SUBSEASONAL GNSS ERRORS IN IGS PRODUCTS

- **Linear rate & annual GPS position errors are well studied**
  - flicker phase noise (time-correlated) dominates velocity errors
  - crustal pressure load models explain only part of annual signals
  - many other effects contribute to annual signals
- **GPS draconitic errors are pervasive**
  - driven partly by subdaily EOP tide model errors in orbits
- **IGS switched from weekly to daily terrestrial frames**
  - allows subseasonal performance studies, since 19 Aug 2012
- **New subseasonal periodic position errors found:**
  - most ACs show ~14 & ~9 d peaks from tidal errors
  - but not yet able to resolve "direct" from "aliased" tide errors
  - GLONASS ACs have 8 & 4 d signals of ground repeat period
  - JPL & GRGS possess other unique, short-period errors

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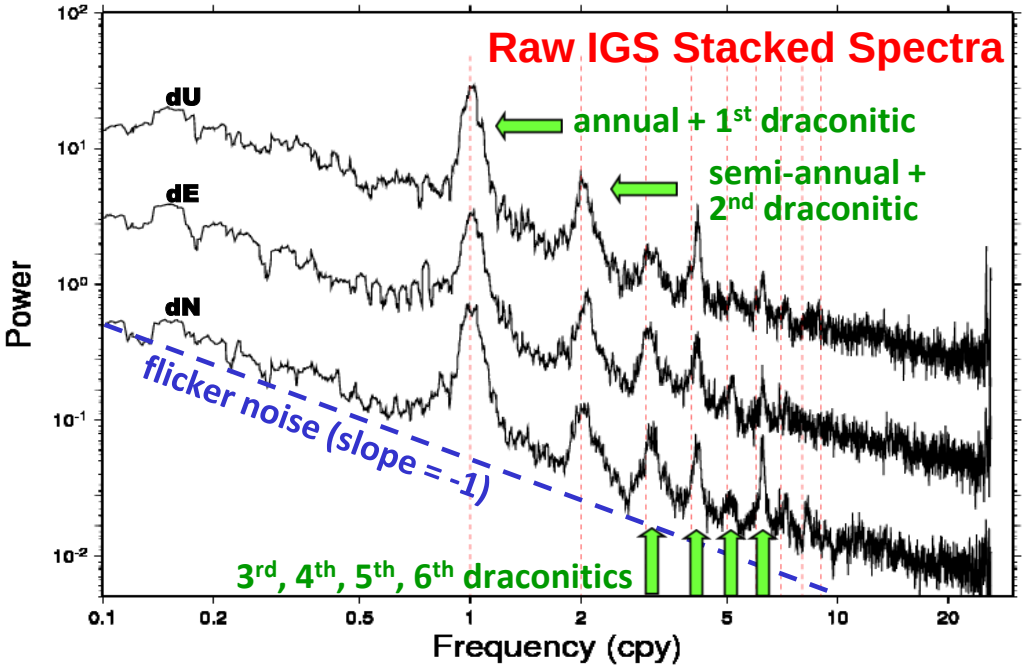
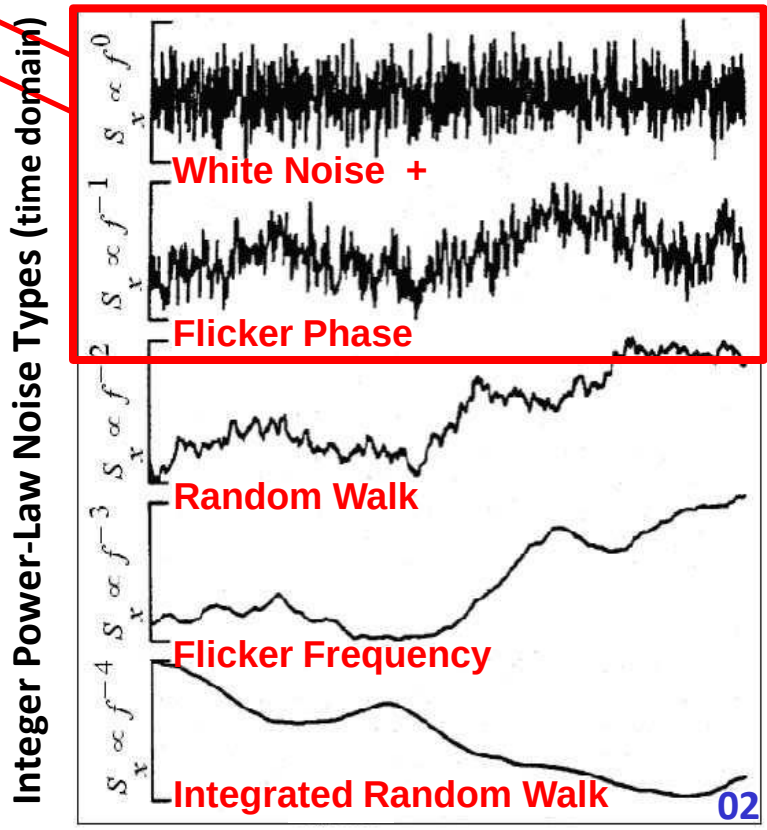
Background: Long-term GPS Position Spectra



- From IGS <u>weekly</u> combined frame residuals, 1996 - 2006
- Background spectra obey <u>flicker phase noise</u> process
  - position errors time-correlated
  - some white noise at highest frequencies

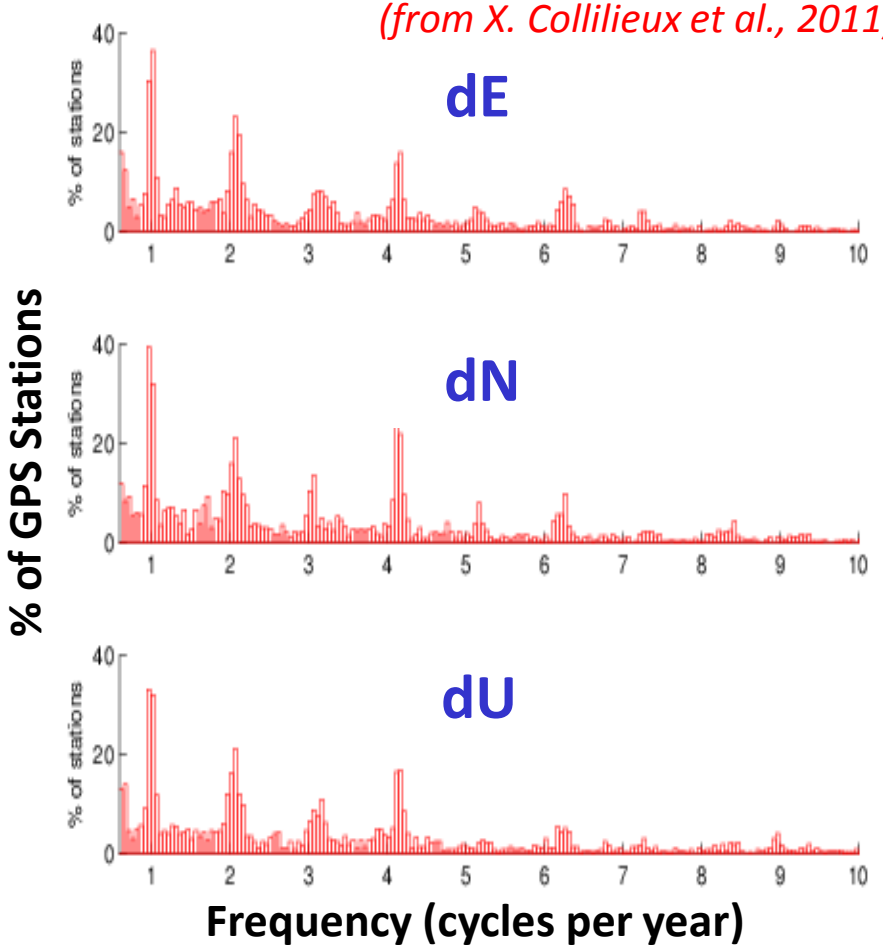
- <u>Periodic spectral peaks</u> at:
  - annual + semi-annual periods
  - harmonics of GPS year (N * 1.04 cpy)
- Surface <u>crustal fluid loads</u> explain only part of annual signals
  - ~50% for dU, ~20% for dN, ~10% for dE
  - other effects: GPS draconitic harmonics, thermal expansion & tilting, IERS model deficiencies, antenna & receiver effects, analysis effects, etc



Harmonics of GPS Draconitic Year are Pervasive

- GPS-sun geometry repeat period
  - "draconitic" year = 351.4 d
  - 1st & 2nd harmonics overlap seasonal signals (for ΔT < 8 yr)
- IGS station coordinates (2006)
  - in all dNEU components
  - harmonics up to at least 6th
- Later found in all IGS products:
  - "geocenter" variations
  - polar motion rates (esp 5th & 7th)
  - LOD (esp 6th)
  - orbit day-boundary jumps (esp 3rd)

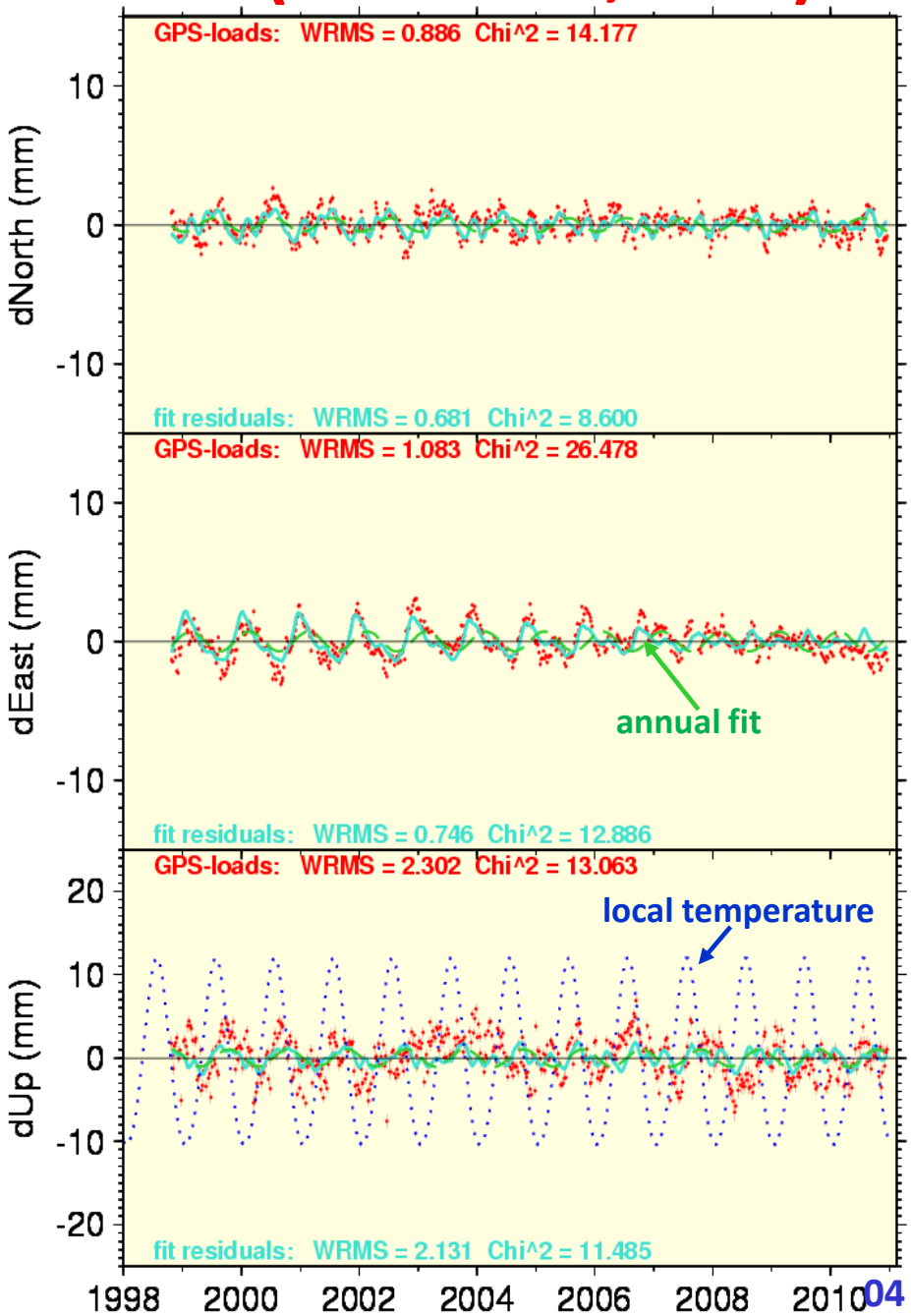
(from X. Collilieux et al., 2011)



- Strong fortnightly signals also common, but Nyquist limited for past IGS weekly station coordinates
- Periodic signals clearer in reprocessed results

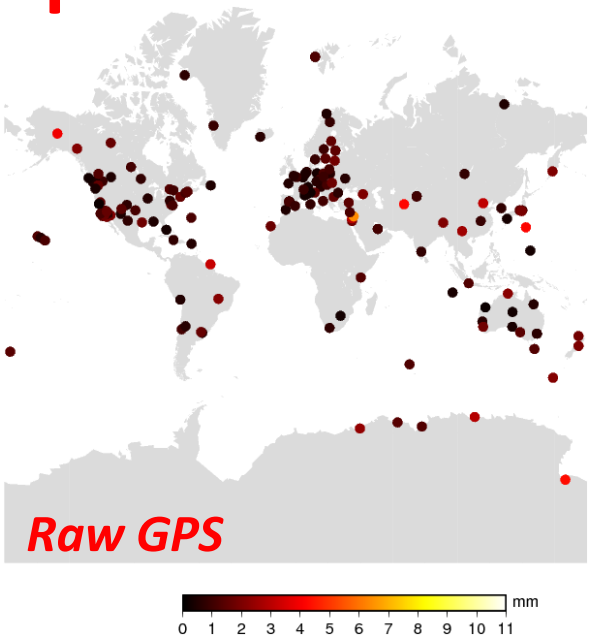
Example of Harmonic Fit: AMC2 (Colorado, USA)

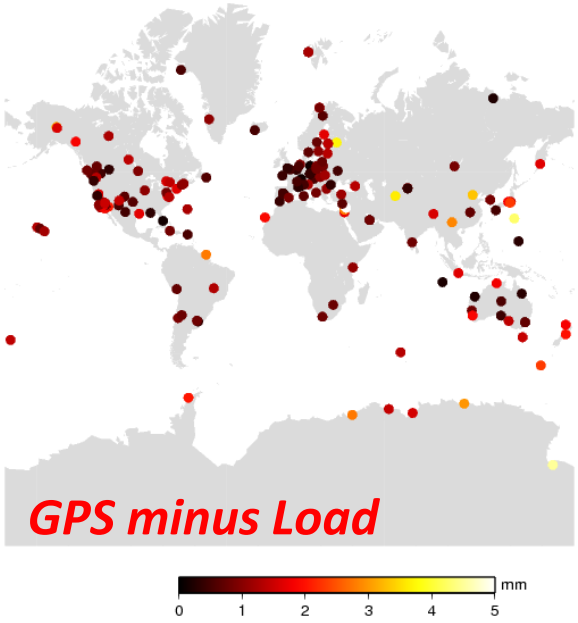
- IGS Repro1 time series residuals
  - these are weekly GPS positions
  - remove model loads (red dots)
  - fit harmonic model of ann + semi-ann + 1st thru 6th draconitics (turquoise line)
  - annual-only fit = green line
- Beating of ann/semi-ann with 1st/2nd draconitics can explain inter-annual amp variations
  - esp for dN & dE
  - fits are often quite significant (for stations with ≥ 250 weeks)
- Post-fit residuals often approach previously inferred noise floors:
  - 0.65 mm WRMS for weekly dN
  - 0.7 mm WRMS for weekly dE
  - 2.2 mm WRMS for weekly dU



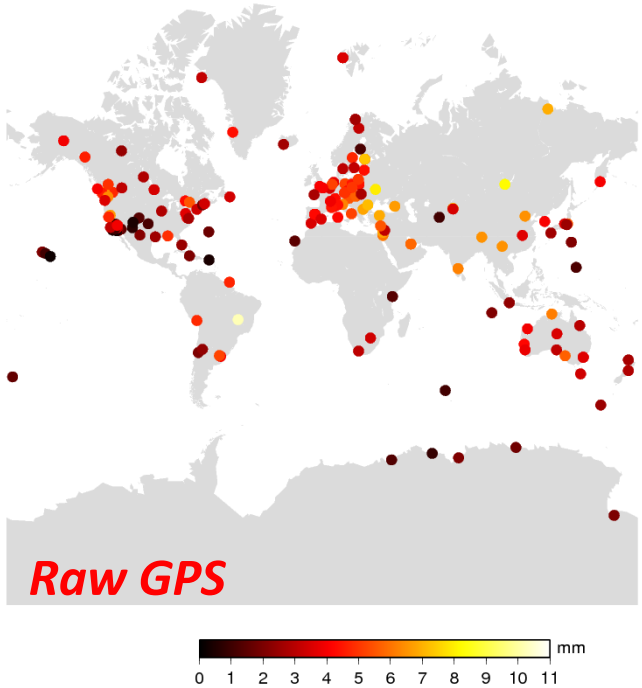
Compare Annual & 1st Draconitic dUp Amplitudes

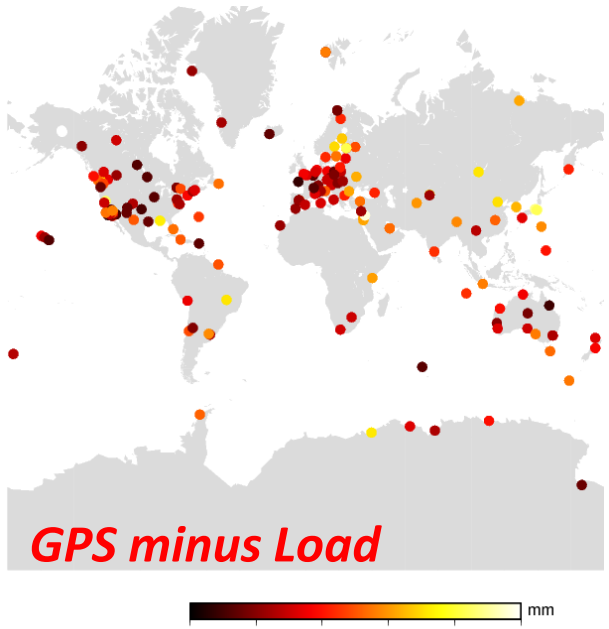
1st Draconitic





Annual





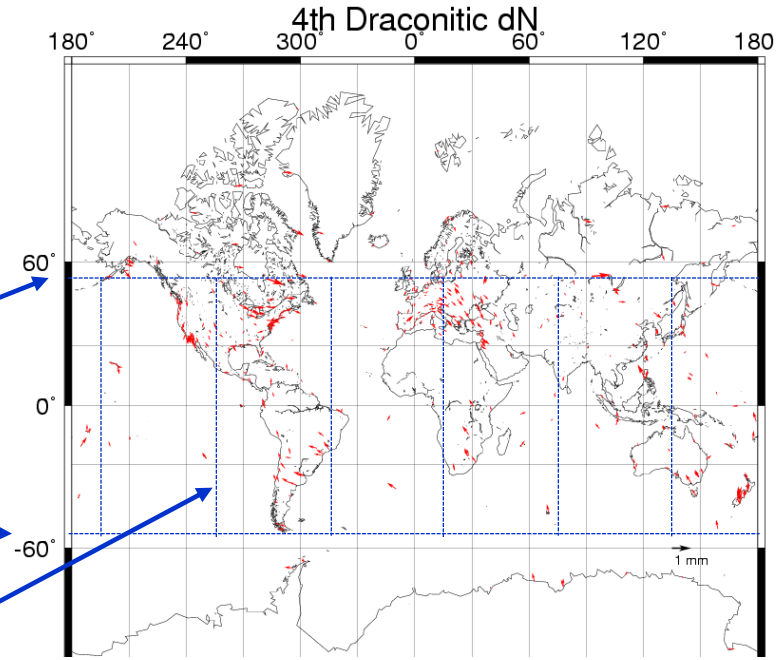
units = mm

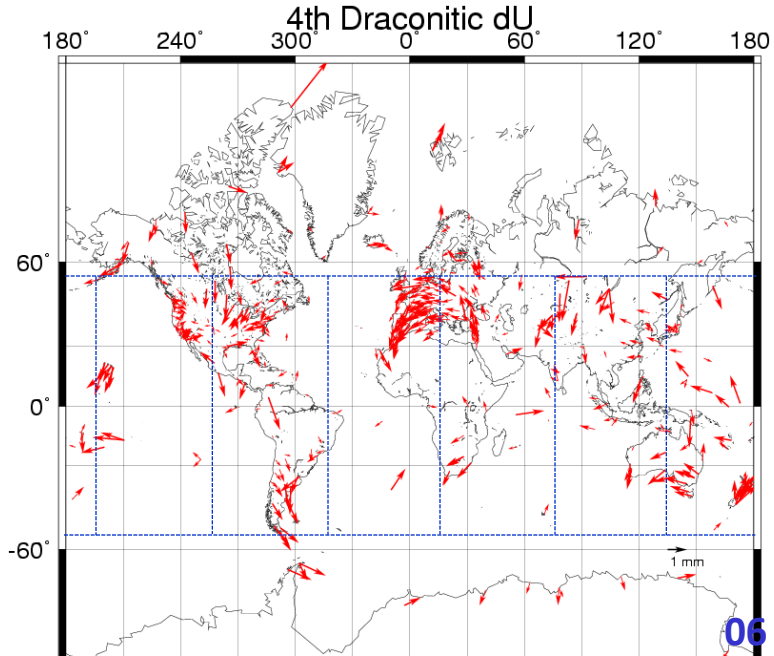
annual & draconitic estimated simultaneously

>10 years of weekly data

Global Distribution of 4th dN & dU Draconitics

- **Strong spatially correlated patterns**
  - not consistent with a local site origin
  - implies draconitic errors involve orbits
- **GPS constellation:**
  - inclination = 55
  - RA longitudes = 17 , 77 , 137 , …, 317





Possible Origins of Draconitic Signals

1) Local multipath effects at stations

- station-satellite geometry repeats every sidereal day, approximately
- 2 GPS orbital periods during 1 Earth inertial revolution
  - actual GPS ground repeat period = (1 solar day - ~245 s)
  - sidereal period (K1) = (1 solar day - 235.9 s)
- for 24-hr sampling (e.g., data analysis), alias period → GPS draconitic year

2) Mismodelling effect in satellite orbits

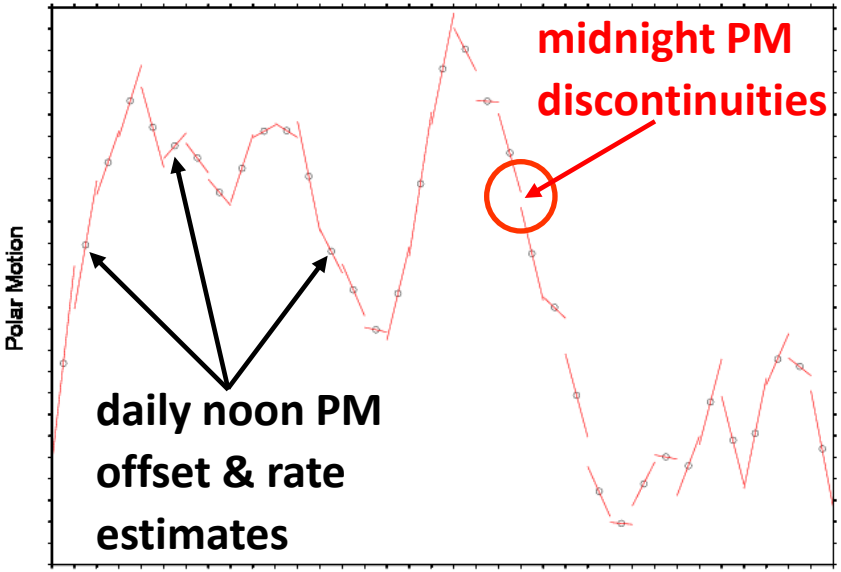
- empirical solar radiation parameters intrinsically linked to orbital period
- implies large-scale spatial correlations of station draconitics, as observed
- larger errors during twice-annual eclipse periods must also contribute

- **Hypothesis: errors in *a priori* IERS model for subdaily EOP tidal variations absorbed into GPS orbits**
  - EOP tide errors resonate with GPS orbital period & efficiently absorbed
  - GPS ground repeat period (near K1) aliases errors to draconitic year
  - 6 GPS orbital planes cause beating and overtone harmonics
  - IERS model is known to have errors at the 10 to 20% level, equivalent to ~2 cm @ GPS altitude
  - errors also alias into EOP estimates & presumably station coordinates

Evidence for Subdaily EOP Tide Model Errors

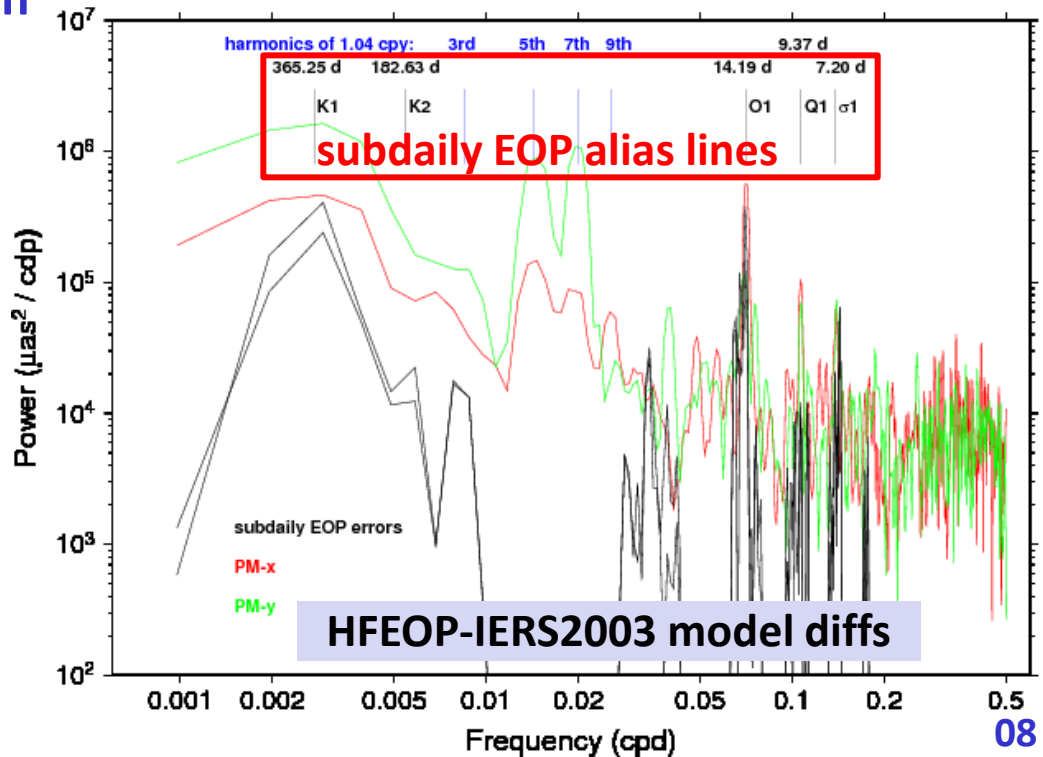
1) Aliases in IGS polar motion rate discontinuity spectra

- compute midnight discontinuities in IGS polar motion time series
- IGS Repro1 data (10 Mar 2005 – 29 Dec 2007)
- most spectral peaks match subdaily alias lines (Kouba, 2003)
- demonstrated with comparison between IERS2003 model & HFEOP VLBI (from J. Gipson)
- also some odd draconitics (via orbits)



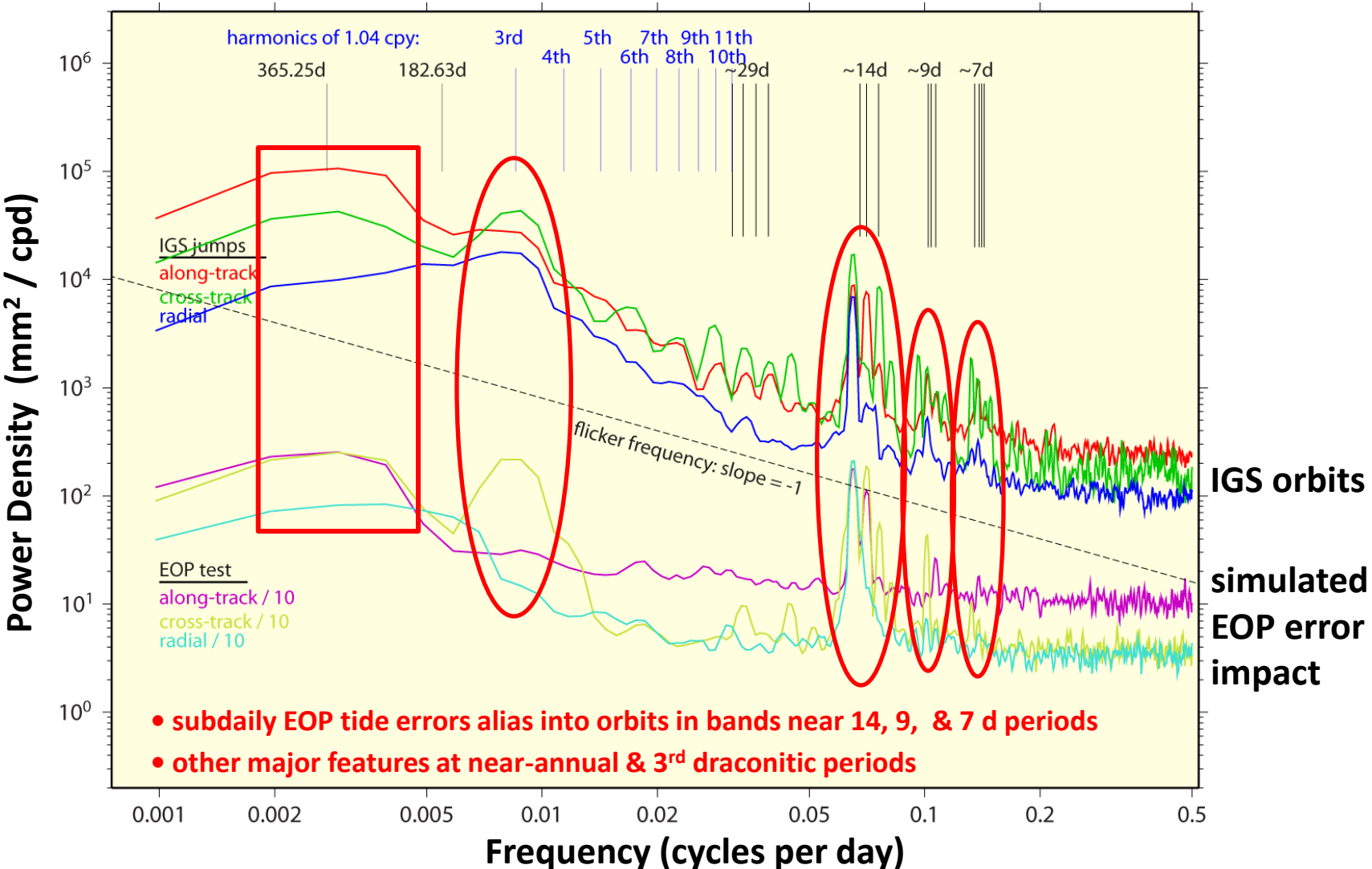
2) Differences among subdaily EOP models

- EOP tide models based on GOT4.7 & TPXO7.1 also differ from IERS2003 by 10 to 20%
- courtesy of R. Ray (2009)



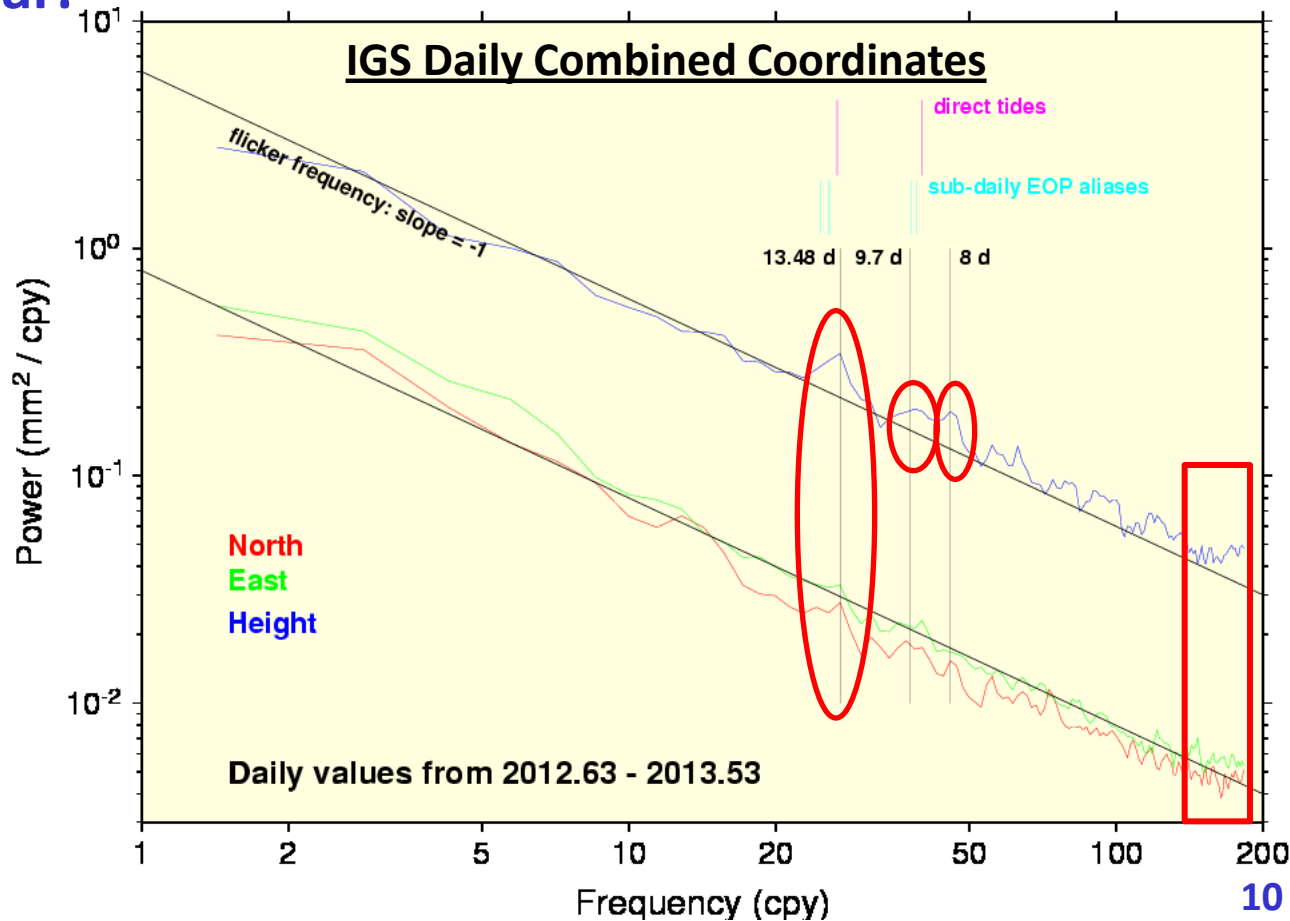
Impact of Subdaily EOP Tide Errors on GPS Orbits

- Spectrum of IGS midnight orbit discontinuities
- Compare to simulation using subdaily EOP tides with ~20% errors
- Effects on station coordinates not studied here



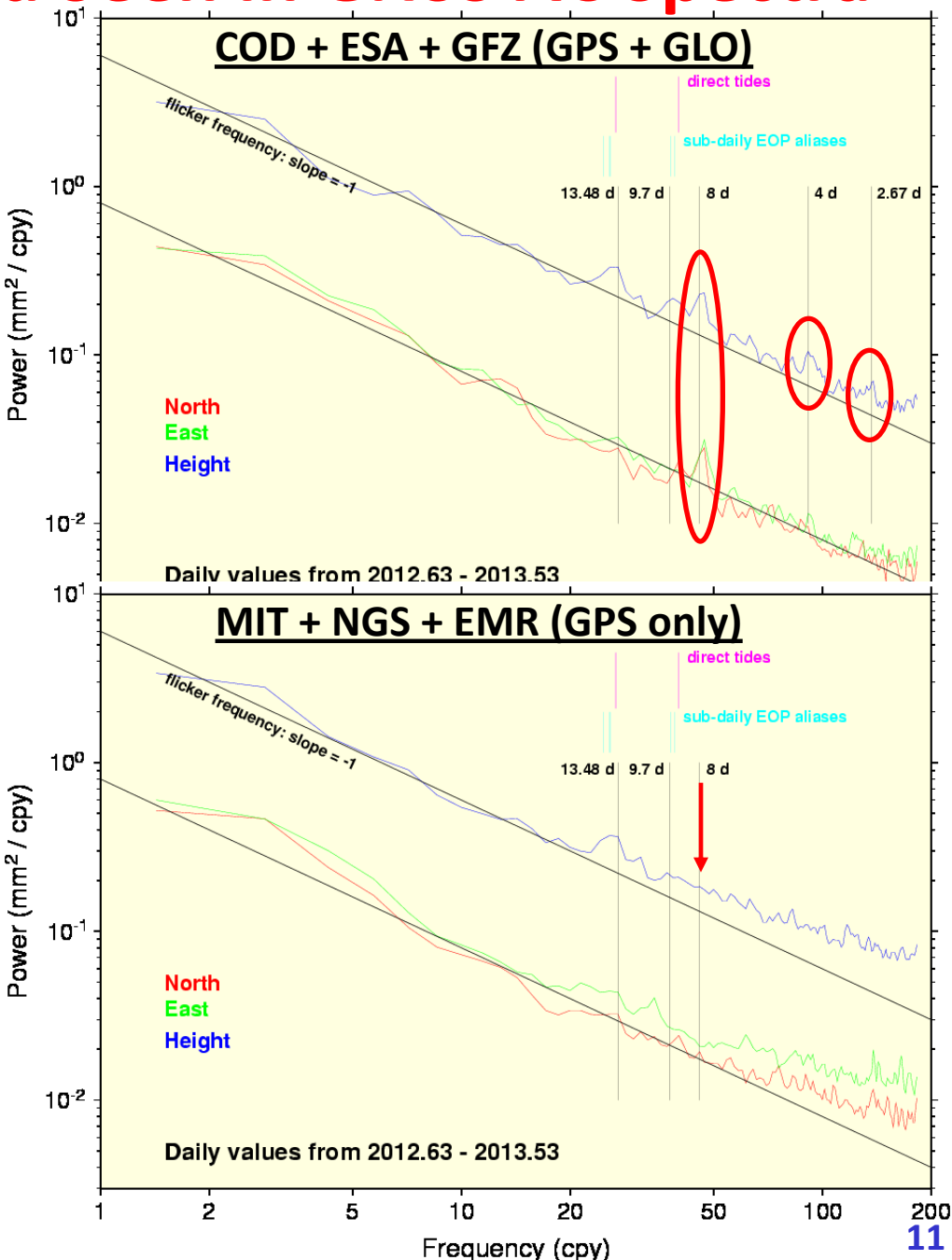
First Look at Daily IGS Position Spectra

- Stack spectra of 306 daily stations from 20 Aug 2012-13 Jul 2013
- Unsmoothed FFTs use ≥ 256 days per station
- Continuum noise very close to flicker process down to ~2.6 d
- White noise floor below ~2.6 d
- Tidal lines visible near:
  - ~13.5 0.8 d
  - ~9.7 ± 0.35 d
- Cannot yet resolve:
  - direct tide errors 13.63/13.66 d & 9.12/9.13 d **not expected but reported by others**
  - subdaily EOP aliases 14.19/14.77 d & 9.6/9.37 d **expected**
- Possible additional peak at ~8.0 d



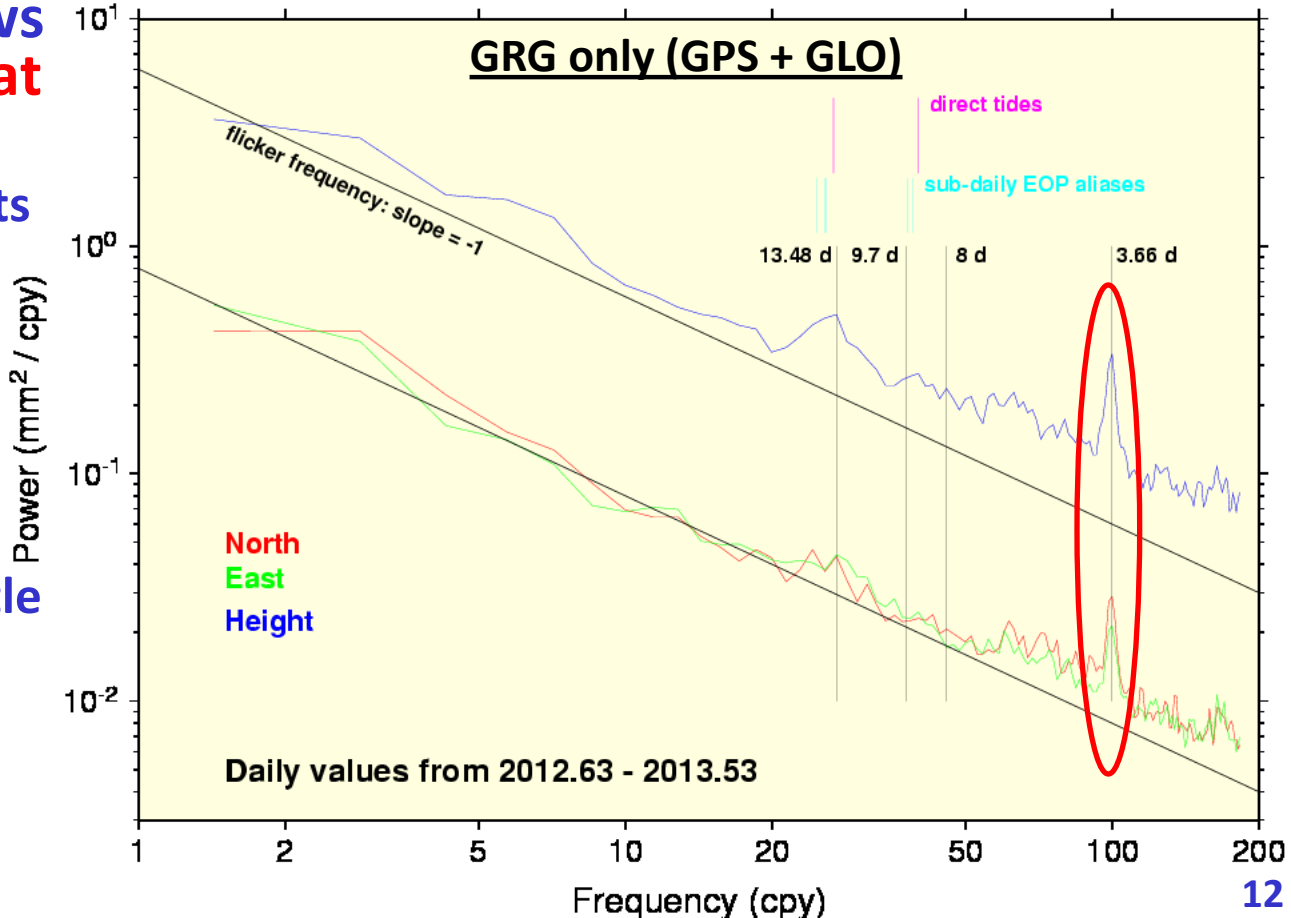
GLONASS Repeat Period Seen in GNSS AC Spectra

- GLONASS ground repeat period is 8 d (17 orbits, each $11^h\ 15^m$)
- 8.0 d peak visible in spectra of GPS+GLO ACs (CODE + ESA + GFZ = 474 AC stations)
- Possible harmonics too:
  - 2^{nd} at 4.0 d
  - 3^{rd} at 2.67 d
- No such peaks seen in spectra of GPS-only ACs (MIT + NGS + EMR = 419 AC stations)
- But these ACs also have more high-frequency noise
- GLONASS data previously found to degrade EOPs too



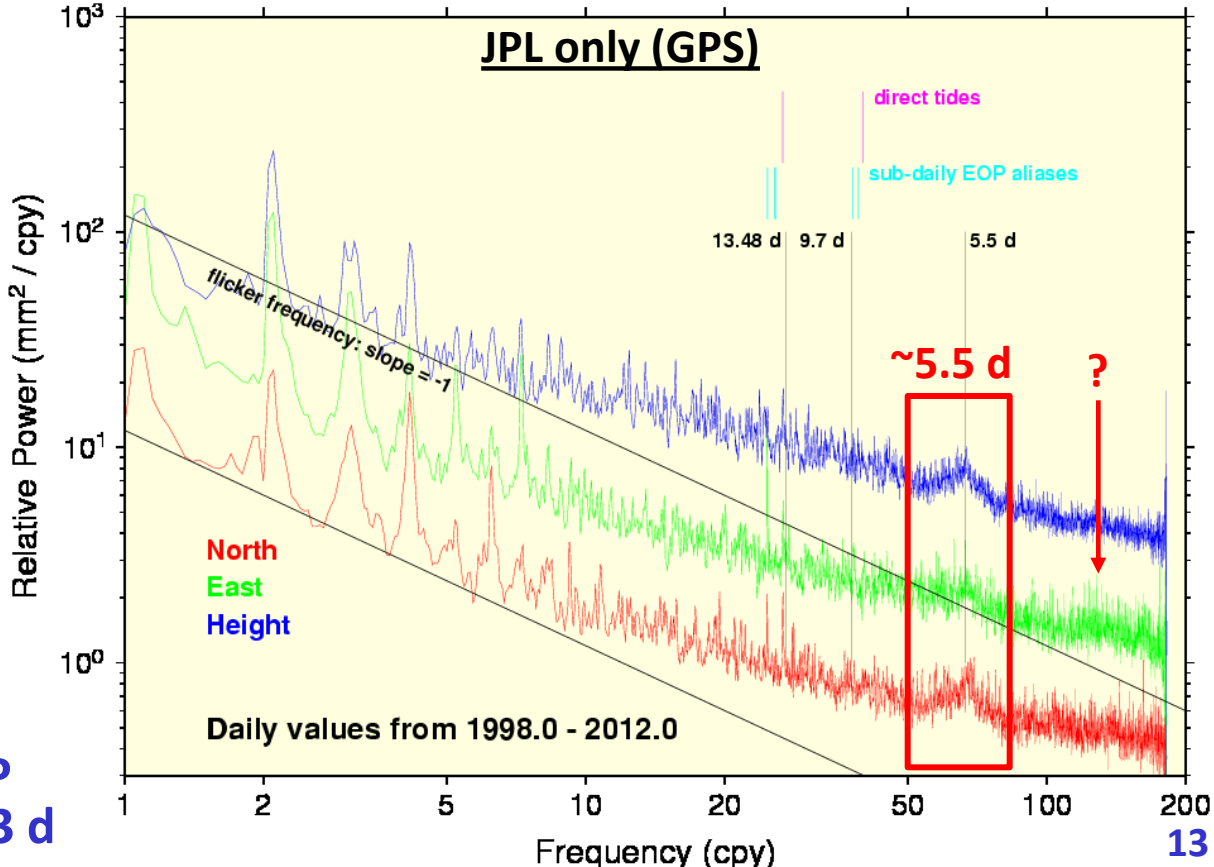
Unexplained 3.7 d Peak for GRGS

- Similar processing as for other ACs, for 114 daily stations
- Likely tidal peak at ~13.5 d; perhaps also near 9.7 d
- GRGS includes GLONASS data but no peak near 8.0 d
  - they heavily deweight GLONASS data compared to GPS
- GRGS uniquely shows strong, sharp peak at ~3.7 d
  - seen in all components
  - no corresponding peak seen in GRG vs IGS orbit differences
- No explanation yet for this feature
  - perhaps a bug or subtle constraint effect



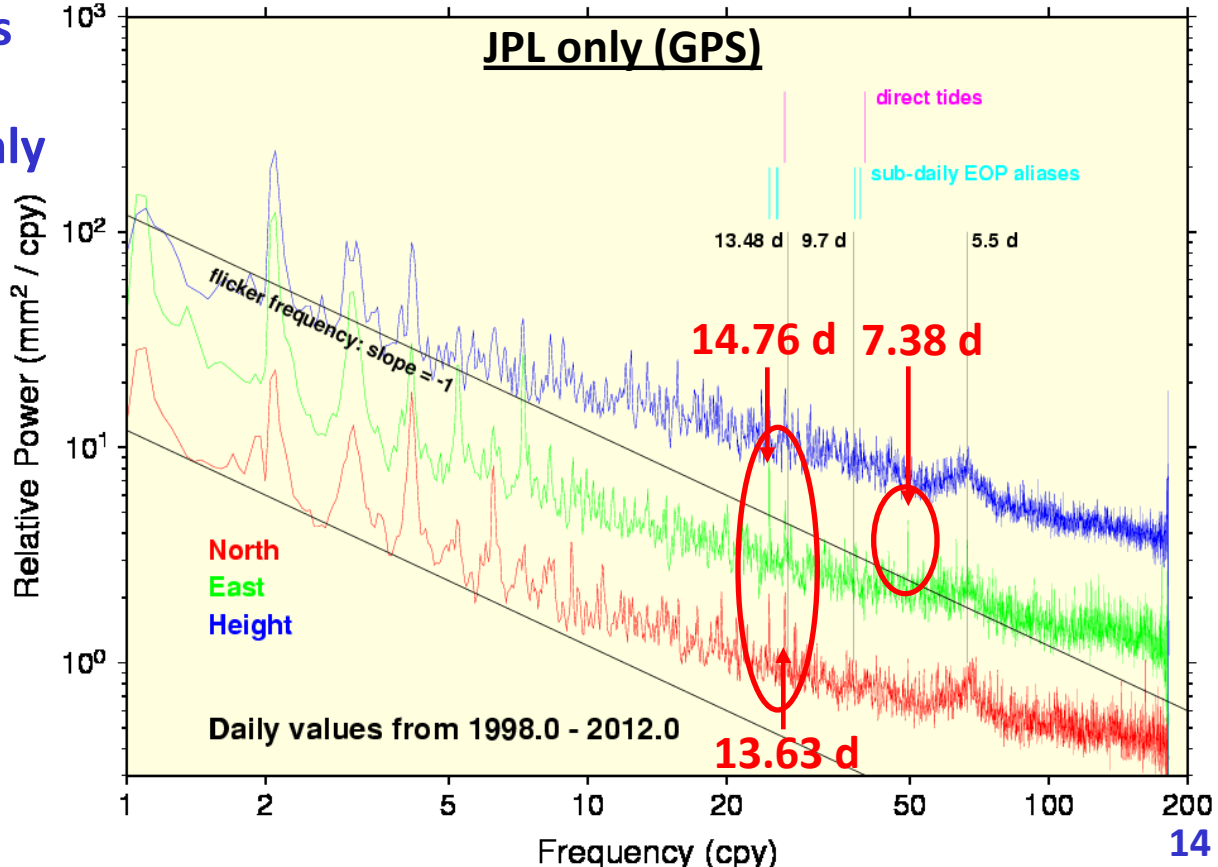
Unexplained ~5.5 d Band for JPL

- Unlike other ACs, JPL's daily IGS frames not usable to assess subseasonal performance because of disjoint network design
- So instead use daily time series at JPL's sideshow website
  - stack periodograms for 183 station time series, each with ≥80% days during 1998.0 – 2012.0 (annual + semi-annual terms removed)
- Find unique broad band of power around ~5.5 d
  - signal also in 2-yr subsets
  - some stations stronger than others
  - previously reported by Amiri-Simkooei (2013) who suggested quasi-periodic effects
  - suspiciously close to alias of ~24-hr EOP tide errors with JPL 30-hr arc period
  - other ACs use 24-hr arcs (except GRGS)
  - if so, aliases of ~12-hr EOP tides expected at 2.5 to ~3 d



JPL has Direct & Aliased Fortnightly Tide Lines

- **Direct (13.63 d) & subdaily aliased (14.76 d) tidal lines both seen**
  - **but, unlike other ACs, only in dN & dE, not dU**
  - **Amiri-Simkooei (2013) found lines at 13.63, 14.2, 14.6, & 14.8 d but did not discuss**
  - **Amiri-Simkooei used multivariate method that does not distinguish position components, so missing dU lines were not noticed**
  - **JPL's fortnightly behavior is distinct from other ACs & difficult to explain**
  - **but could be sensitive only to tide rotation errors**
- **Unique sharp line at ~7.38 d**
  - **only in dE, not dN & dU**
  - **maybe alias of μ2 tide errors**
  - **by why dE only?**



Conclusions

- IGS now producing daily combined & AC terrestrial frames
  - permits subseasonal error analysis, since 19 Aug 2012
  - repro2 results will enable long-term analysis
- Most ACs show fortnightly signals in all components
  - ~9 d signals also likely, at least for some ACs
  - JPL is unique with only dN & dE fortnightly signals, not dU
  - direct vs aliased subdaily tidal sources not yet resolvable
  - subdaily EOP tidal aliases expected from polar motion rate analysis
- Errors in IERS subdaily EOP tide model also likely to generate pervasive GPS draconitics
  - due to efficient coupling into orbits, then aliasing to longer periods
- GPS+GLONASS ACs show ~8 d signals in all components
  - ~4 d signals also likely
  - probably effect of GLONASS ground repeat period
- GRGS & JPL show unique short-period features
  - strong 3.7 d line for GRGS & 7.38 d line for JPL unexplained
  - broad 5.5 d band for JPL possibly related to 30-hr arcs

Thank You !