# SYSTEMATIC ERRORS IN GPS POSITION ESTIMATES

- Context & objectives
- Case studies – three perspectives:
  - Power spectra of dN,dE,dU residuals
  - Correlations of dN,dE,dU variations with TEQC metrics
  - Correlations dU RMS with day-boundary clock jumps
- Hypothesis for antenna mount-related GPS errors
- Preliminary test of hypothesis
- Conclusions & consequences

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IGS Workshop 2006, 11 May 2006

# Context & Objectives

- **Compare weekly GPS frames with long-term reference frame**
  - gives time series of N,E,U station residuals
  - annual signals (especially) are common at nearly all GPS sites

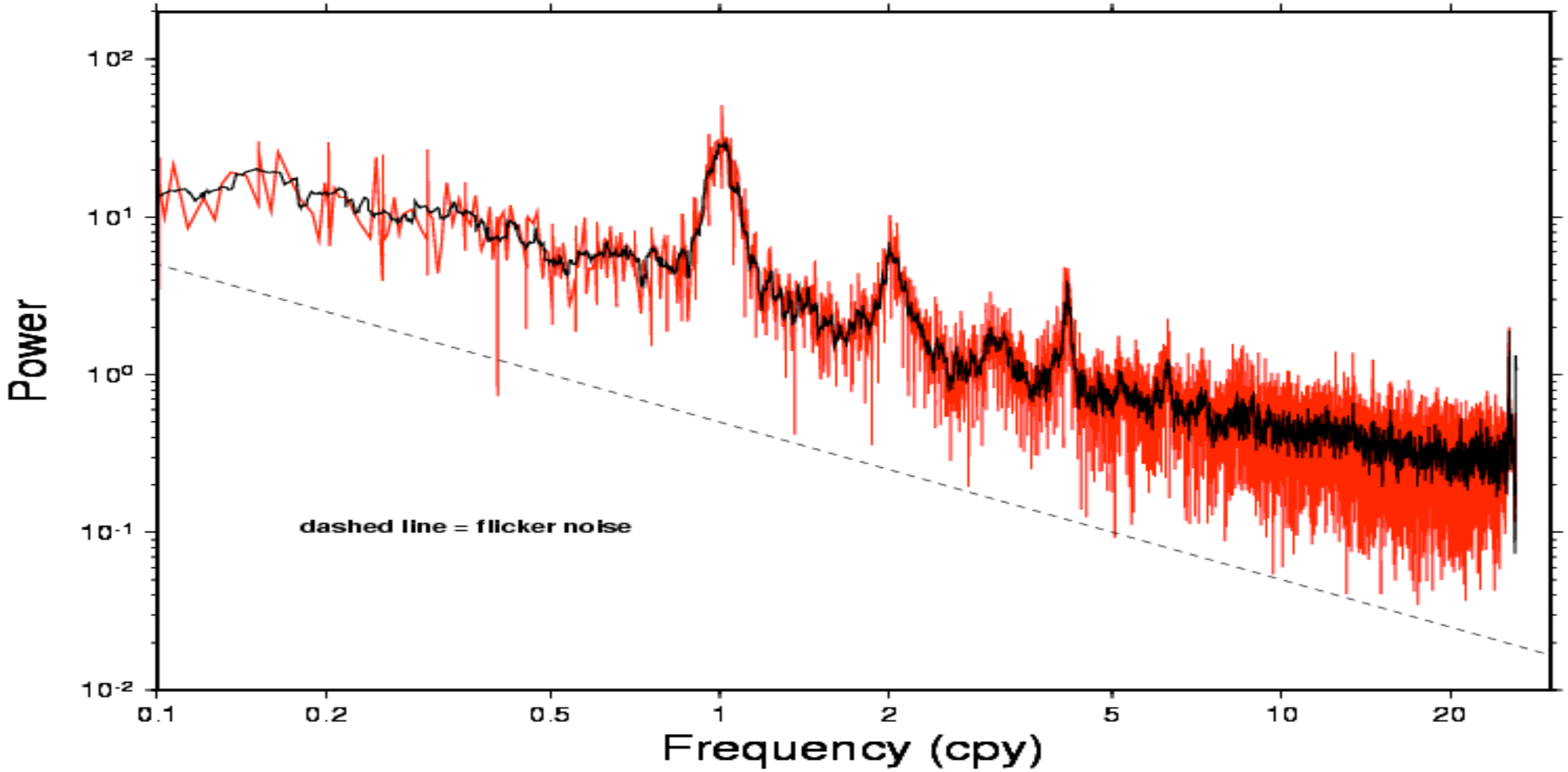
- **Geophysical interpretation**
  - GPS residuals can reveal geophysical processes that induce non-linear relative motions
  - much attention recently on apparent deformations due to transport of global fluid mass loads
  - but this view could be biased by unrecognized GPS errors

- **Question: How well do we understand GPS technique errors & their role in apparent non-linear motions ?**
  - identify important internal, technique-related errors
  - consider novel error mechanisms
  - try to quantify error contributions

# Acknowledgements

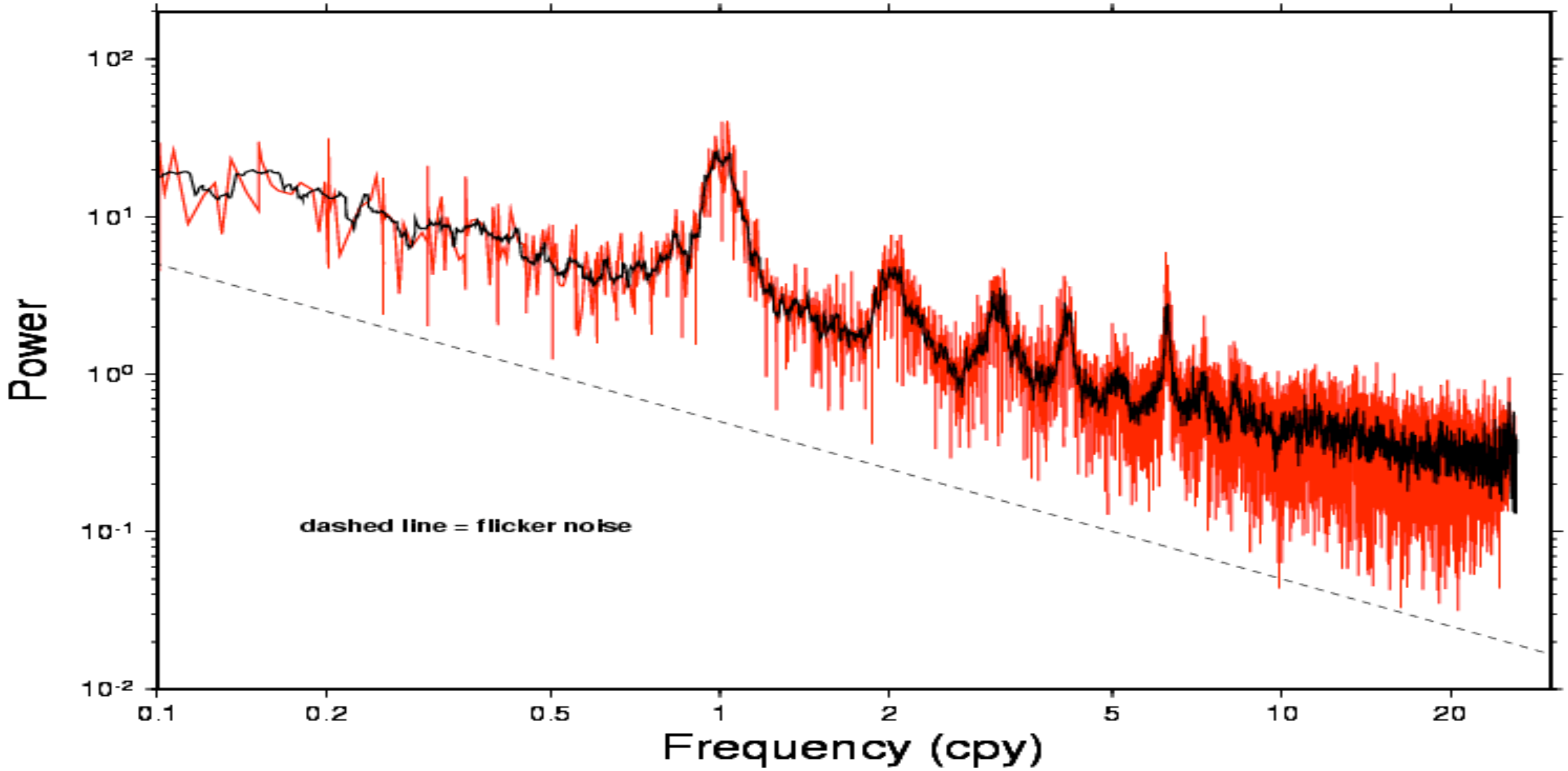

- Rémi Ferland – weekly IGS SINEX combinations (at NRCanada)
- Zuheir Altamimi – dN,dE,dU residuals from rigorous stacking of IGS solutions (at IGN)
- Lou Estey – TEQC utility from UNAVCO
- Ken Senior – IGS clock products (at NRL)
- Tonie van Dam – insights into geophysical loading signals
- Xavier Collilieux – studies of ITRF2005 residuals & scale

# Stacked Power Spectrum of dU Residuals



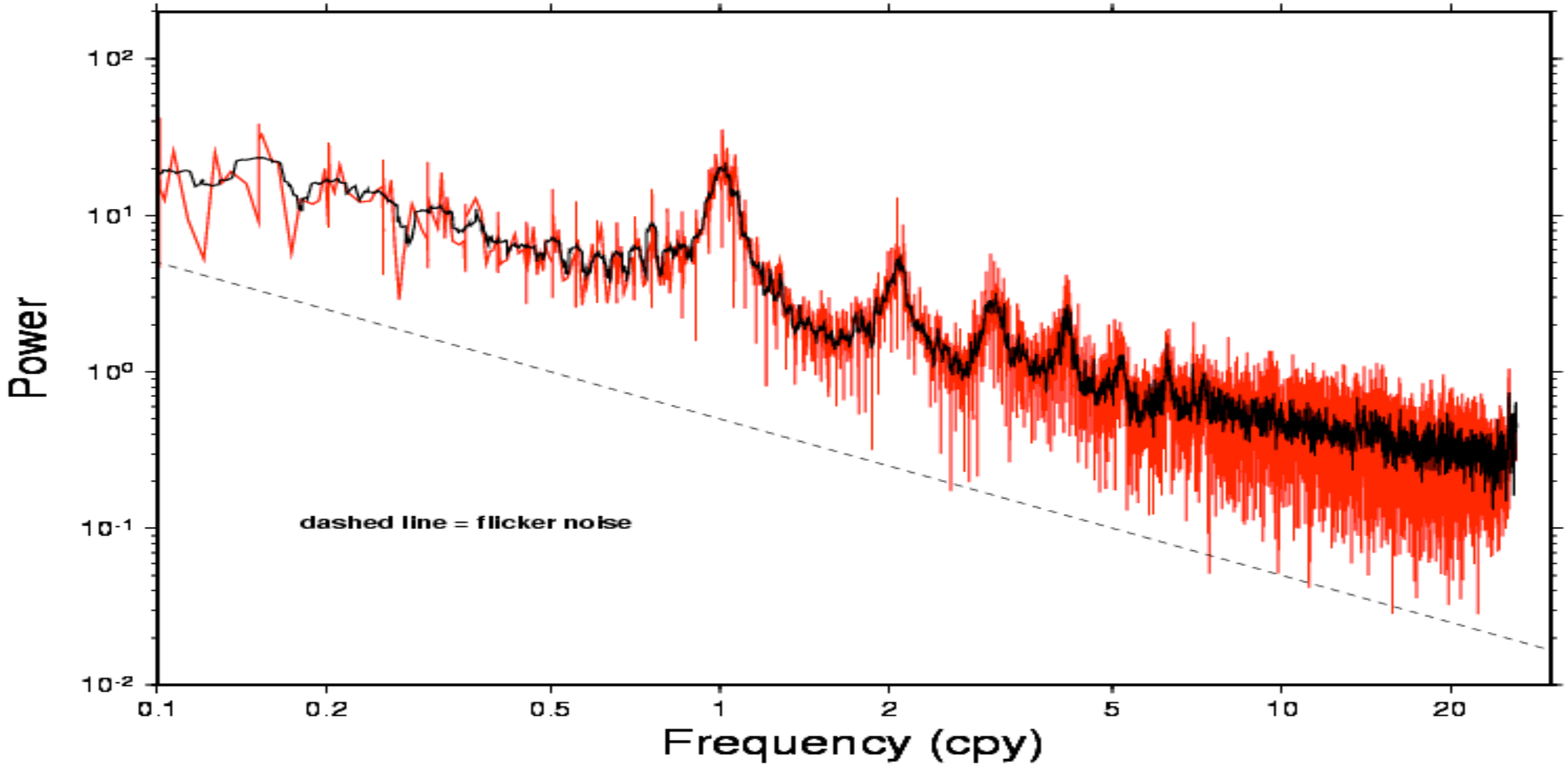

- stacked power spectra for 167 IGS sites with >200 weekly points during 1996.0 – 2006.0 (from Z. Altamimi)
- smoothed by 10-point bin averaging (red)
- smoothed by boxcar filter with 0.03 cpy window (**black**)

# Stacked Power Spectrum of dN Residuals



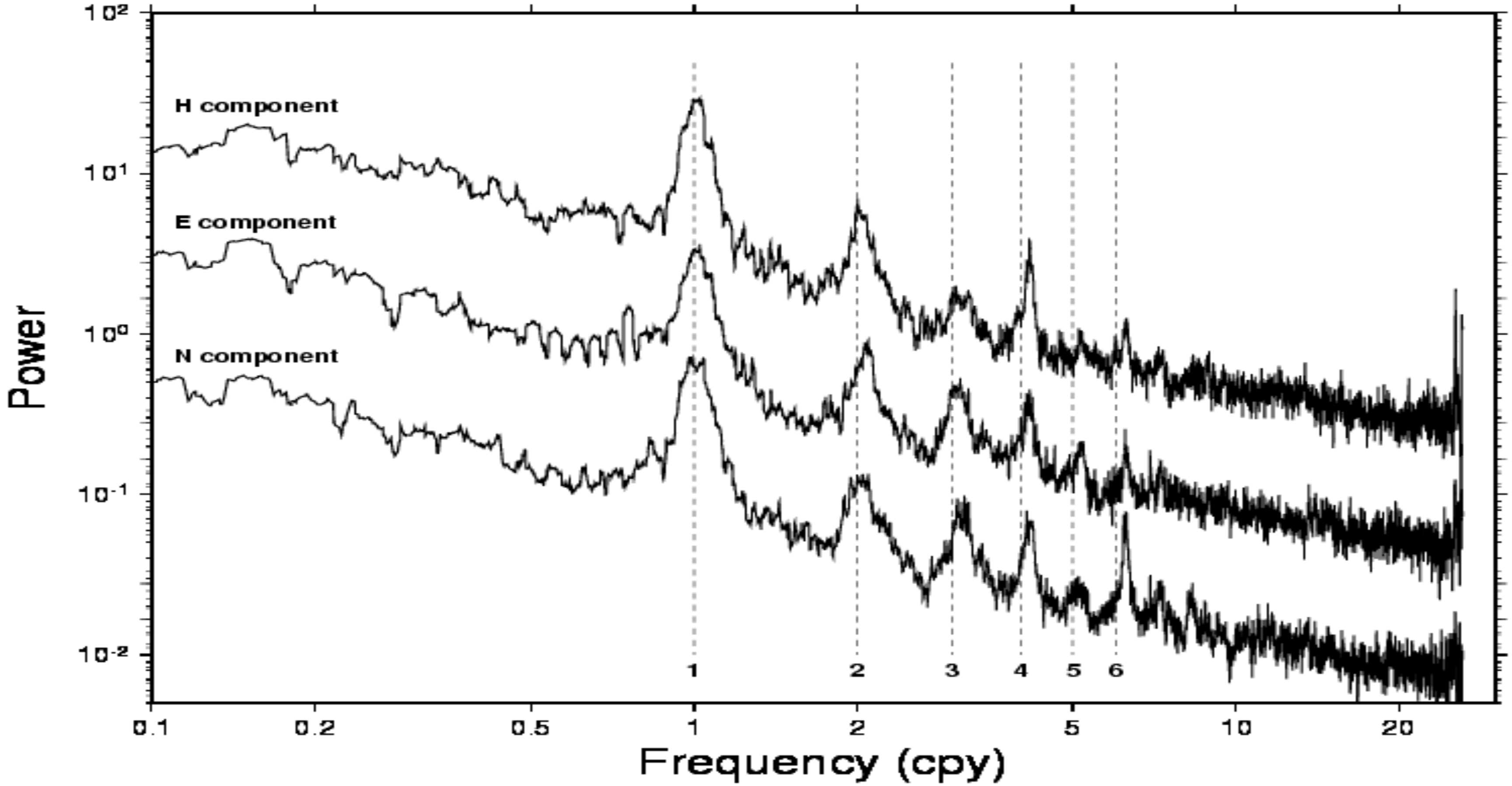

- stacked power spectra for 167 IGS sites with >200 weekly points during 1996.0 – 2006.0 (from Z. Altamimi)
- smoothed by 10-point bin averaging (red)
- smoothed by boxcar filter with 0.03 cpy window (**black**)

# Stacked Power Spectrum of dE Residuals



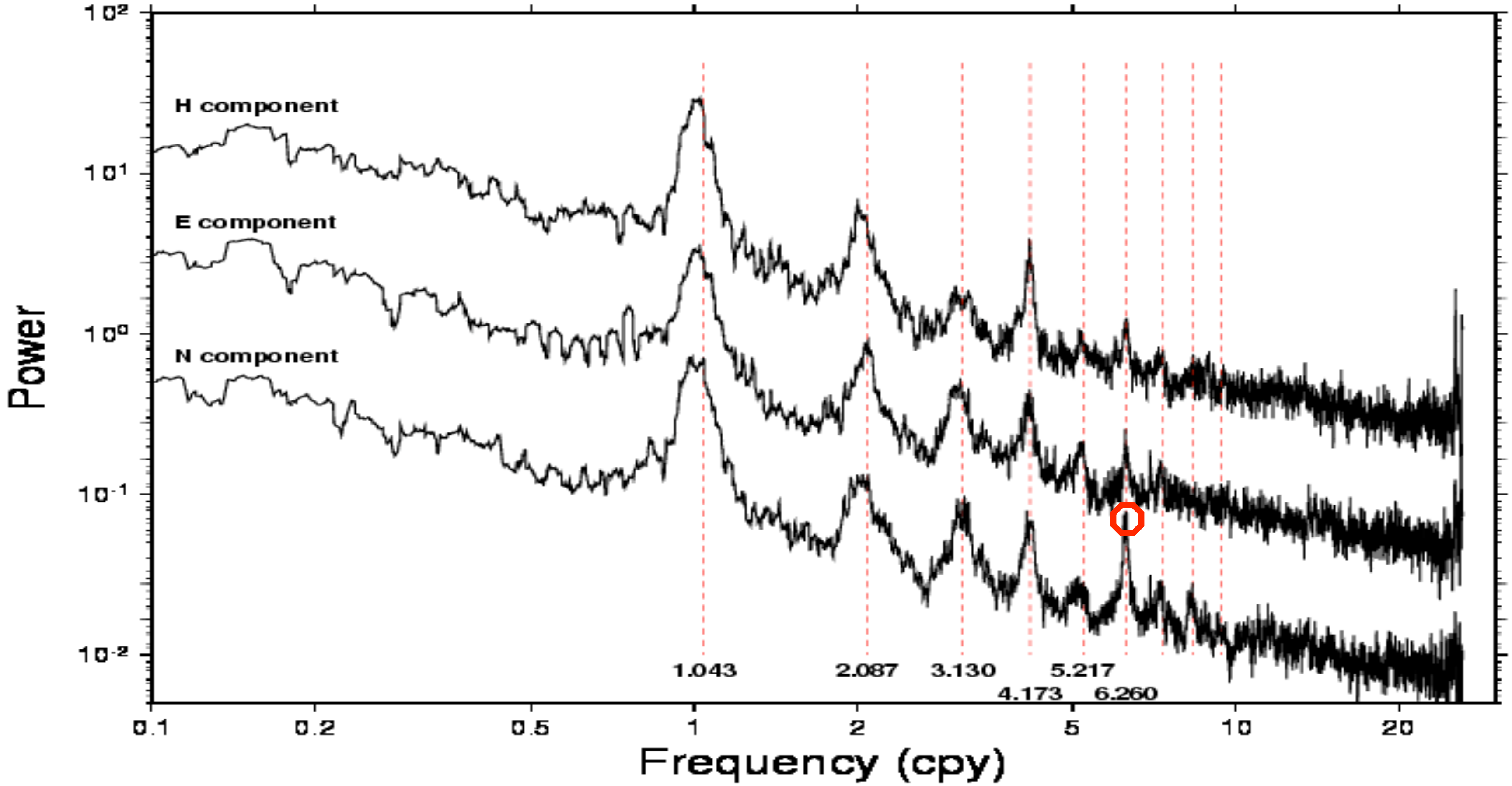

- stacked power spectra for 167 IGS sites with >200 weekly points during 1996.0 – 2006.0 (from Z. Altamimi)
- smoothed by 10-point bin averaging (red)
- smoothed by boxcar filter with 0.03 cpy window (black)

# Compare Smoothed, Stacked GPS Spectra



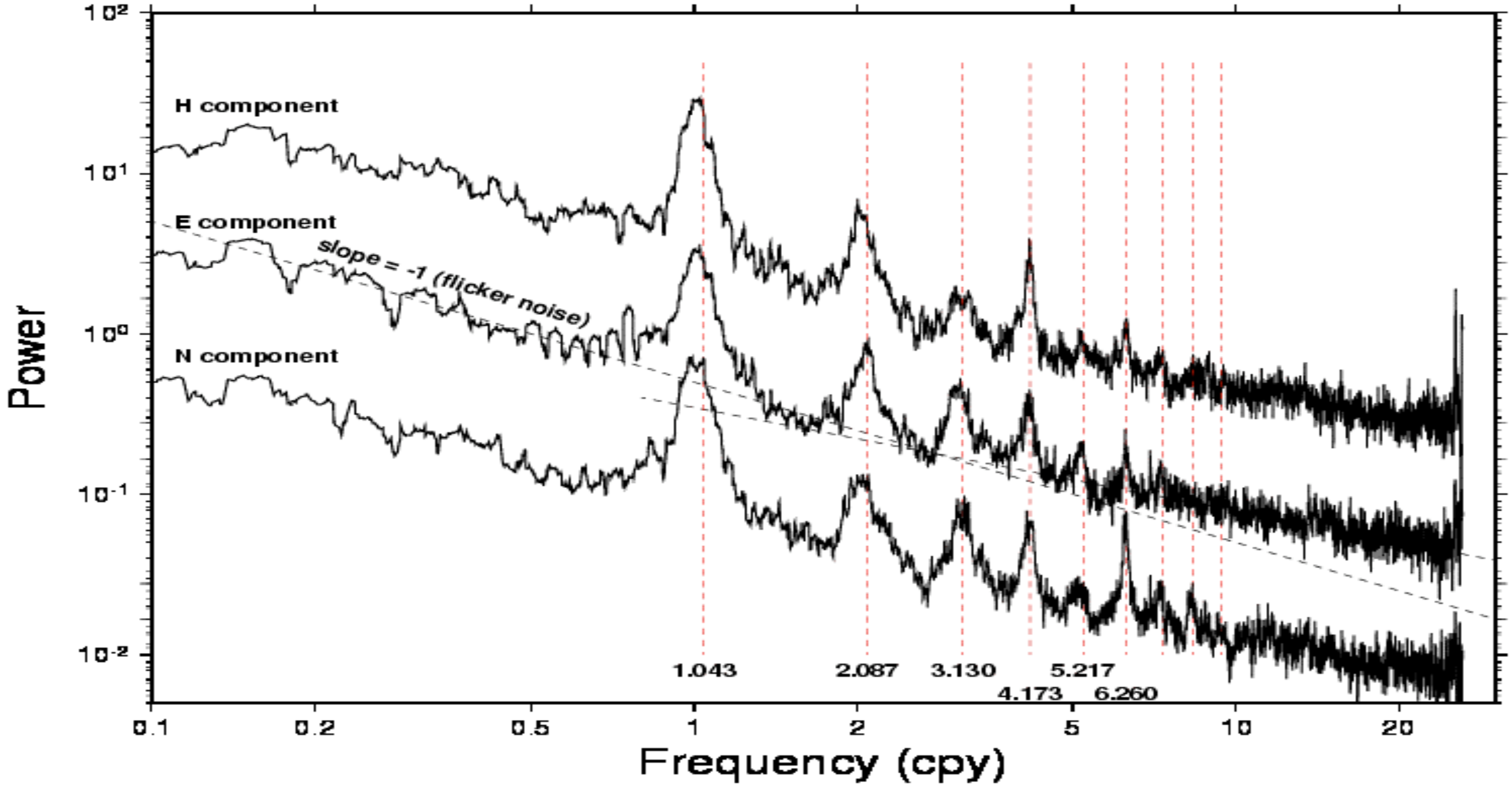

- spectra are very similar for all 3 components
- harmonics of ~1 cpy seen up to at least ~6 cpy
- 3rd & higher harmonics not at even 1.0 cpy intervals

# Frequencies of Overtones Peaks



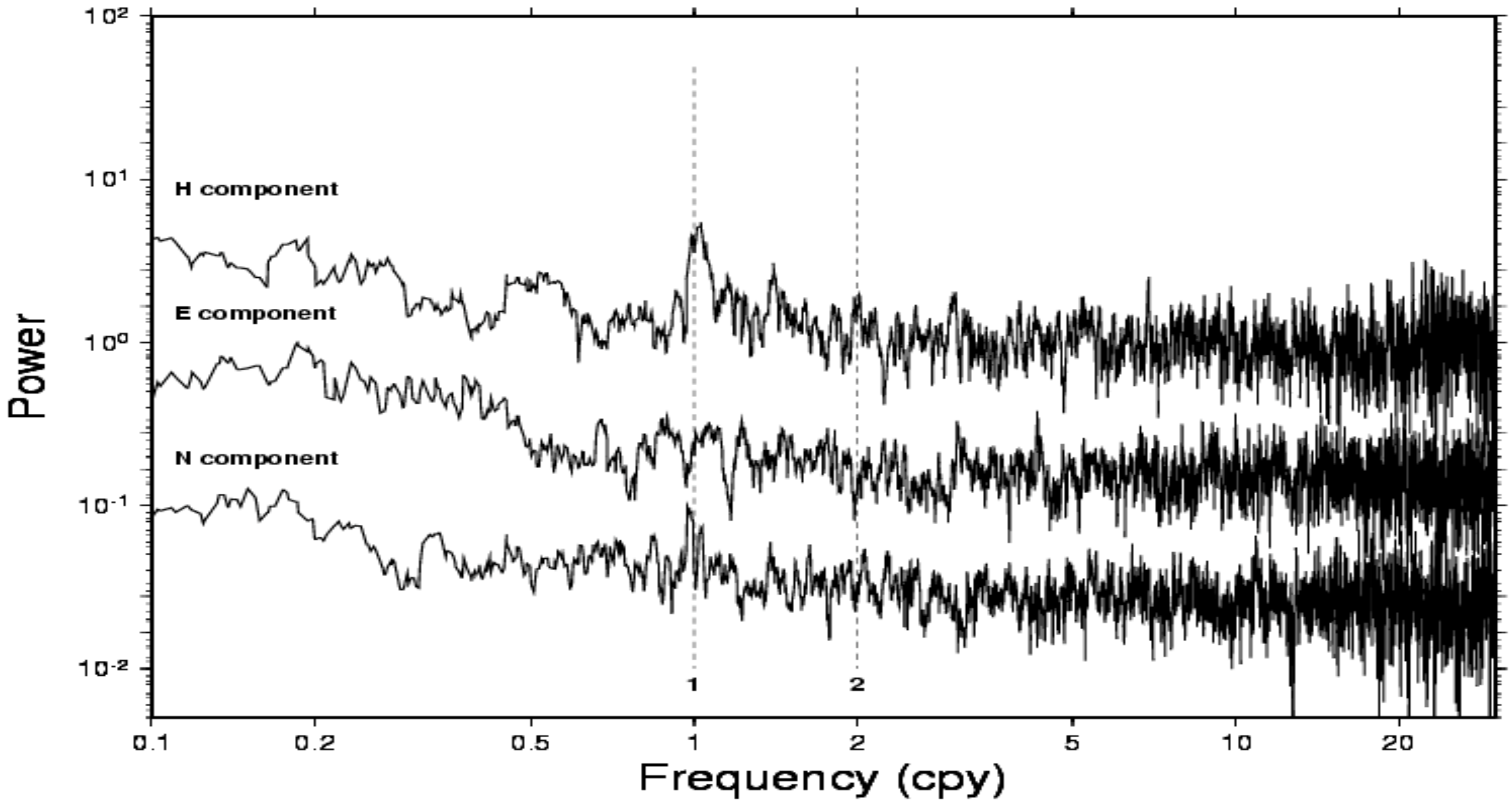

- compute harmonic frequencies based on 6$^{th}$ dN tone, assuming linear overtones
- linear overtones of ~1.043 cpy fundamental fit well
- should also have peak at 1.0 cpy due to geophysical loads, etc

# Spectra of GPS Background Noise



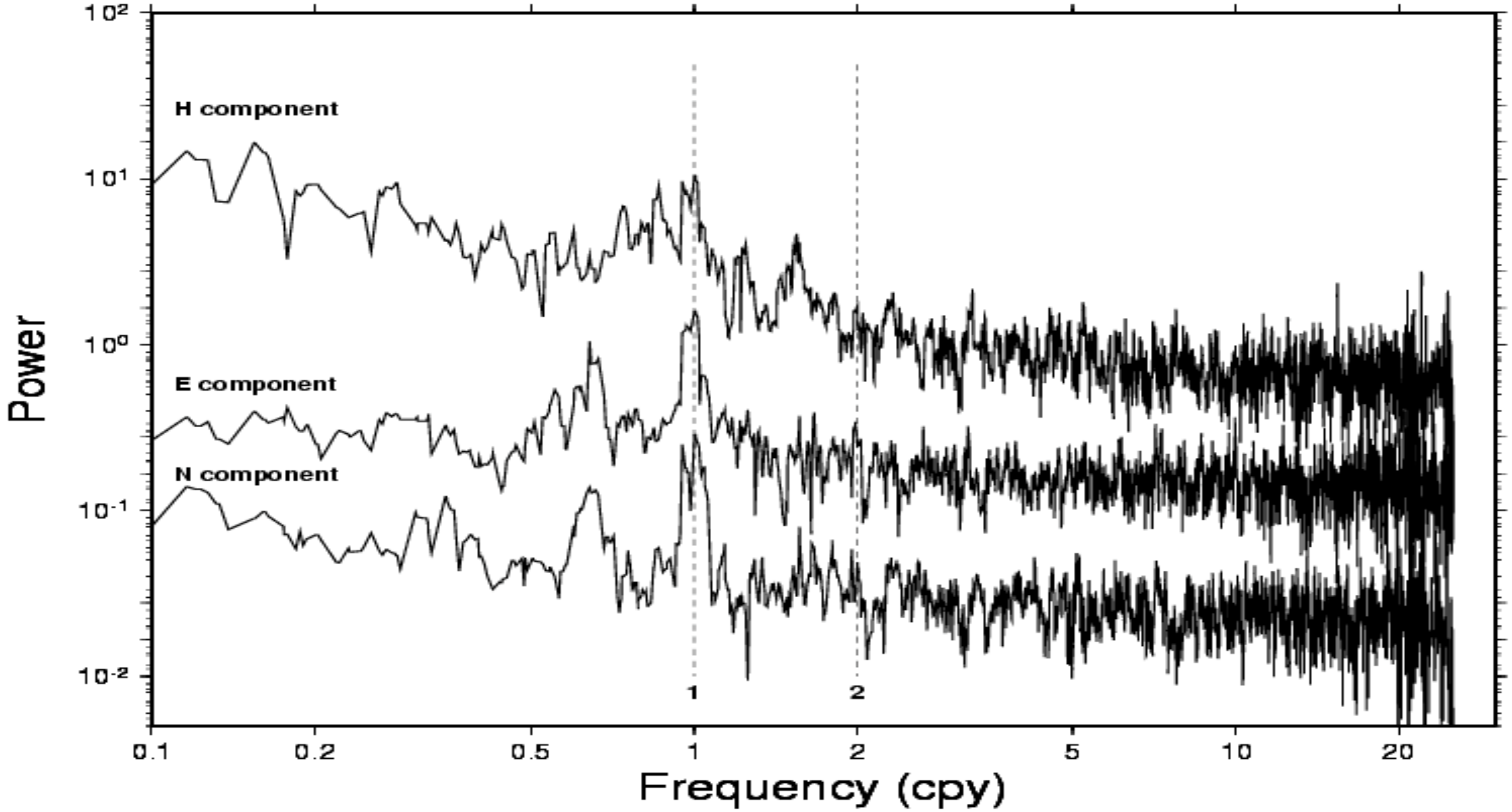

- flicker noise may describe background spectrum of residuals down to periods of a few months
- at shorter intervals, residuals become whiter

# Smoothed Spectra of VLBI Residuals




- same procedures as for GPS spectra, for 21 sites with >200 24-hr sessions
- only clear peak is ~1 cpy in dU residuals
- spectra dominated by white noise

# Smoothed Spectra of SLR Residuals




- same procedures as for GPS spectra, for 18 sites with >200 weekly points
- ~1 cpy peaks seen in all components, but no harmonics
- spectra dominated by white noise

# Smoothed, Decimated GPS Spectra

- **test effect of larger GPS data volume by decimating spectra, then smoothing**
- **spectra become much noisier but some harmonics still visible**
- **probably does not explain most differences with VLBI/SLR**

# Smoothed, Stacked Spectra of GPS Sigmas

- stacked power spectra for 167 IGS sites with >200 weekly points during 1996.0 – 2006.0 (from Z. Altamimi)
- smoothed by boxcar filter with 0.03 cpy window
- only clear peak is at ~2 cpy – unlike position spectra

# Correlations with Instrumental Changes & TEQC Metrics

- TEQC is a GPS utility from UNAVCO to *translate*, *edit*, *quality check* RINEX data files
- QC metrics include: (10° elevation cut used here)
  - total obs
  - number of deleted obs
  - % complete dual-frequency obs
  - number of phase cycle slips
  - code multipath RMS variations at L1 & L2 (MP1 & MP2)
  - many other details
- most IGS data are routinely QCed

# FORT: Instrumental Changes

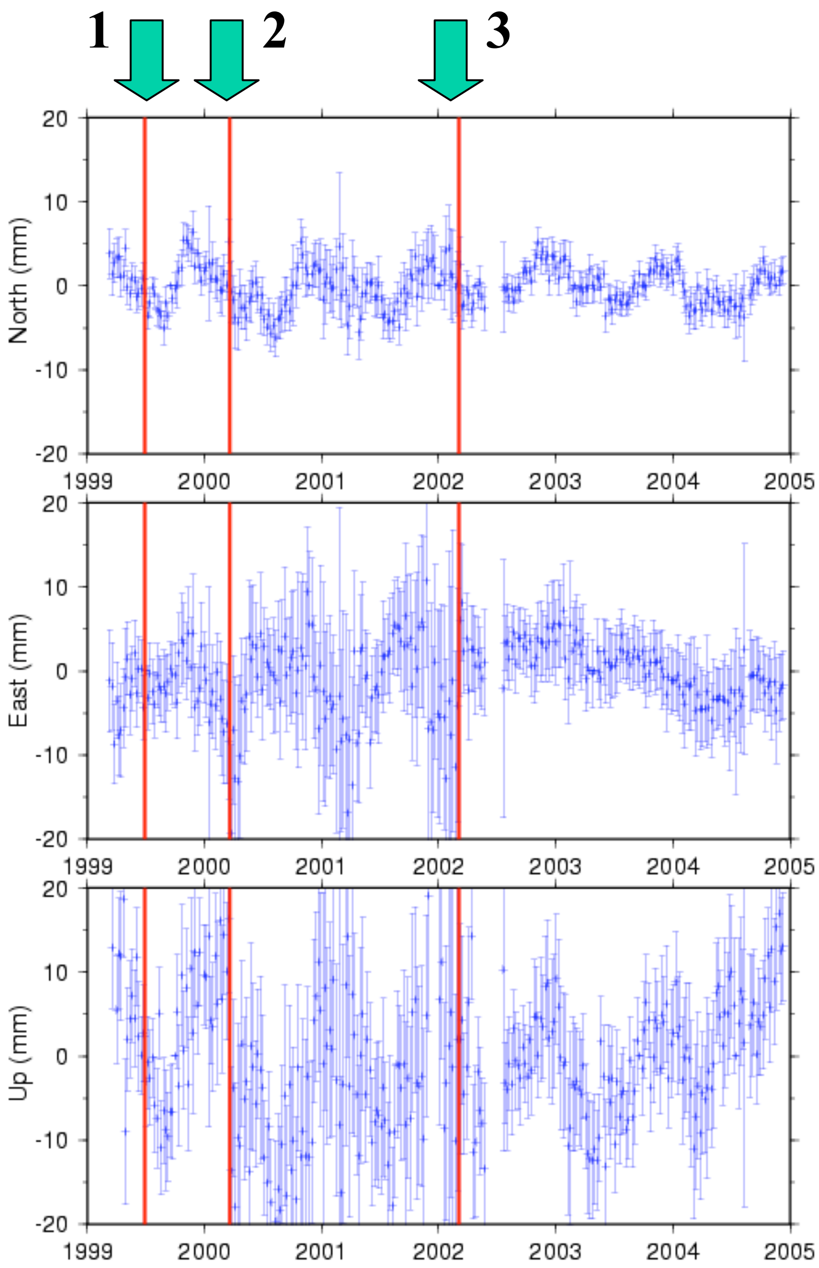
- changes:
  1) 1999.5: new firmware
  2) 2000.2: new antenna
  3) 2002.2: new firmware
     (to fix TR L2 tracking)

- wtd annual fits, before & after 2002.2 firmware mod

- 

| | 1999-2002.2 | | 2002.2-2005 |
|---|---|---|---|
| N: | 2.46 ± 0.26 | | 2.01 ± 0.22 |
| E: | 2.36 ± 0.69 | ▶ | 1.06 ± 0.48 |
| U: | 8.34 ± 0.96 | ▶ | 4.32 ± 0.79 |

- annual E,U signals halved after last firmware change



# NOUM: Receiver Changes

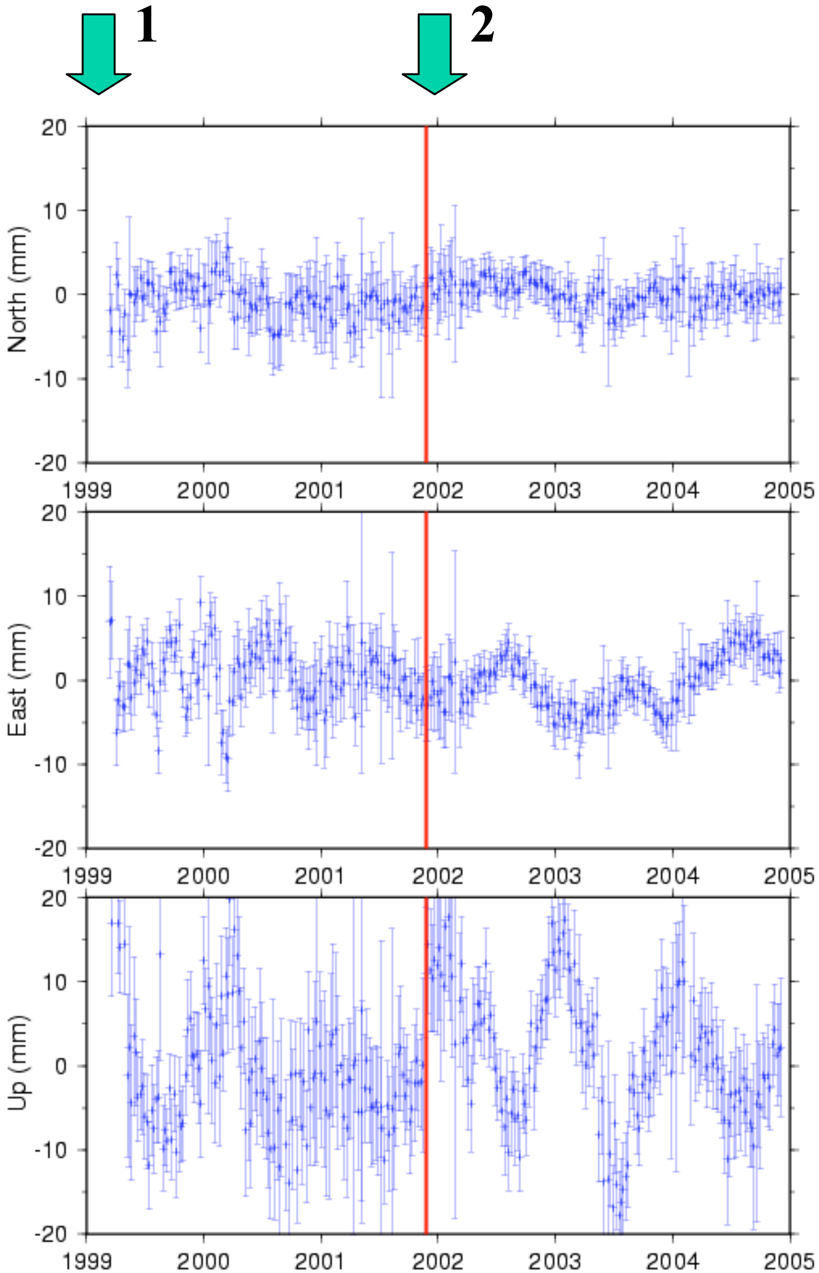
- receiver changes:
  1) →2001.9: Trimble 4000/4700
  2) 2001.9→: Trimble 5700

- wtd annual fits, before & after 2001.9

| | 1999-2001.9 | | 2001.9-2005 |
|---|---|---|---|
| N: | 0.74 ± 0.39 | | 0.40 ± 0.28 |
| E: | 1.25 ± 0.41 | ▶ | 2.42 ± 0.29 |
| U: | 7.61 ± 0.87 | | 7.95 ± 0.63 |

- annual E variations doubled after receiver change

- this is an island site

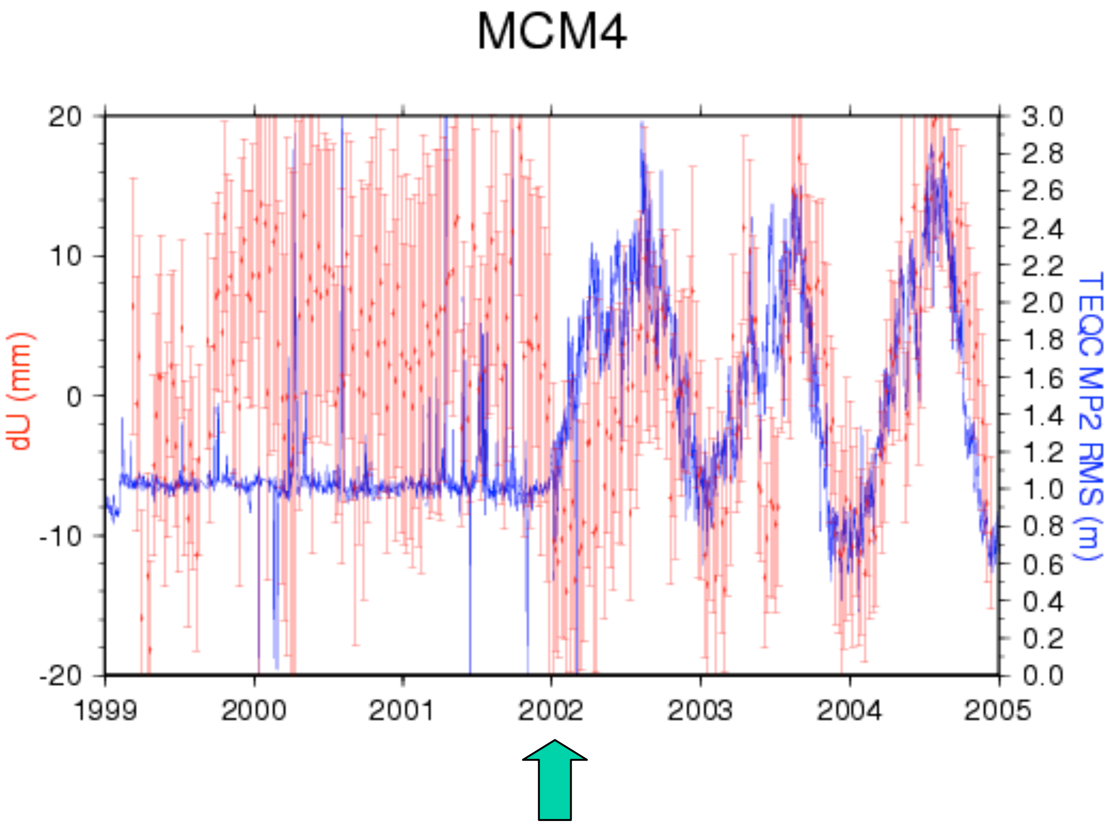


# MCM4:  dU versus Receiver Change & MP2

- at MCM4 (McMurdo), start of annual height & annual MP1, MP2 variations coincide

- annual signals begin with receiver swap (03 Jan 2002)

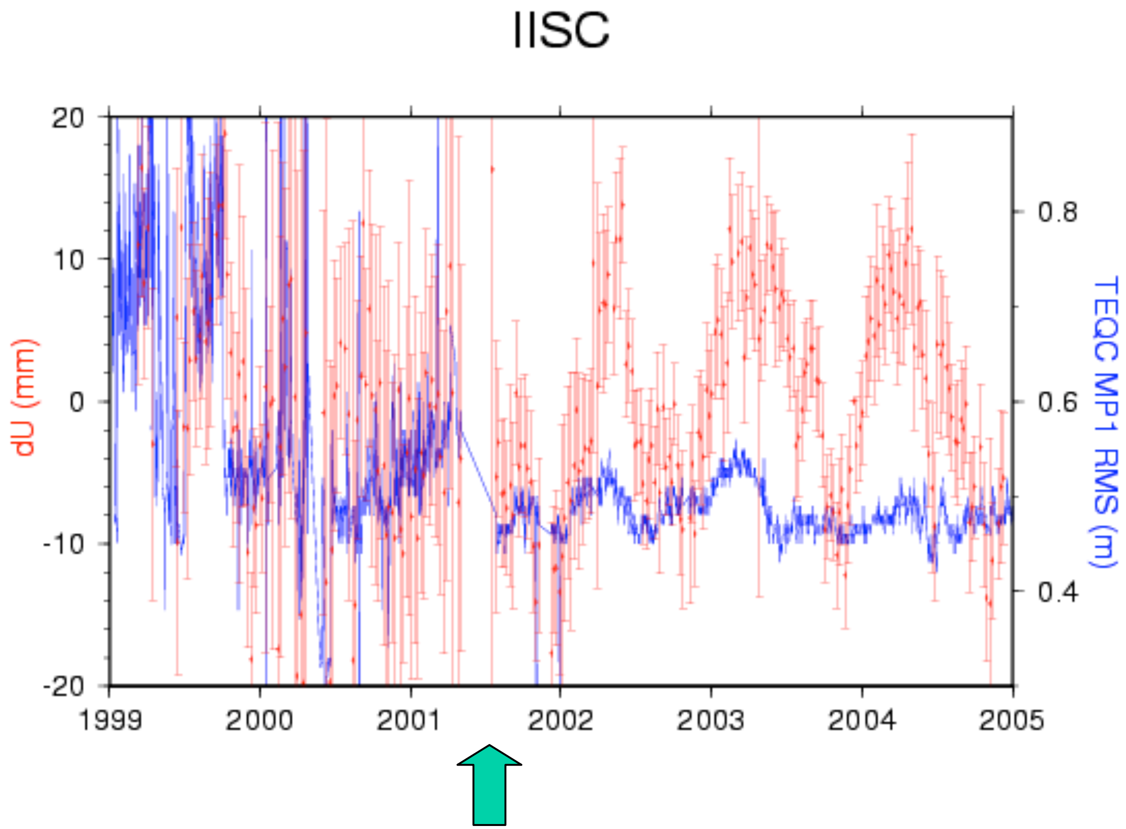
- TurboRogue SNR-8000 changed to ACT SNR-12




- strongly suggests common instrumental basis for code multipath & height changes responding to seasonal forcing

# IISC: dU versus MP1

- IISC (Bangalore) dU correlates well with MP1
- annual signals begin with receiver swap (17 Jul 2001)
- TurboRogue SNR-8000 changed to Ashtech Z12

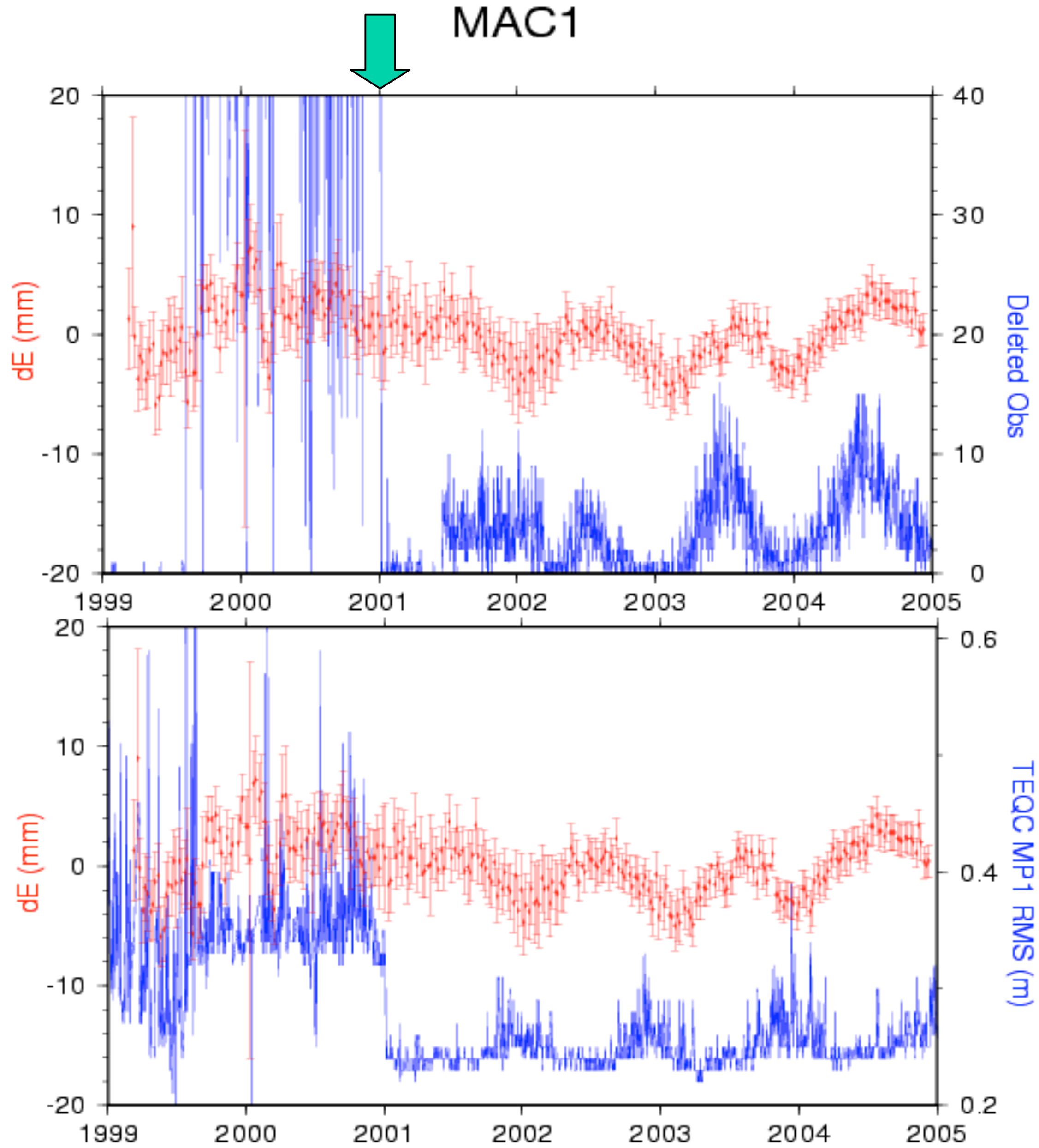


# MAC1: dE versus Deleted Obs & MP1

- MAC1 (MacQuarie Island) dE correlates well with number of deleted obs & MP1

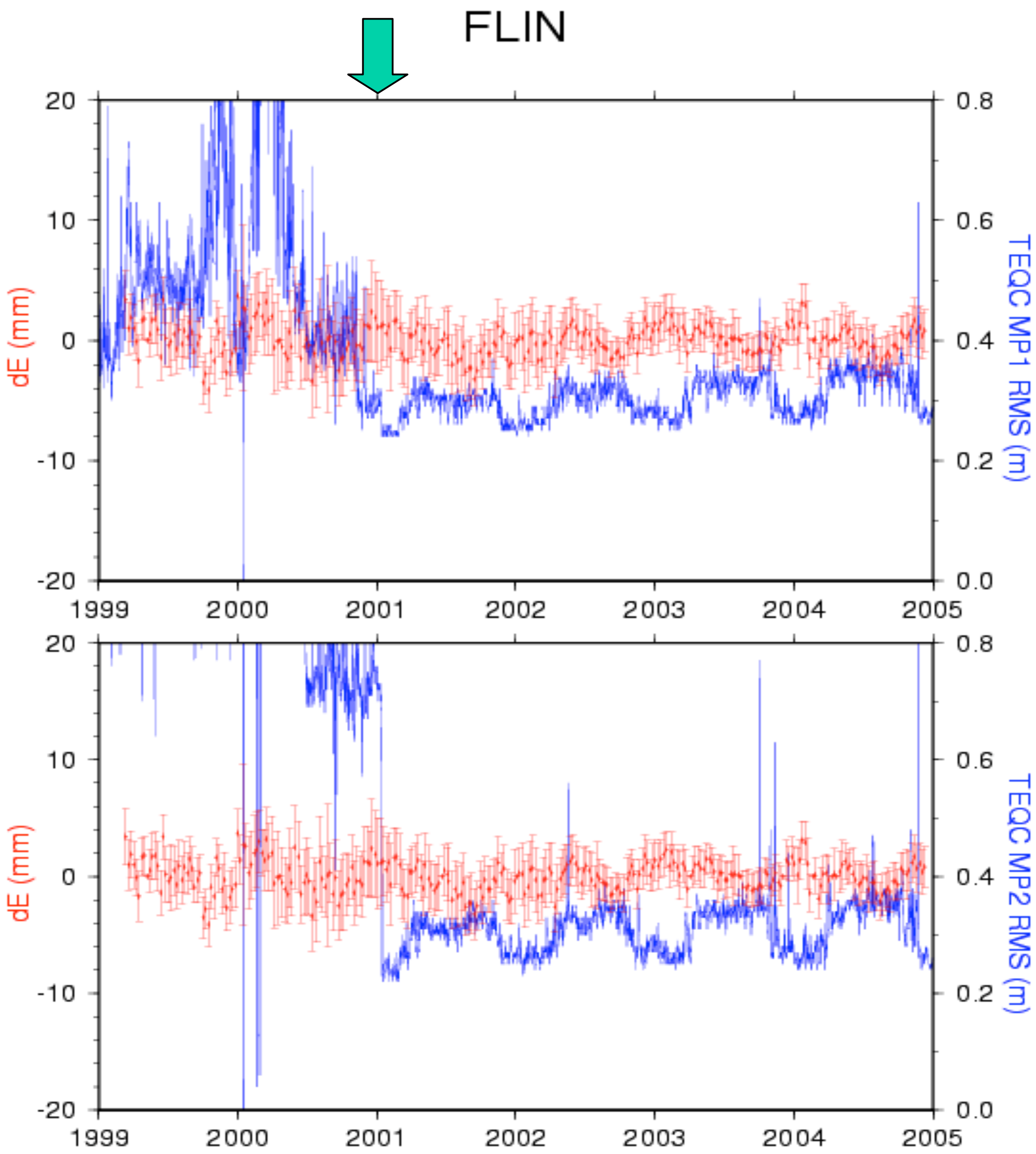
- changes in behavior correspond with receiver change (04 Jan 2001)

- Ashtech Z12 changed to ACT ICS-4000Z



# FLIN: dE versus MP1 & MP2

- **FLIN (Flin Flon) dE correlates well with MP1 & MP2**
- **changes in behavior correspond with receiver change (13 Jan 2001)**
- **TurboRogue SNR-8000 changed to ACT Benchmark**

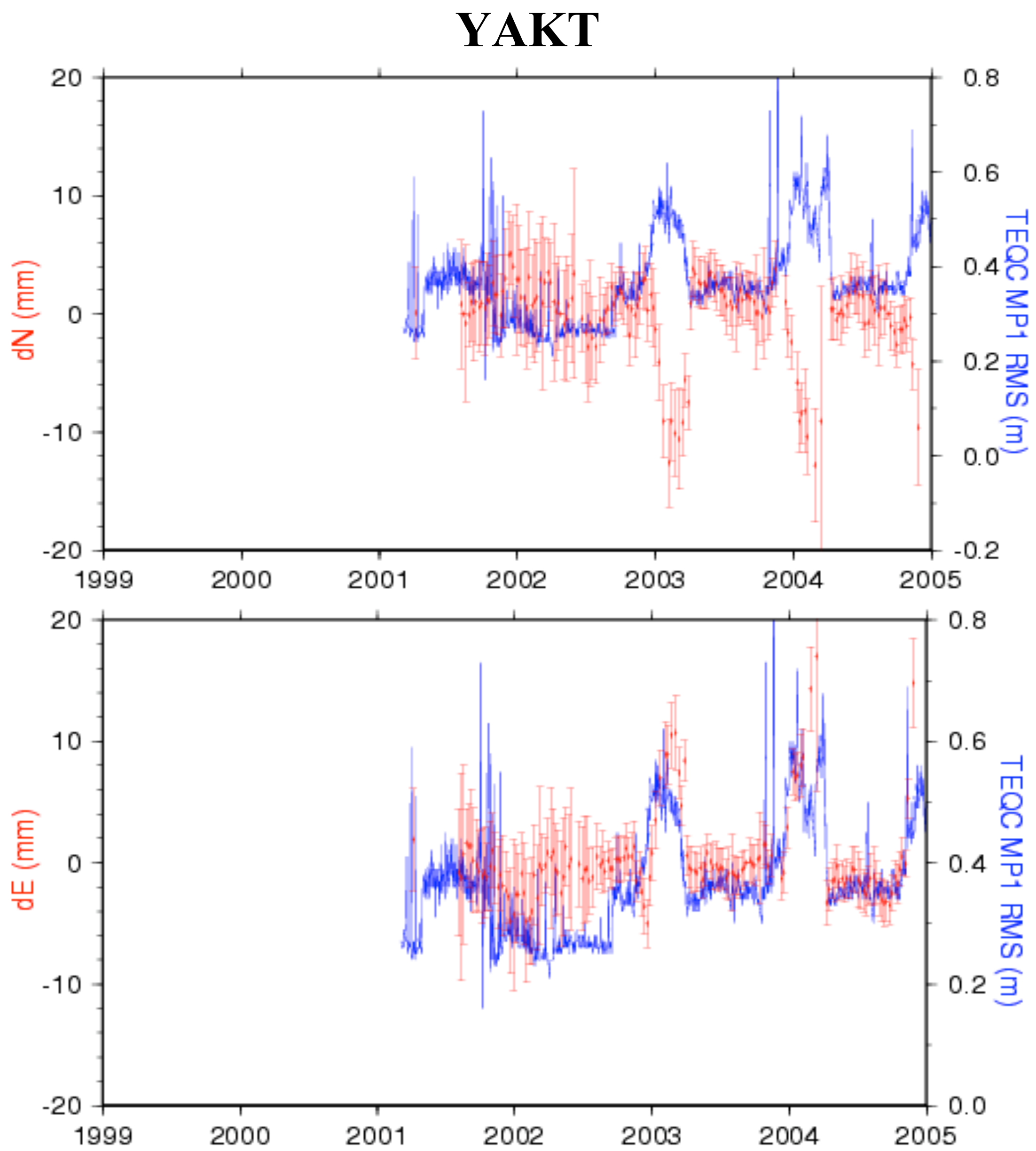


# YAKT: dN & dE versus MP1

- YAKT (Yakutsk) dN & dE correlate well with MP1

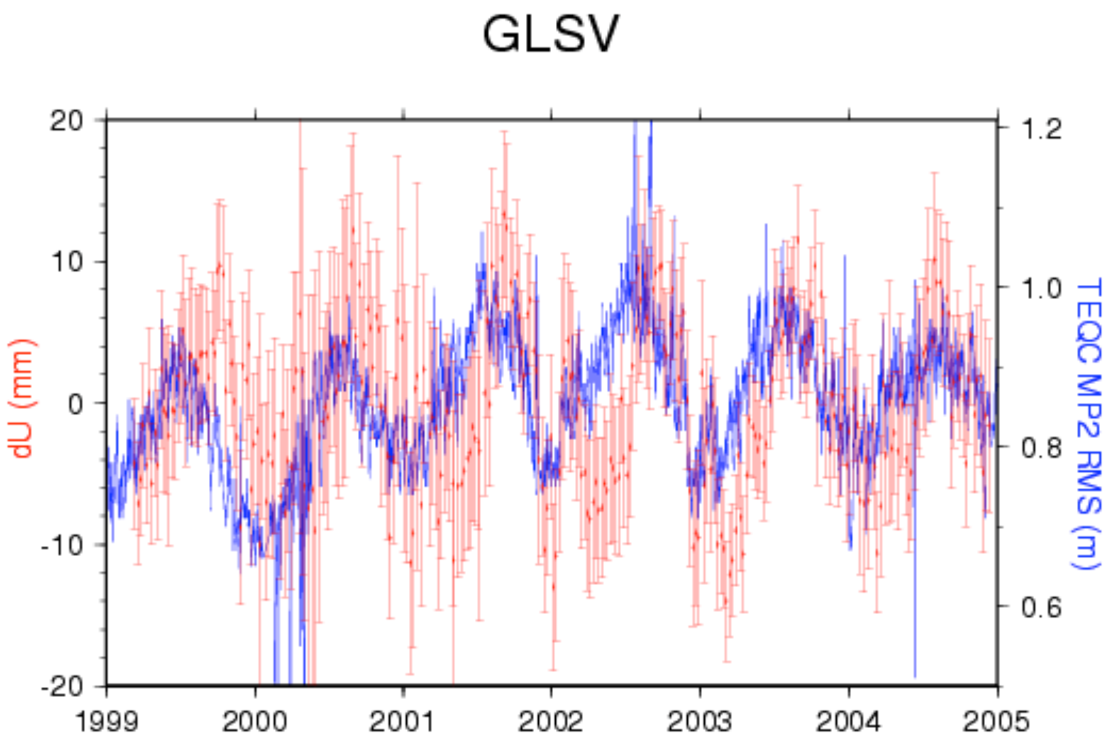
- instrumental mechanism is known in this case

- in winters, snow covers antenna [Steblov & Kogan, 2005]



# GLSV: dU versus MP2

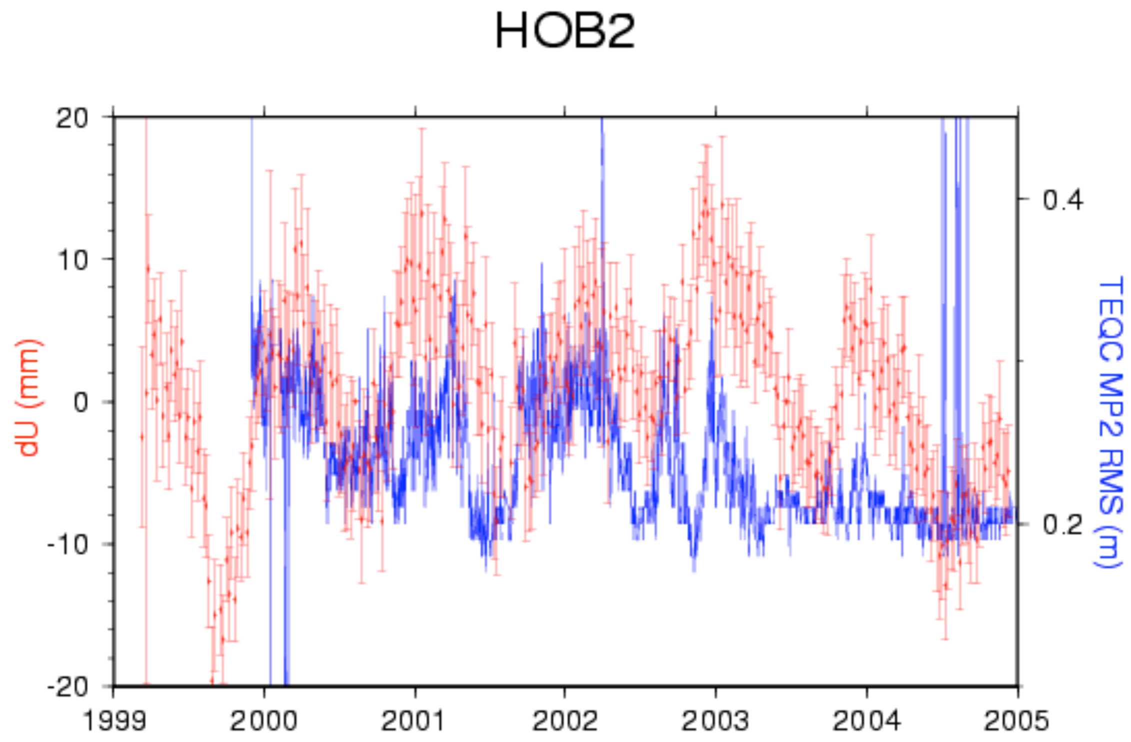
- **GLSV (Kiev) dU correlates well with MP2**
- **MP1 & MP2 often correlate with dU variations at other sites**




- **NOTE: does *not* imply code multipath *causes* annual height changes**
- **only implies possible common instrumental response to seasonal forcing that affects dU, MP2, & other quality metrics**

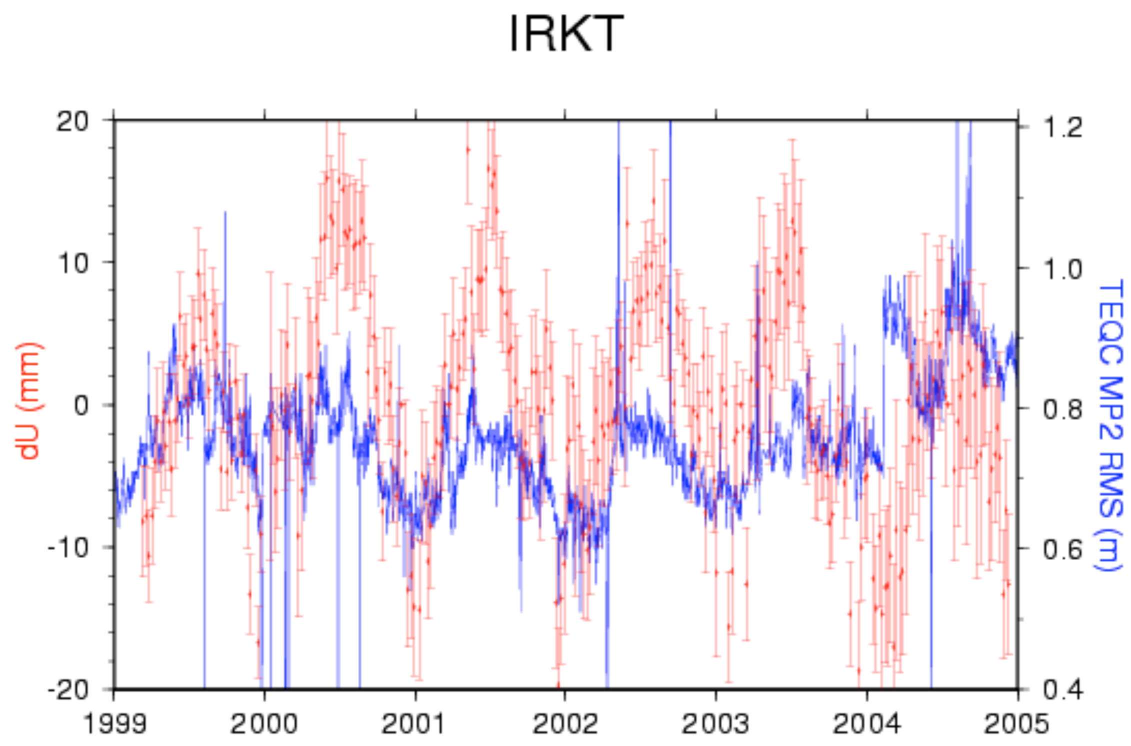
# HOB2: dU versus MP2

- **HOB2 (Hobart) dU correlates well with MP2**



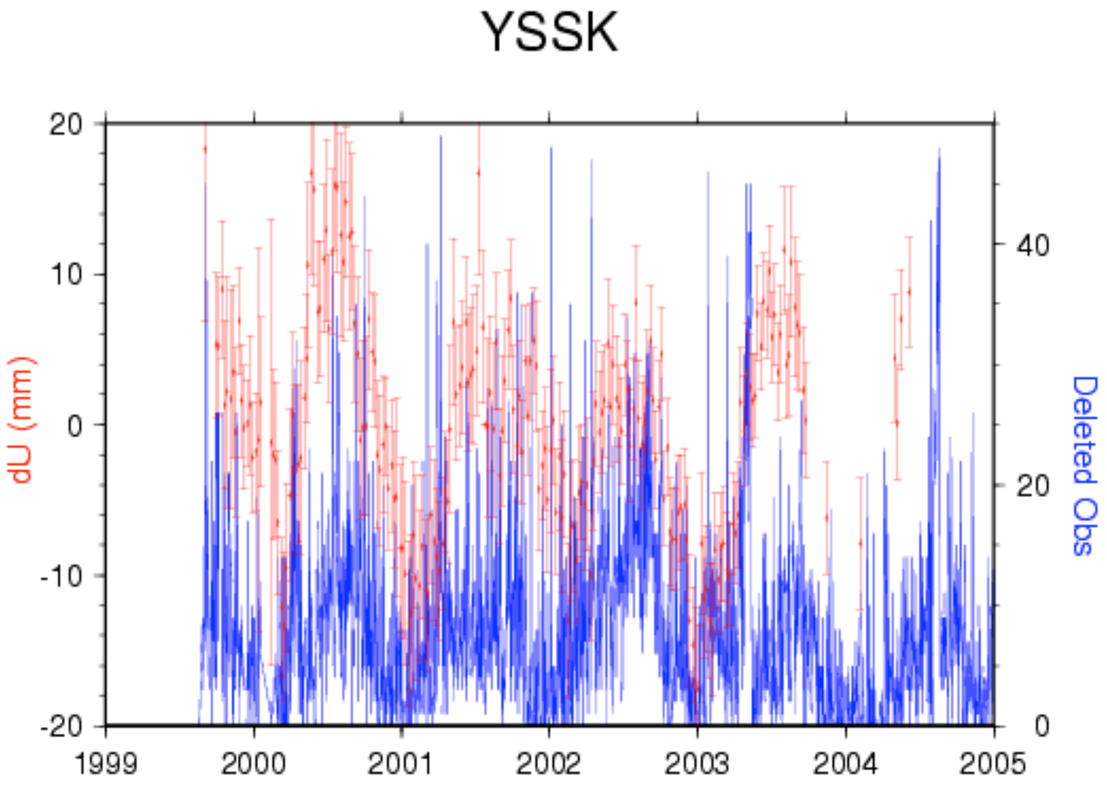
# IRKT: dU versus MP2

- **IRKT (Irkutsk) dU correlates well with MP2**



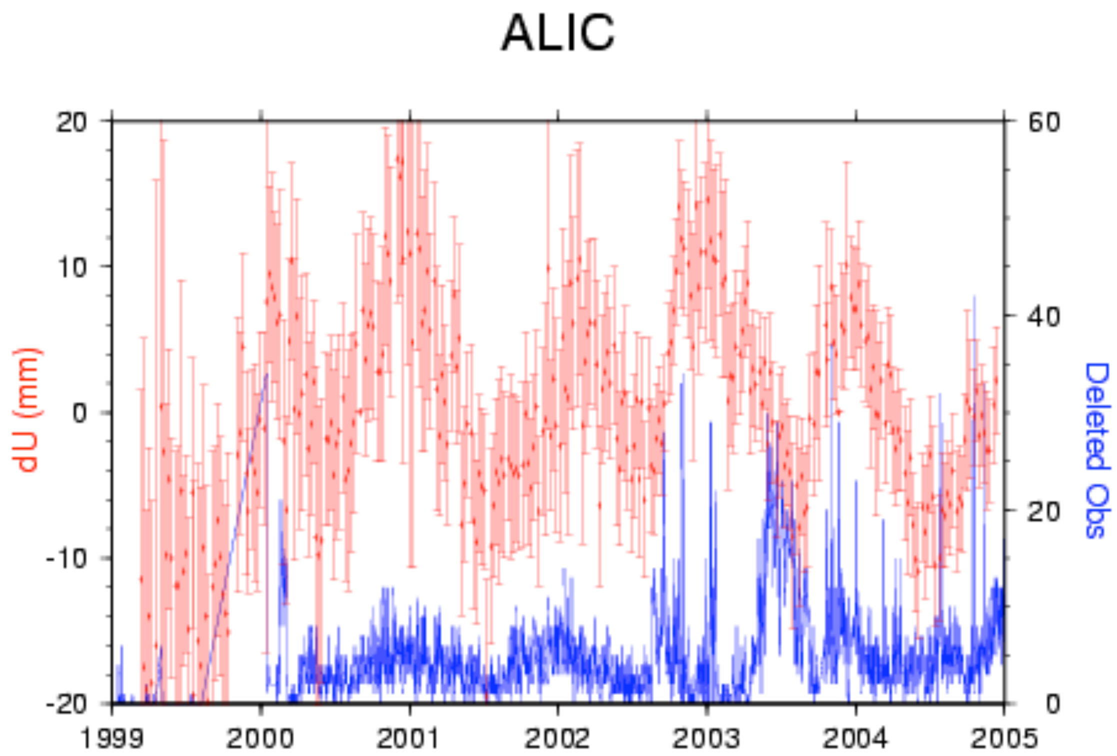
# YSSK:  dU versus Deleted Obs

- YSSK (Yuzhno-Sakhalinsk)  dU correlates well with number of deleted obs (per day)



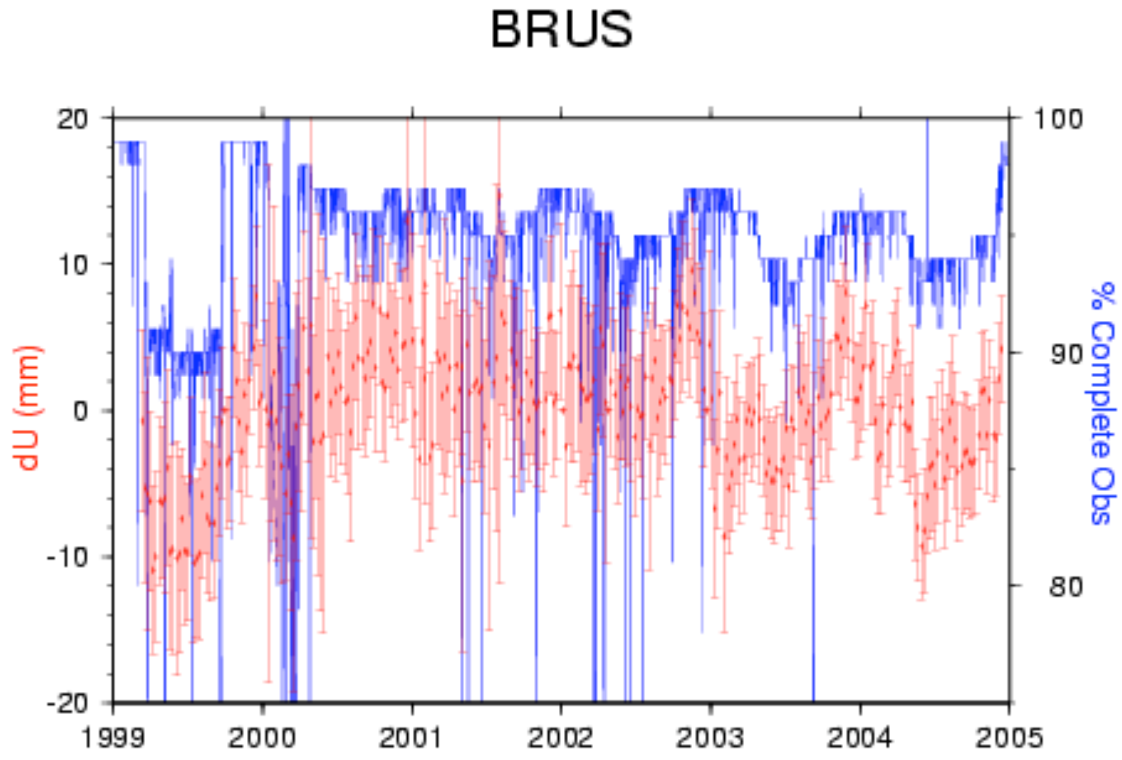
# ALIC: dU versus Deleted Obs

- **ALIC (Alice Springs) dU correlates well with number of deleted obs (per day)**



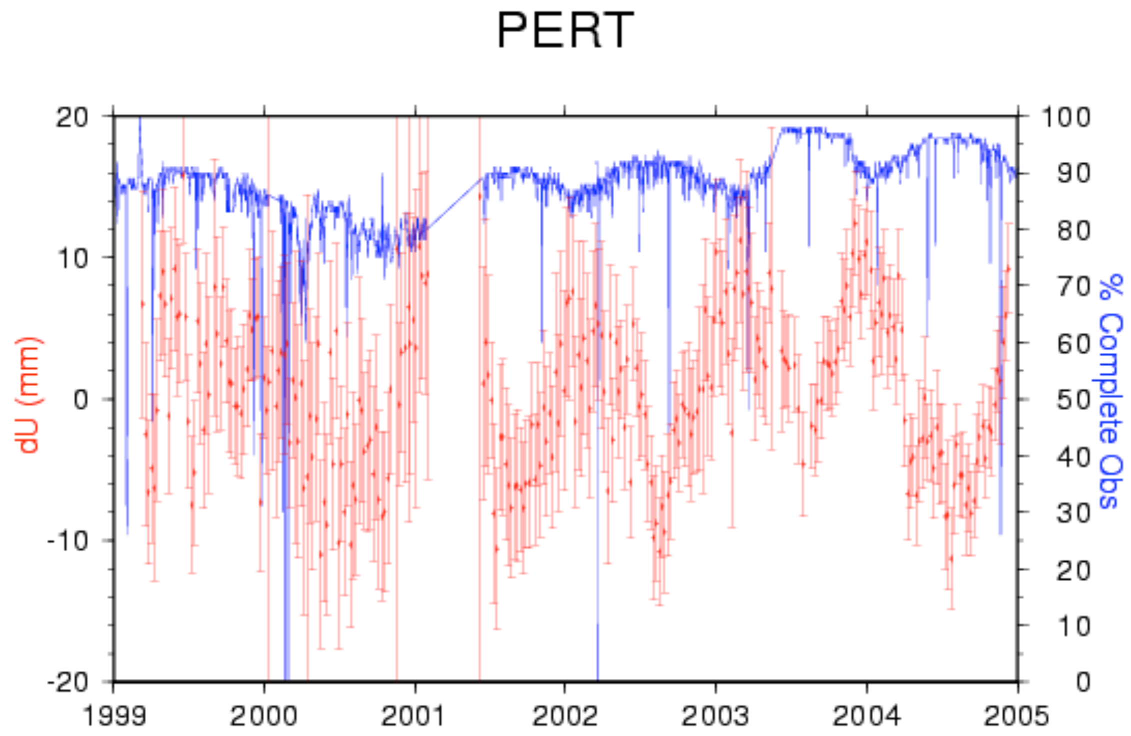
# BRUS: dU versus % Complete Obs

- **BRUS (Brussels) dU correlates well with % complete obs**



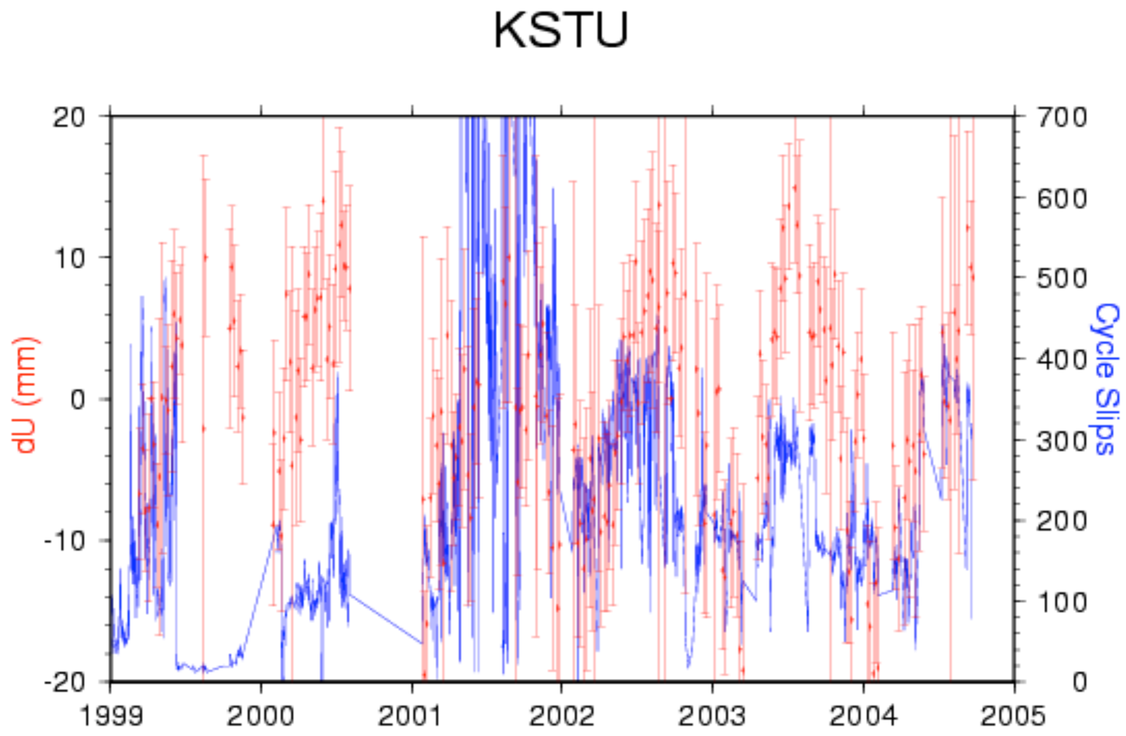
# PERT: dU versus % Complete Obs

- **PERT (Perth) dU correlates well with % complete obs**



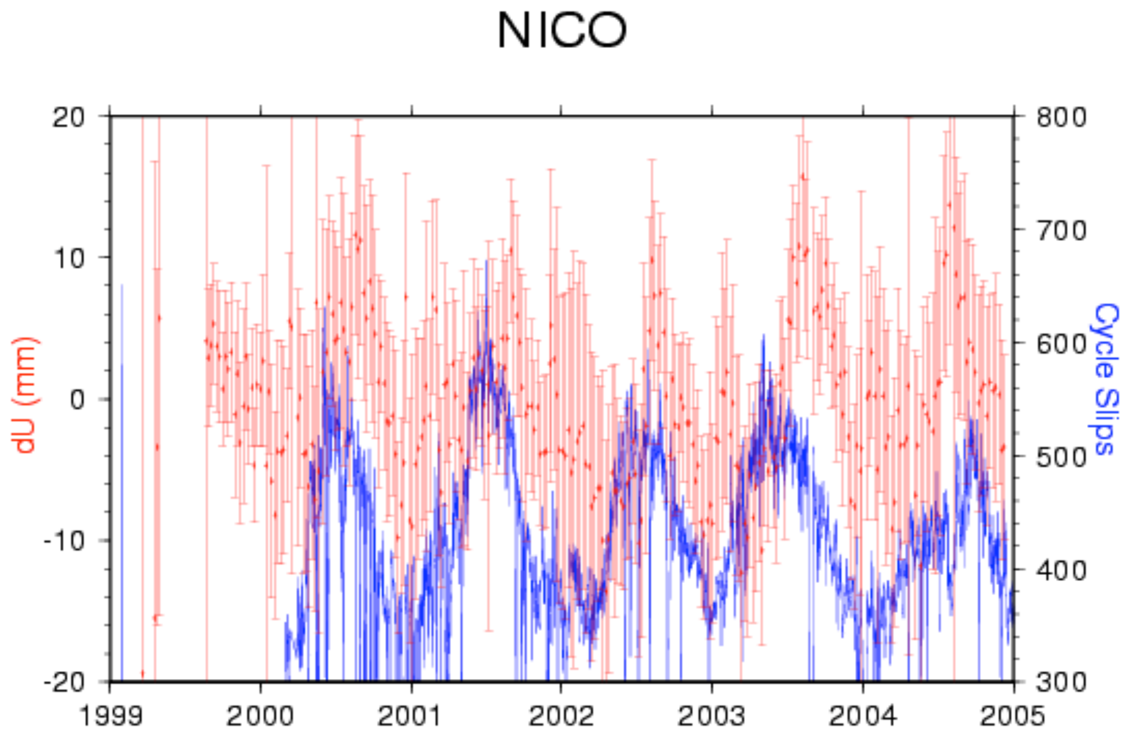
# KSTU: dU versus Cycle Slips

- **KSTU (Kransnoyarsk) dU correlates well with number of cycle slips (per day)**



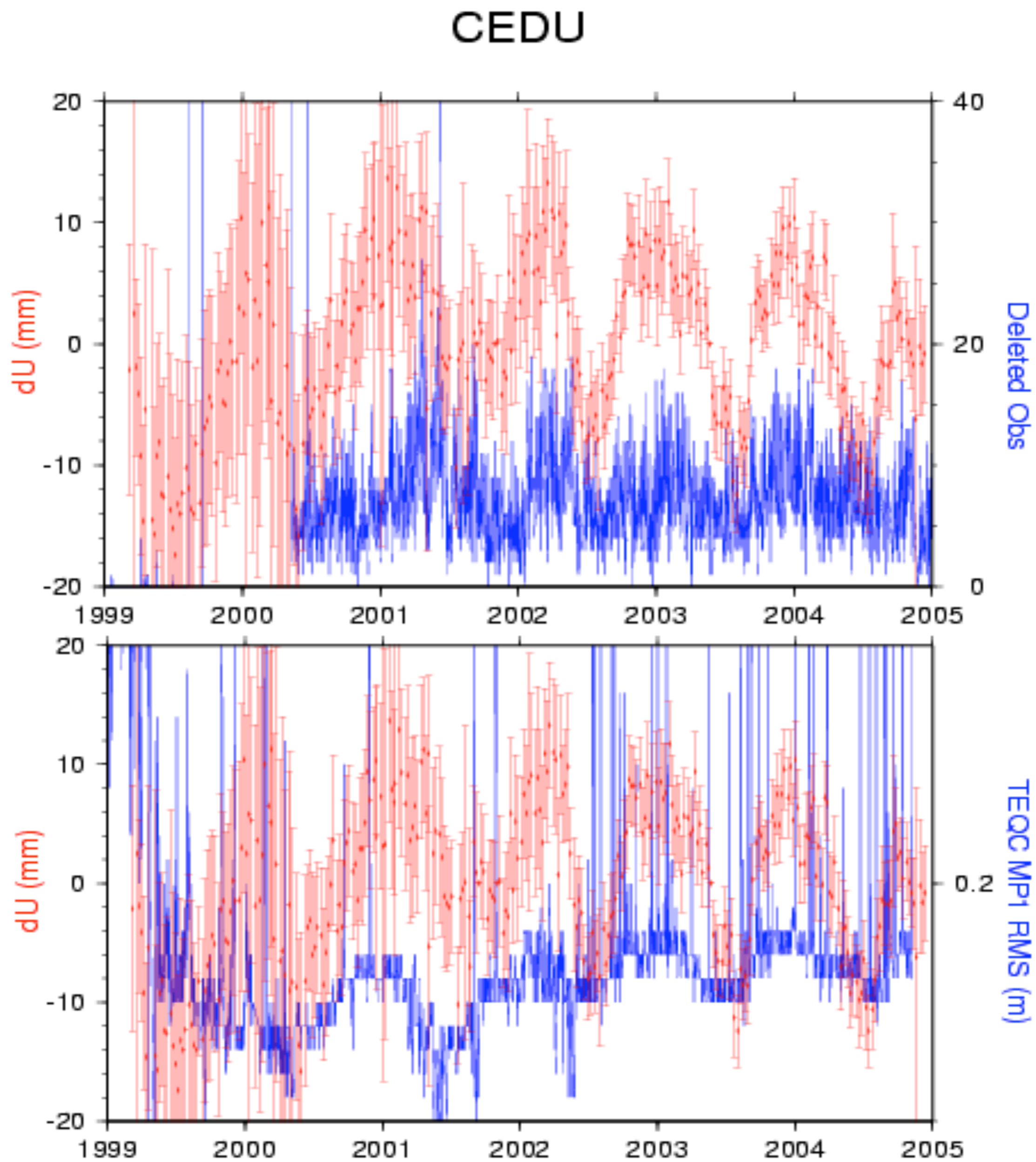
# NICO: dU versus Cycle Slips

- **NICO (Nicosia) dU correlates well with number of cycle slips (per day)**



# CEDU: dU versus Deleted Obs & MP1

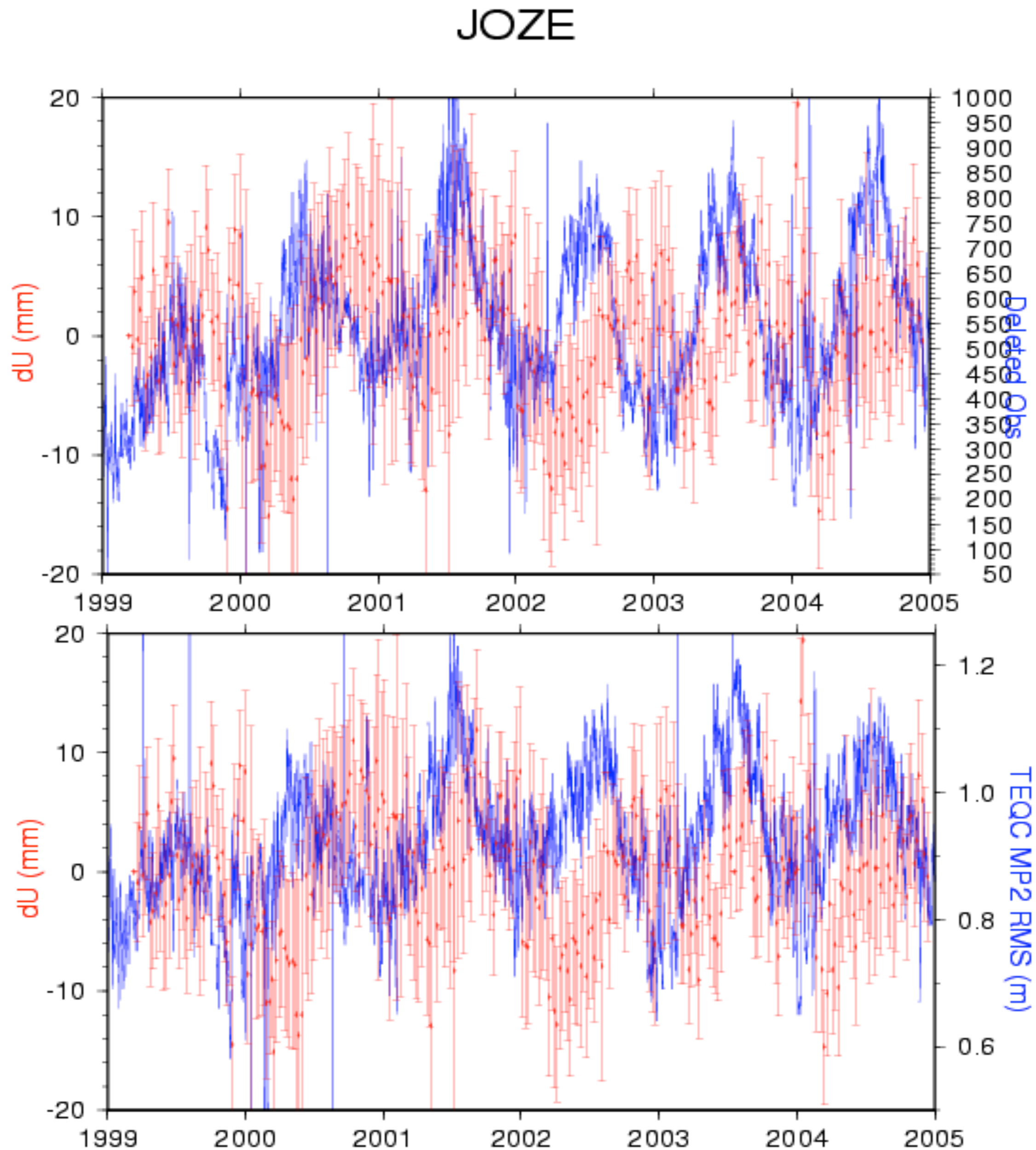
- CEDU (Ceduna) dU correlates well with number of deleted obs & MP1



# JOZE: dU versus Deleted Obs & MP2

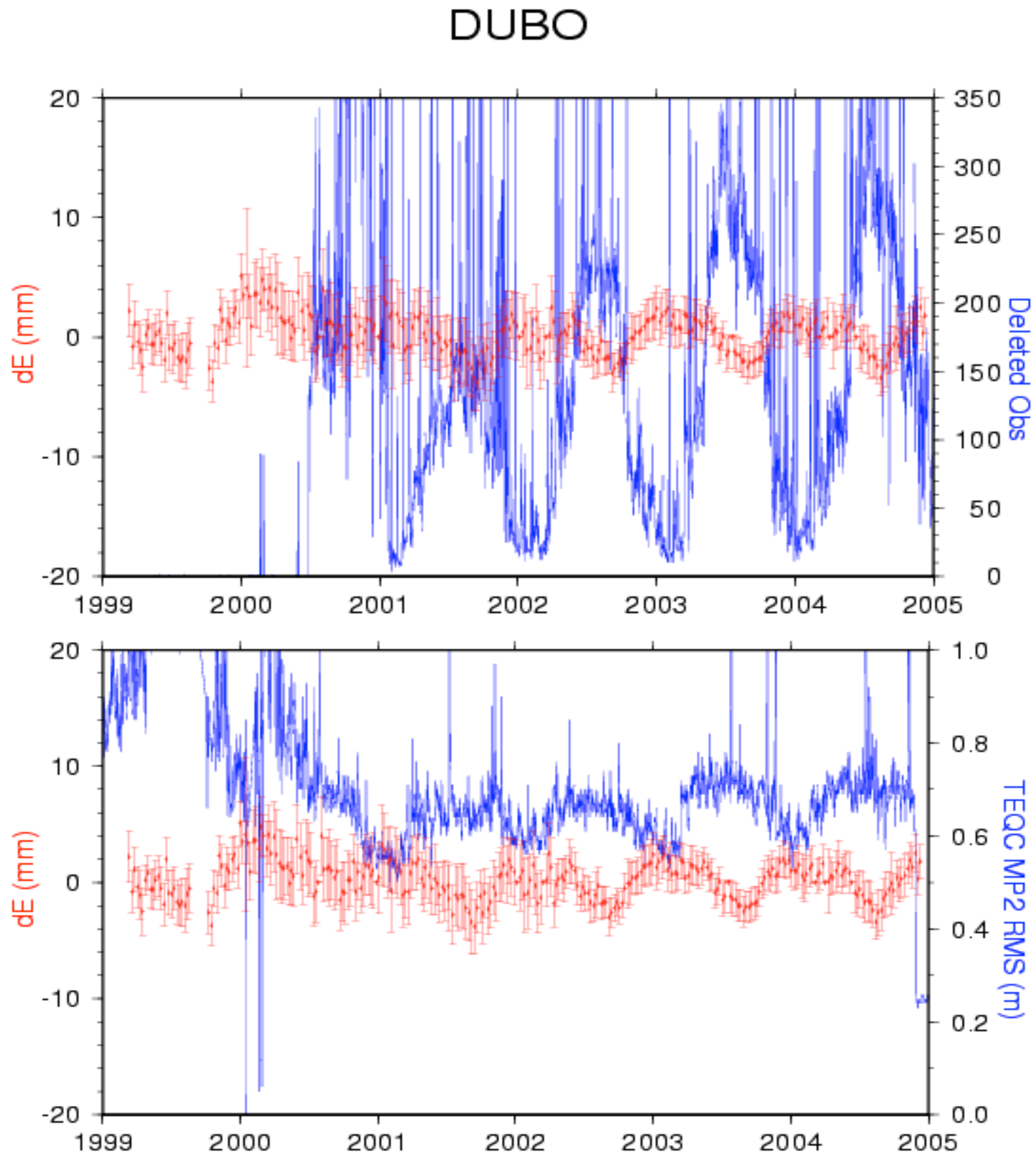
- JOZE (Jozefoslaw) dU correlates well with number of deleted obs & MP2

- seem to be phase shifted



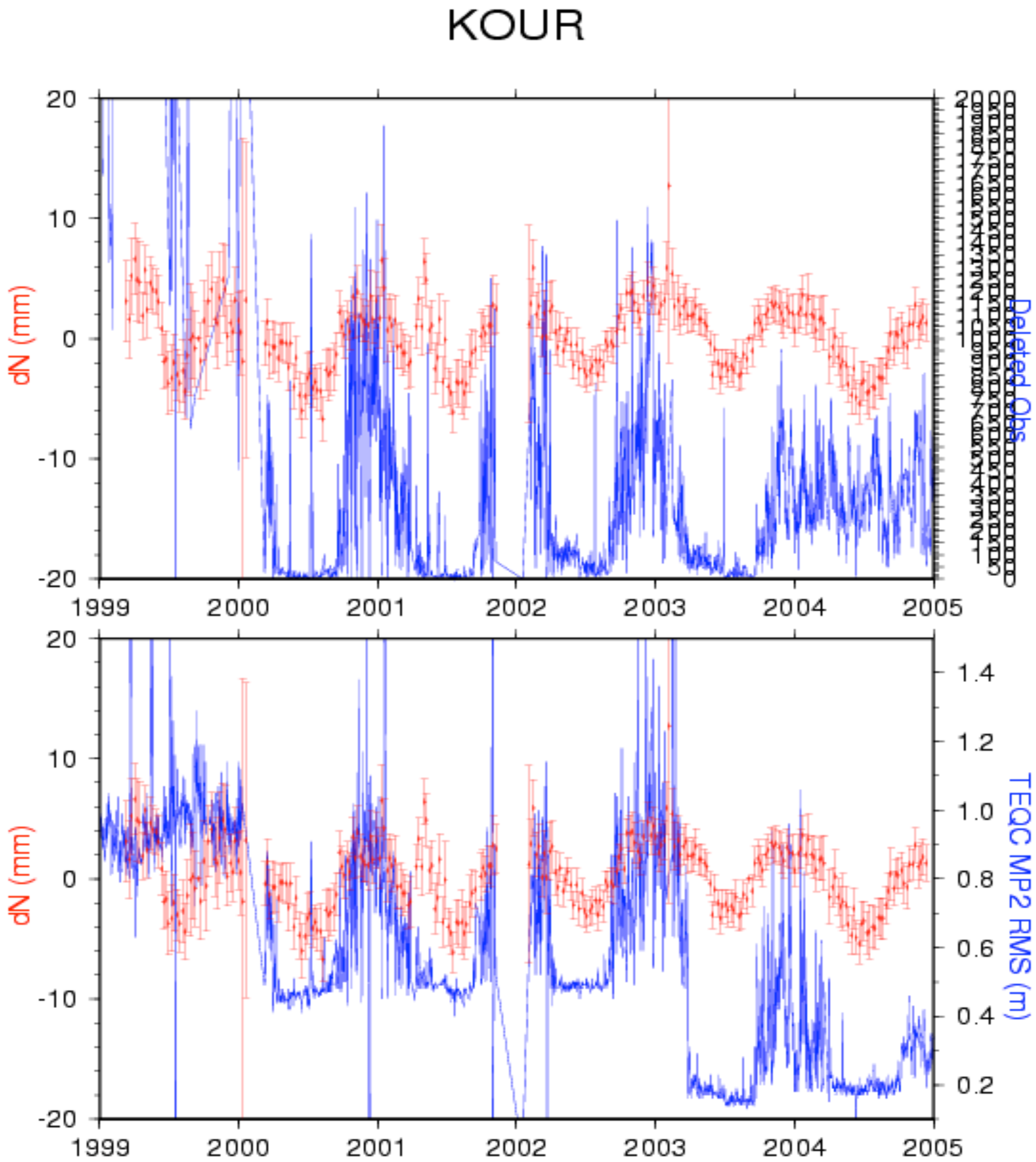
# DUBO: dE versus Deleted Obs & MP2

- **DUBO (Lac du Bonnet) dE correlates well with number of deleted obs & MP2**



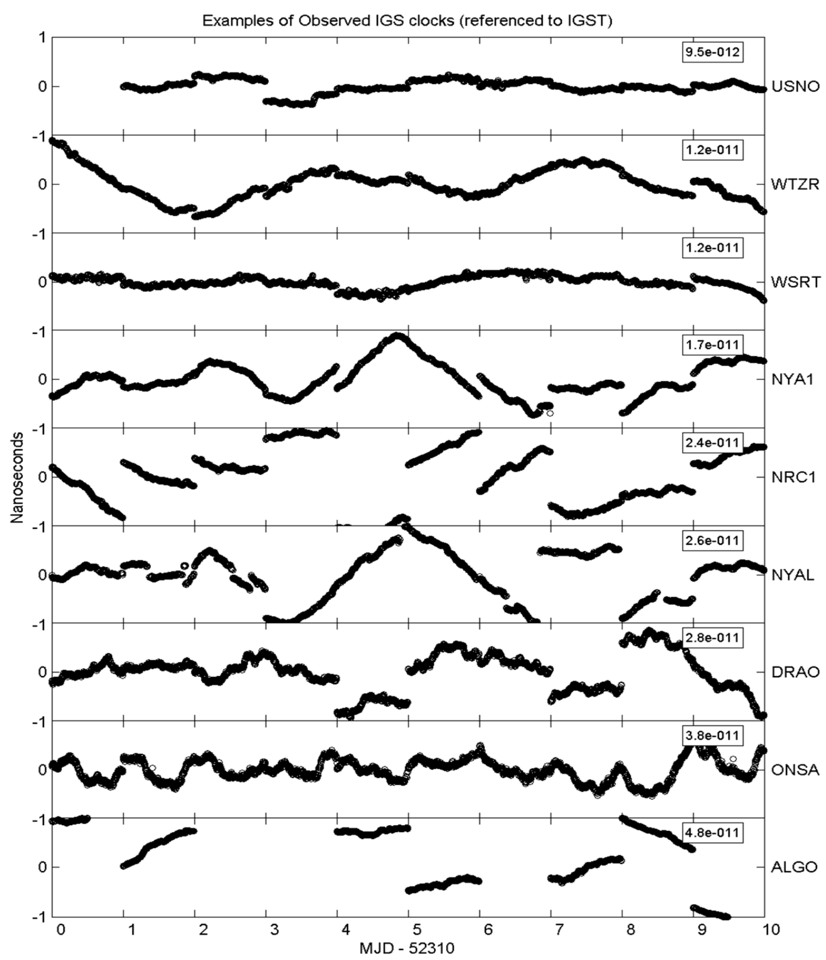
# KOUR: dN versus Deleted Obs & MP2

- **KOUR (Kourou) dN correlates well with number of deleted obs & MP2**



# Day-boundary Clock Jumps

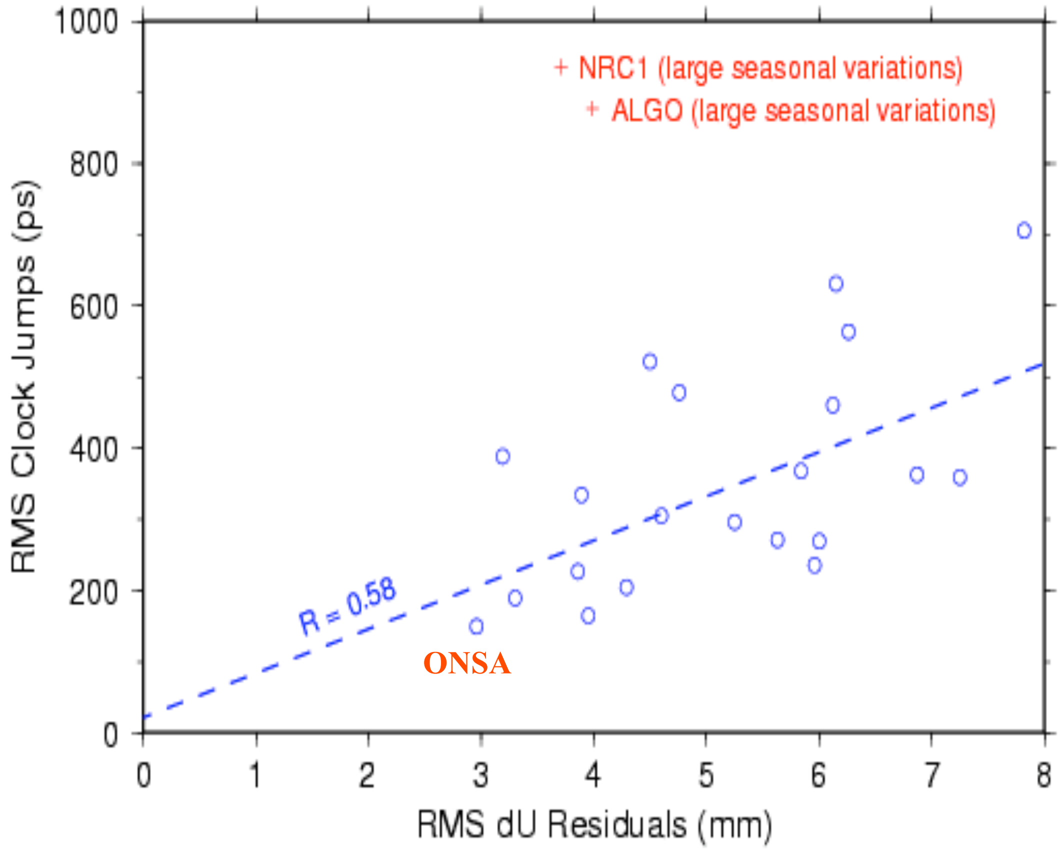
- clock bias accuracy is determined by mean code noise per arc
- for 24-hr arc with code σ = 1 m, clock accuracy should be ~120 ps
- can test accuracy by measuring clock jumps at day boundaries (H-maser stations only)
- observed clock accuracies vary hugely among stations (120 – 1500 ps)




- presumably caused by variable local code multipath conditions
- long-wavelength *(near-field) code multipath* most important

# Day-boundary Clock Jumps vs dU Residuals

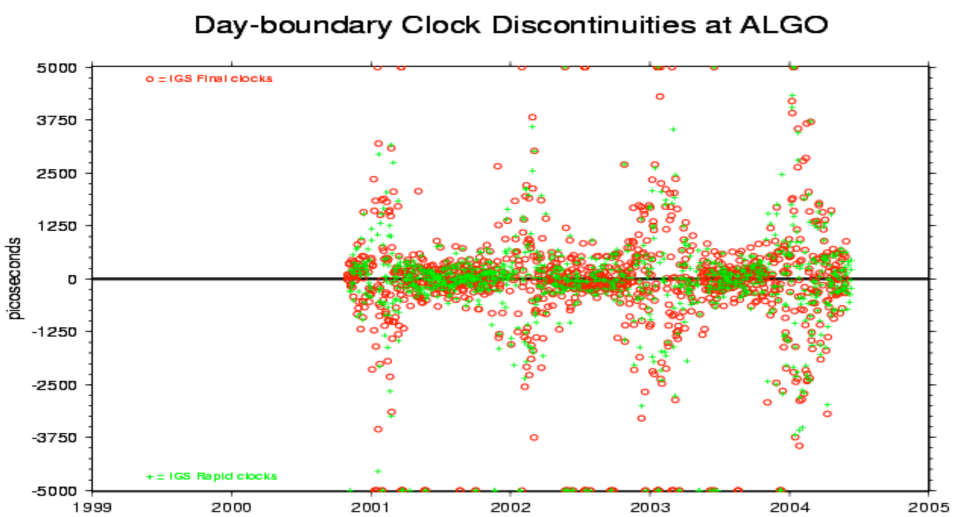
- dU residuals correlated with day-boundary clock jumps
- ALGO & NRC1 clocks affected by some other strong temperature-dependent effect also
- clock jumps reflect long-wavelength code MP; dU accuracy set by phase data

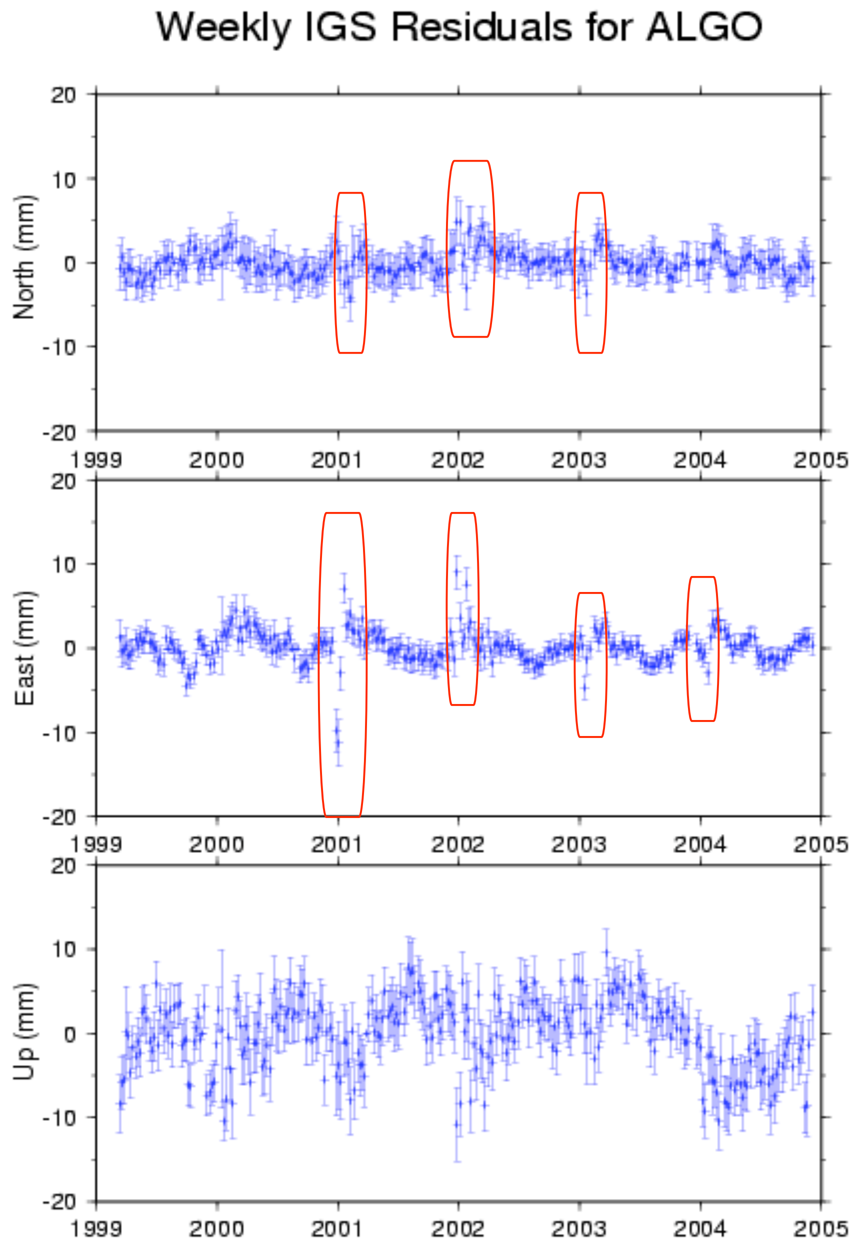



- correlation suggests that dU residuals also have large instrumental component, perhaps near-field phase MP

# ALGO: Seasonal Effects

- every winter ALGO shows large position anomalies
  - IGS deletes outliers >5 σ
- ALGO day-boundary clock jumps also increase in winters
- implies common near-field multipath effect



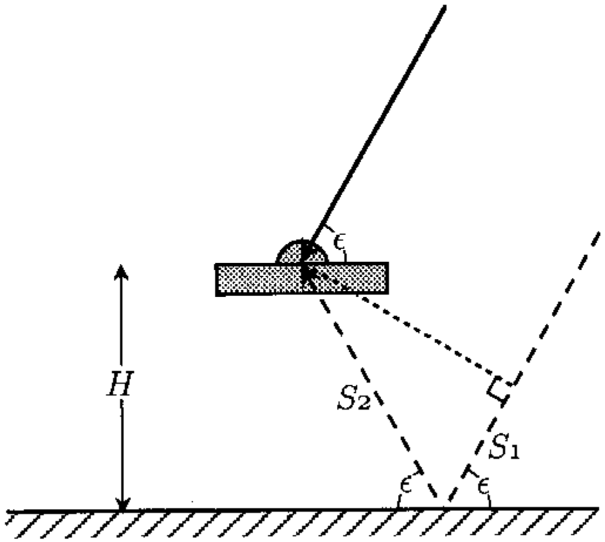
# Lessons Learned from Case Studies

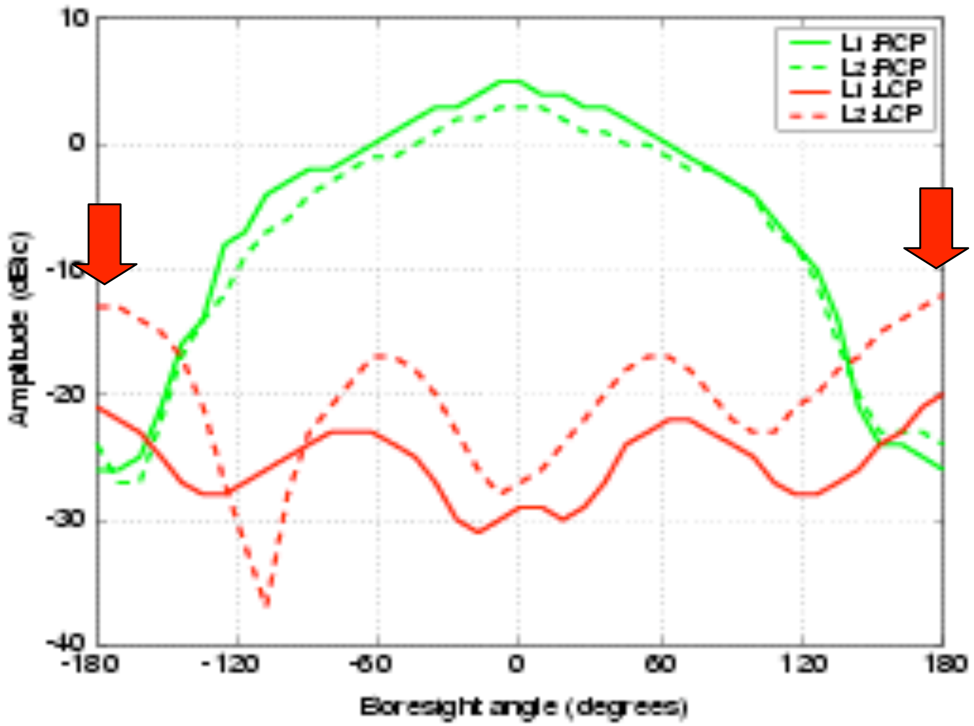
- equipment changes are clearly associated with some N,E,U changes
- annual (& harmonic) N,E,U variations are pervasive & appear mostly non-geophysical
- annual N,E,U variations often correlated with QC metrics
- all imply instrumental basis for some GPS position variations
- correlation of RMS clock jumps with RMS dU suggests near-field multipath is involved with both

- **Hypothesis**: antenna mounted over flat reflecting surface sensitive to standing-wave back-reflection multipath errors
  - problem described by Elósegui et al. (JGR, 1995)
  - 1) magnitude of errors may vary seasonally via surface reflectivity changes (snow, ice, rain, …)
  - 2) annual signals may be alias of repeat satellite geometry/MP signature (~K1) & 1-day RINEX/analysis sampling (~S1)

# Near-field Multipath Mechanism

- expect longest-period MP errors when H (phase center to back surface) is smallest [Elósegui et al., 1995]
- special problems when H is near multiples of phase quarter-wavelength
- RCP reflections enter from behind as LCP
- choke-ring design esp sensitive to L2 reflections from below [Byun et al. 2002]
- most IGS RF stations use antenna mount over surface!

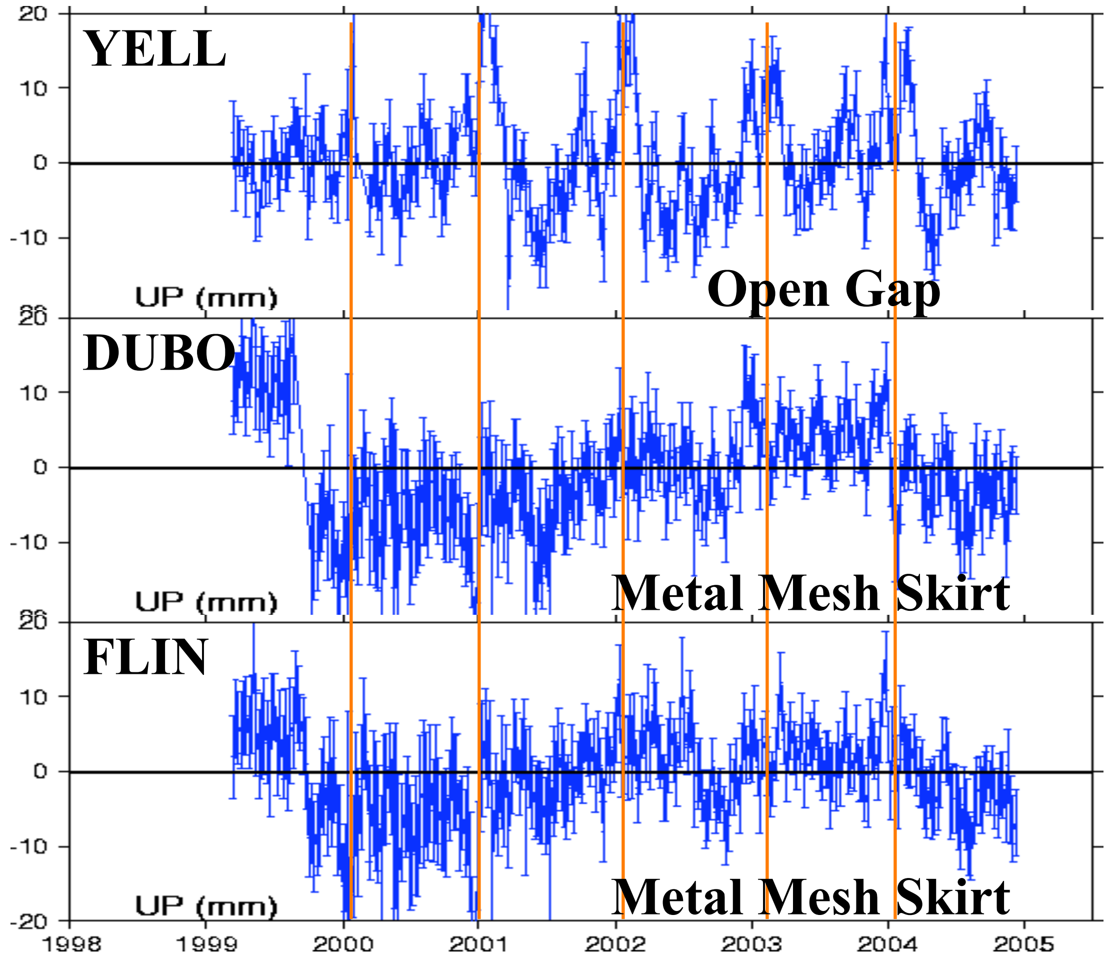


# Empirical Test of Hypothesis

- 3 nearby, similar Canadian sites provide a test case
- YELL has *open gap* between antenna & pillar top
  - 10-cm spacing
  - annual: 3.65 ± 0.30 mm

    @ 93.3° ± 4.6°




- DUBO & FLIN use *metal mesh shirts* to screen gap
  - DUBO: 10-cm spacing
  - annual: 1.59 ± 0.37 mm

    @ 347.2° ± 14.1°

  - FLIN: 15-cm spacing
  - annual: 1.74 ± 0.35 mm

    @ 355.6° ± 12.7°

# Conclusions

- **Widespread annual GPS N,E,U variations probably *not caused* mostly by large-scale geophysical processes**
- **Likely to contain systematic instrumental errors**
  - **probably related to very common configuration of antenna mounted over near-field reflecting surface**
  - **sensitive to seasonal multipath changes**
- **Interpretation of most annual dU signals as large-scale loading changes due to fluid transport is *suspect***
  - **loading theory OK, but application to GPS questionable**
  - **technique errors probably dominate except for largest loads**
  - **magnitude & distribution of inferred loading is distorted**
- **Some apparent GPS loads are undoubtedly real**
  - **esp. for large signals, e.g., Amazon (~30 mm), Australia, ...**

# Consequences

- **Predominant errors in IGS short-term frames are probably seasonal instrumental effects**
  - **needs further demonstration & understanding**
- **If all stations performed as well as the best, WRMS frame stability would be:**
  - **~ 4.0 mm for dU variations (weekly)**
  - **~ 1.1 mm for dN, dE variations (weekly)**
- **Actual performance poorer in winters by ~70%**
- **Reference frame/GPS errors will likely obscure global loading signals for indefinite future**
- ***Improvements will require major Reference Frame infrastructure upgrades***
  - **"best" station configuration not really well understood**

BRFT

# Thank You

# for mounting your antennas away from reflecting surfaces!