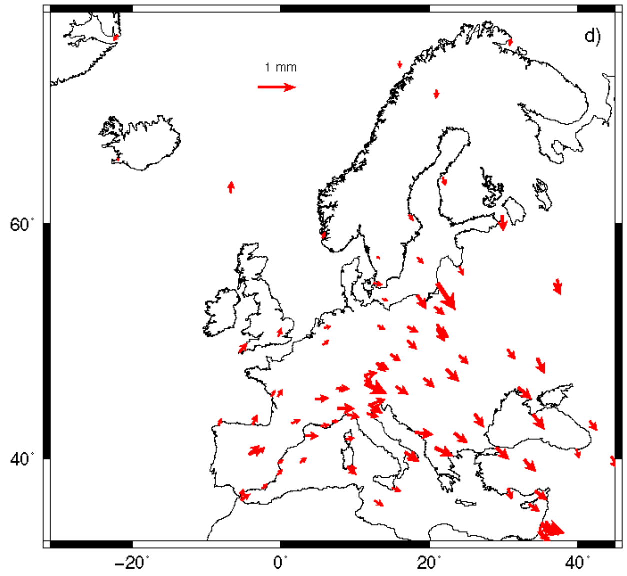
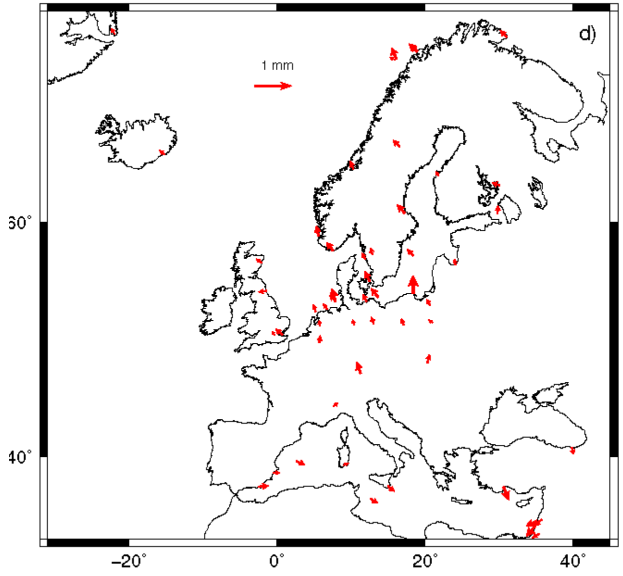


# 4th GPS Draconitic in Europe

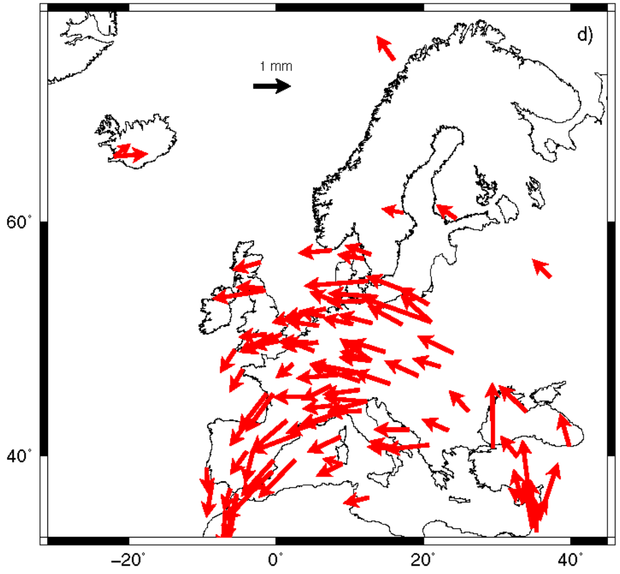
**dN**




**dE**




**dU**



# Summary & Conclusions

- **Load corrections reduce WRMS & annual amps for most stations**
  - but most residual variation remains, esp for dN & dE
  - implies load models are inaccurate &/or other sources of scatter/error
- **Station weekly scatter can be decomposed into 3 categories:**

| | dN | dE | dU |
|---|---|---|---|
| global average floor $WRMS_o$ (mm) | 0.65 | 0.7 | 2.2 |
| median annual amp WRMS (mm) | 0.7 | 0.6 | 2.8 |
| (for $A^2$ = 0.6; about half due to loads) | | | |
| median local site $WRMS_i$ (mm) | 1.0 | 1.1 | 2.9 |
| total WRMS (mm) | 1.4 | 1.45 | 4.6 |

- **Harmonics of GPS draconitic period are pervasive**
  - strong spatial correlations imply a major orbit-related source (see Griffiths & Ray, G54A-01, this afternoon)
  - but significant draconitics in close pair differences imply smaller local contributions likely too
  - 1.04 cpy signal must contribute to observed annual variations but magnitude is unknown
- **Major non-load technique improvements still badly needed!**