Analysis of IGS repro3 Station Position Time Series

Paul Rebischung[1], Xavier Collilieux[2], Laurent Metivier[1], Zuheir Altamimi[2], and Kristel Chanard[2]

[1]Université de Paris
[2]Université de Paris, Institut de physique du globe de Paris, CNRS, IGN

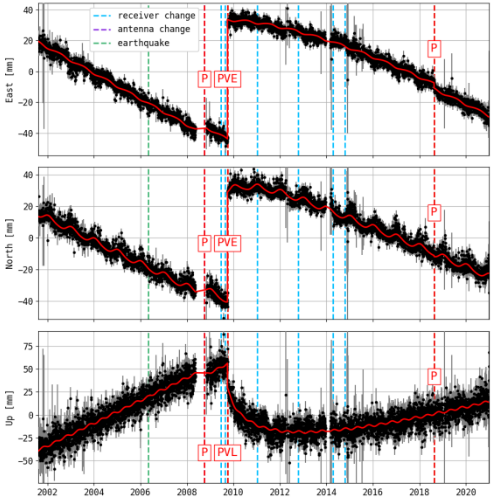
November 21, 2022

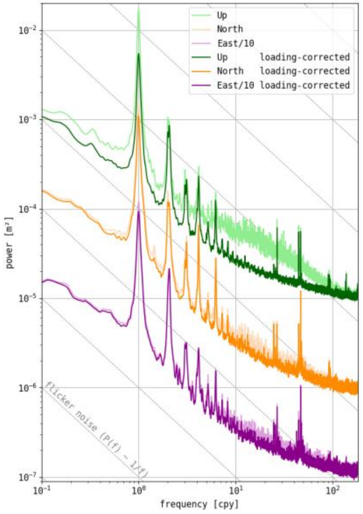
Abstract

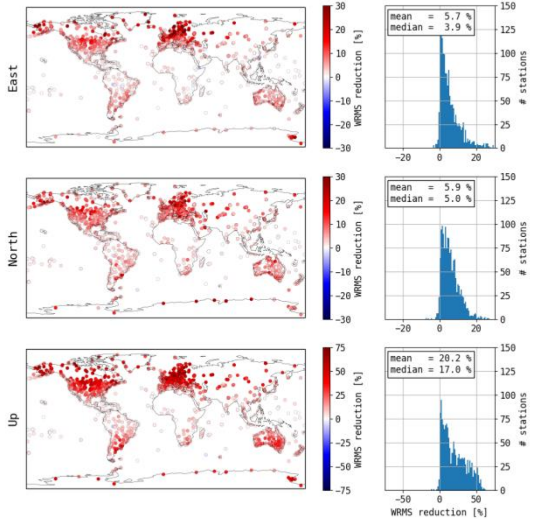
The IGS contribution to ITRF2020, based on the third IGS reprocessing campaign (repro3), comprises daily position estimates for 1905 globally distributed GNSS stations. As an essential step of the ITRF2020 preparation, a detailed analysis of the IGS repro3 station position time series has been carried out, including identification of offsets, modeling of post-seismic displacements, confrontation with deformation predicted by geophysical loading models, and characterization of systematic and random errors. This presentation covers the different aspects of this analysis, the methods used and the lessons learned.

Analysis of IGS repro3 station position time series

Paul Rebischung, Xavier Collilieux, Laurent Métivier, Zuheir Altamimi, Kristel Chanard



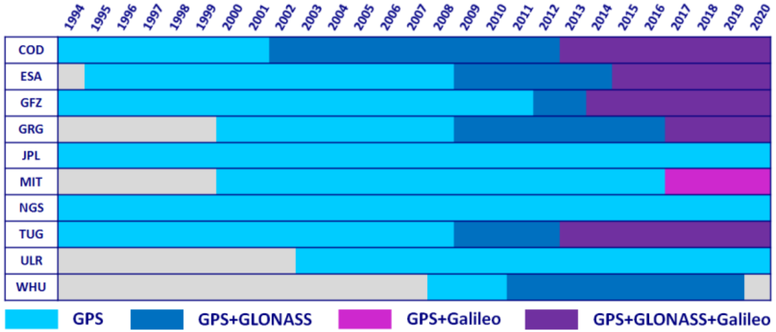




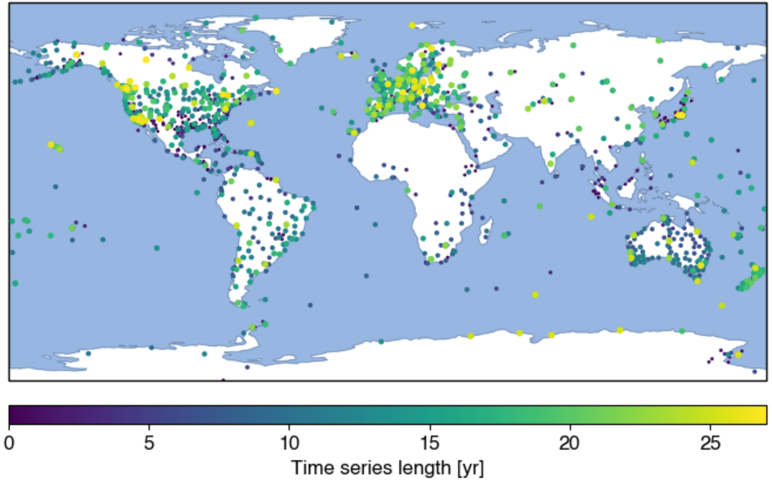
AGU Fall Meeting 2021, 13–17 December

The third IGS reprocessing campaign (repro3)

AC contributions to repro3



repro3 station network



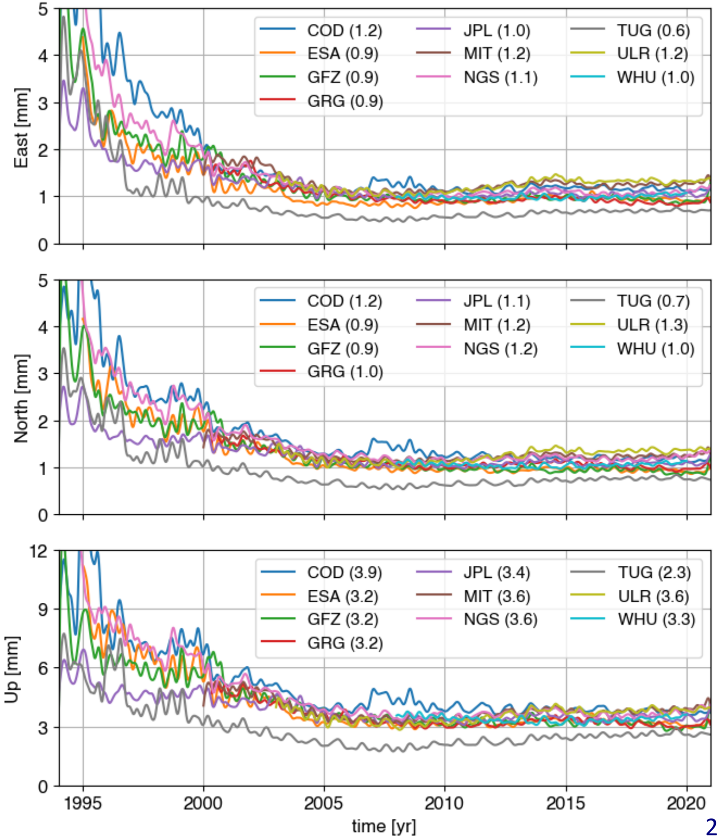
Quick facts

- 10 contributing ACs (7 multi-GNSS)
- Span: 1994-2020
- Inter-AC agreement after 2005:
  ≈1 mm in horizontal
  3–4 mm in vertical

Daily combined repro3 solutions
=
IGS contribution to ITRF2020

- 1905 stations
- Average span: 11 yr

(Smoothed) median formal errors of station positions in re-weighted daily AC solutions

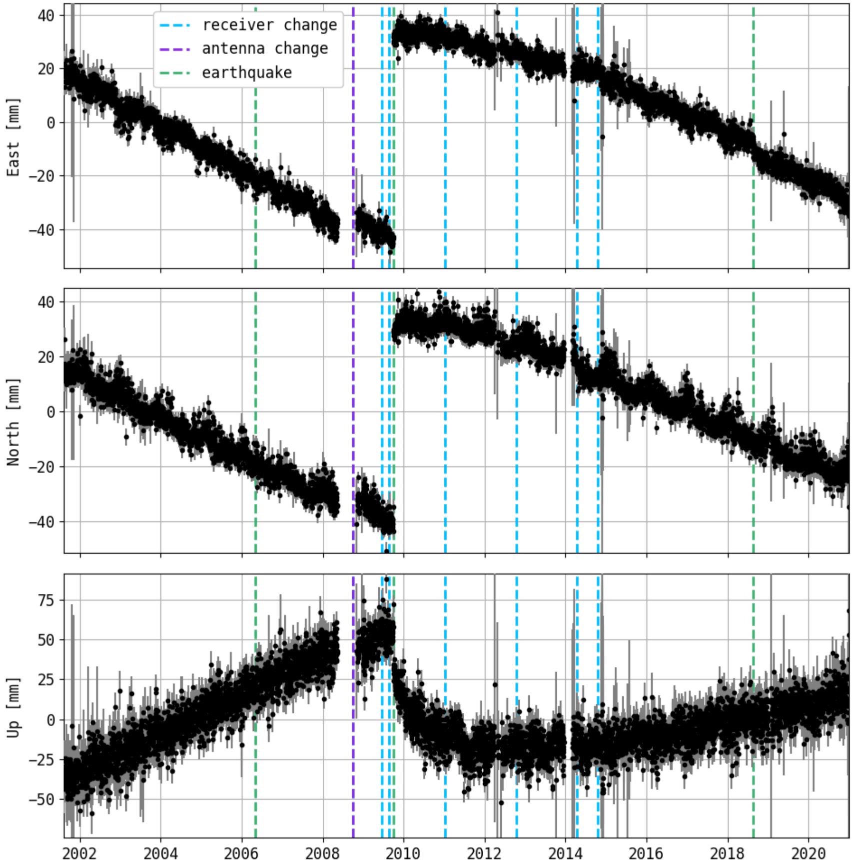


Analysis of IGS repro3 station position time series

1. Offset detection & post-seismic displacements (PSD) modeling
2. Confrontation with GGFC loading deformation models (Boy, 2021)
3. Spectral analysis
4. Modeling of ≈periodic signals
5. Noise analysis

Offset detection & PSD modeling

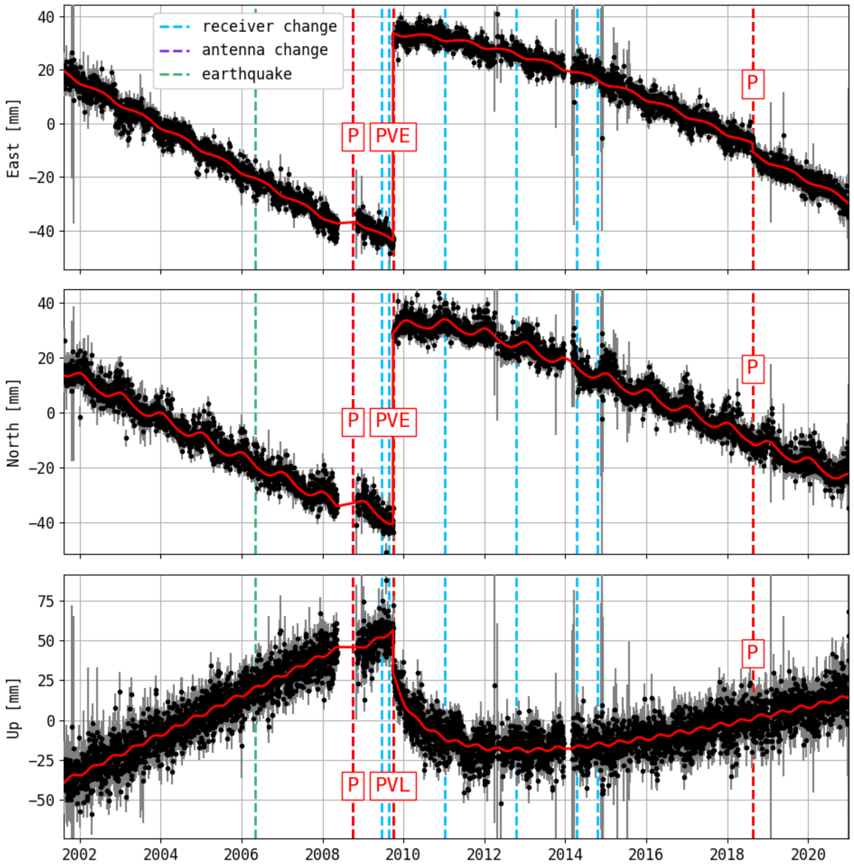
Example: ASPA (Pago Pago, American Samoa)



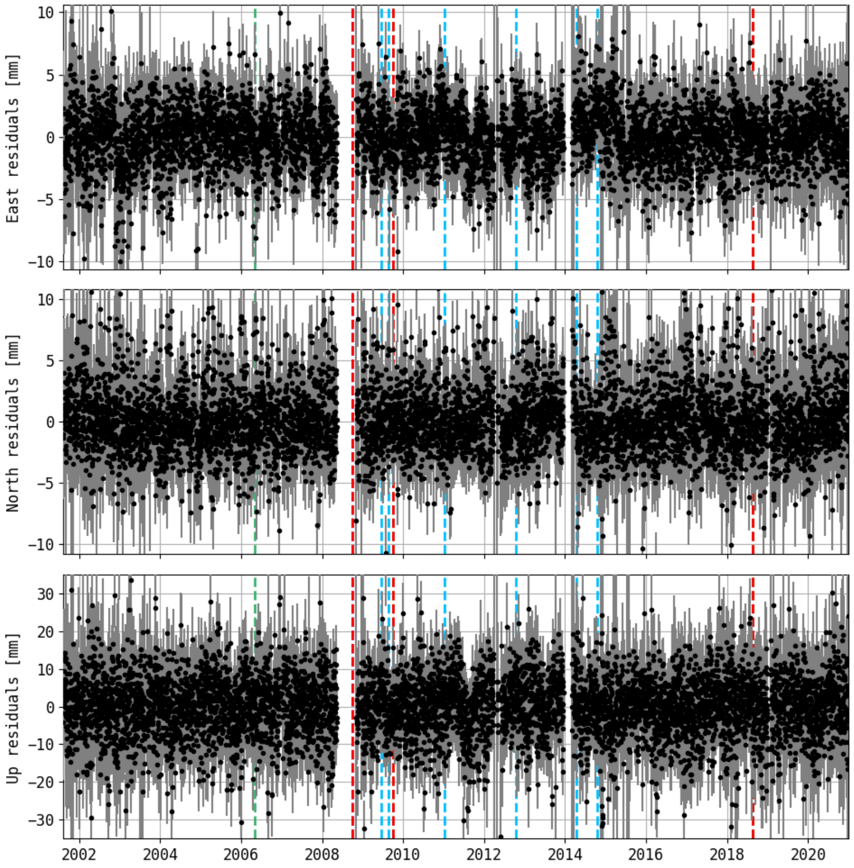
- **Ancillary data:**
  - **Antenna & receiver changes**
    (from site logs)
  - **Predicted co-seismic displacements**
    (from CMT catalog, Métivier et al. (2014)'s preferred scaling laws and Okada (1985)'s dislocation model)
- **Start with linear + annual + semi-annual fit**
- **Iteratively add:**
  - **Position offsets (P)**
  - **Velocity changes (V)**
  - **Exponentials (E)**
  - **Logarithms (L)**
- **Until no more offsets nor post-seismic displacements are visible in the residuals**

Offset detection & PSD modeling

Example: ASPA (Pago Pago, American Samoa)



Residuals



Offset detection & PSD modeling

- Initial ‘manual’ offset detection led to an over-segmentation of the time series.

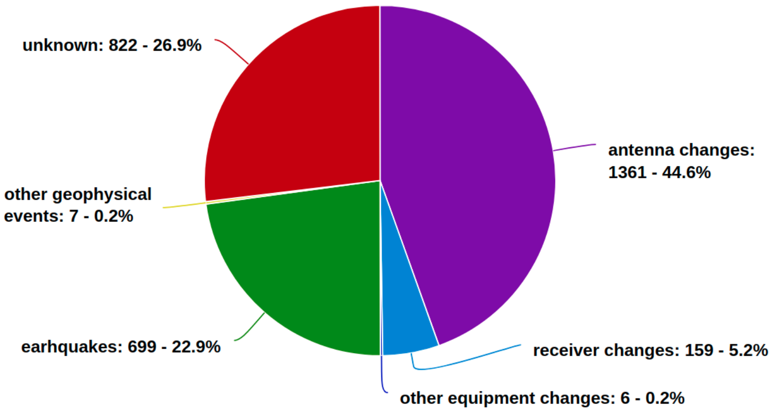
→ Iterative refinement of offsets and PSD models
  – Adjust realistic trajectory + noise models to each time series, namely:
    - Current offsets, velocity changes and PSD functions
    - Complete set of periodic signals (see slide 20)
    - Variable white noise + power-law noise
  – Test significance of each position offset, velocity change and PSD function (likelihood ratio test)
  – Use test results as an aid (i.e., not blindly) to remove model components with low significance

Offset detection & PSD modeling

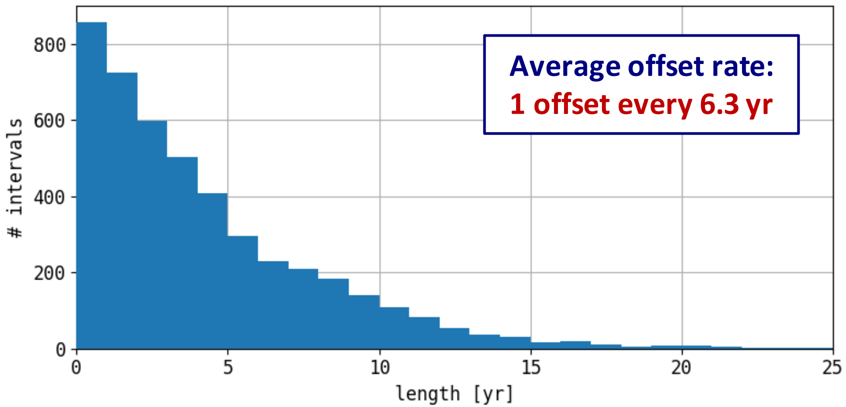
- Initial 'manual' offset detection led to an over-segmentation of the time series.

→ Iterative refinement of offsets and PSD models
  - Adjust realistic trajectory + noise models to each time series, namely:
    - Current offsets, velocity changes and PSD functions
    - Complete set of periodic signals (see slide 20)
    - Variable white noise + power-law noise
  - Test significance of each position offset, velocity change and PSD function (likelihood ratio test)
  - Use test results as an aid (i.e., not blindly) to remove model components with low significance

Distribution of detected offsets

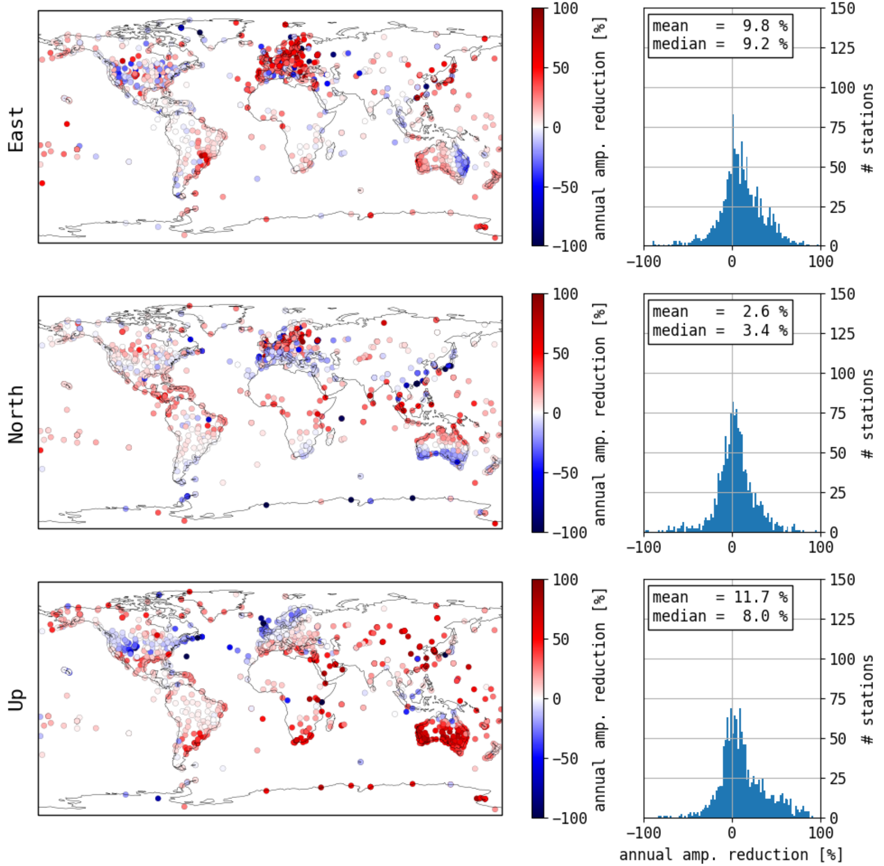


Lengths of inter-offset intervals

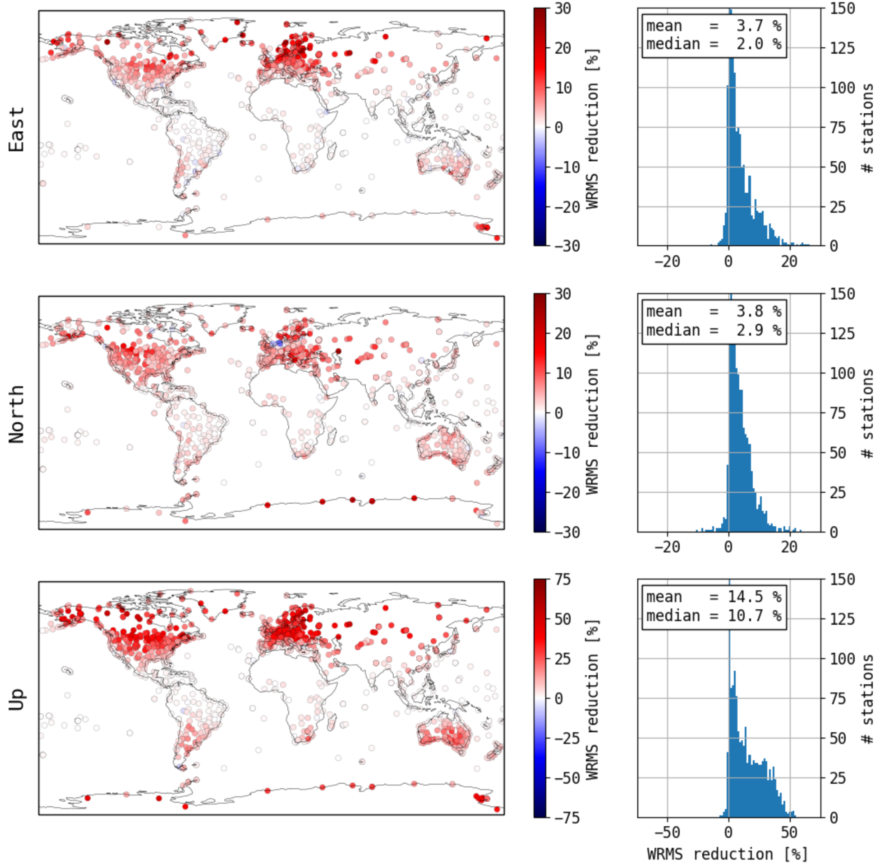


Confrontation with GGFC loading models: atmosphere

Relative reduction of annual amplitudes (repro3 – ERA5-IB vs. repro3)

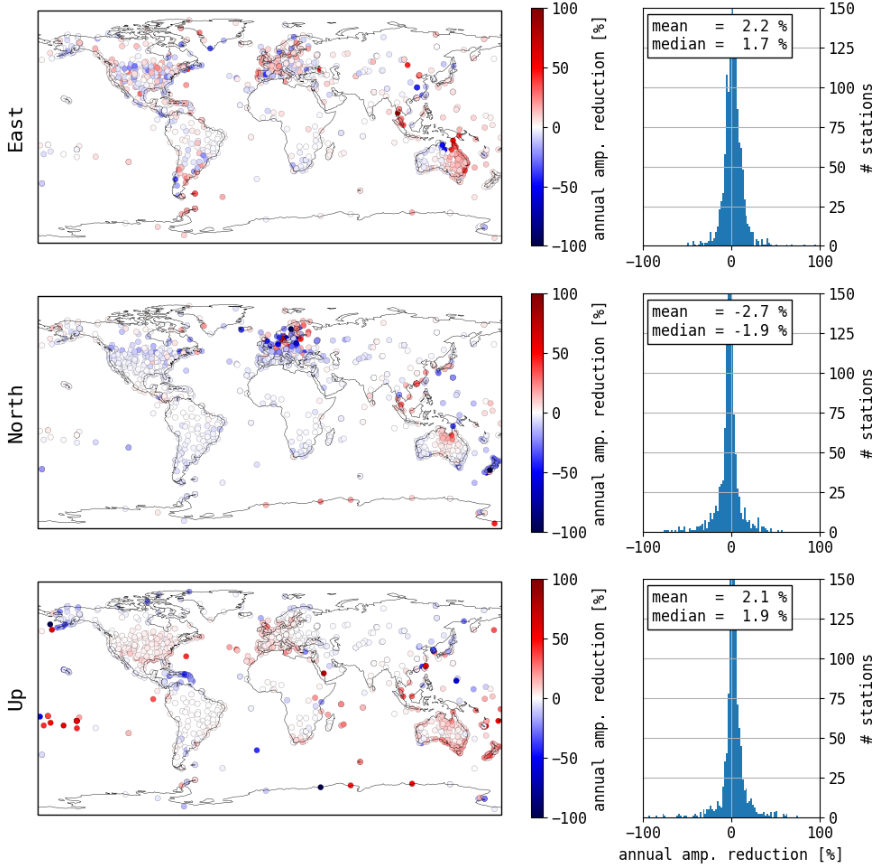


Relative reduction of non-seasonal scatter (repro3 – ERA5-IB vs. repro3)

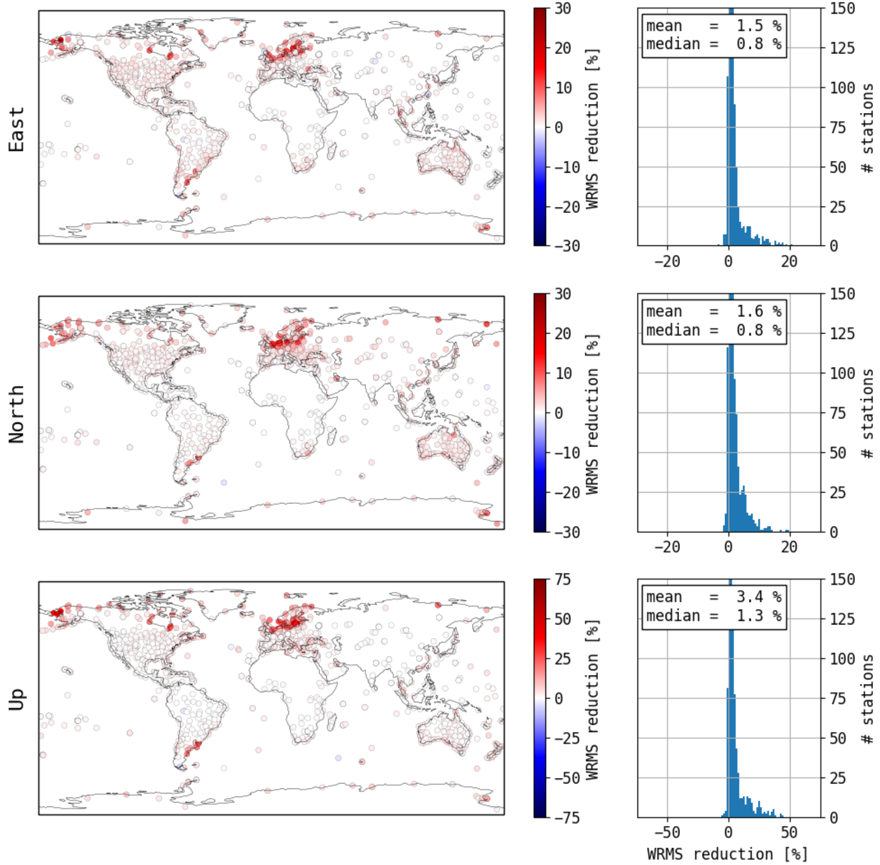


Confrontation with GGFC loading models: ocean

Relative reduction of annual amplitudes
(repro3 – ERA5-TUGO vs. repro3 – ERA5-IB)

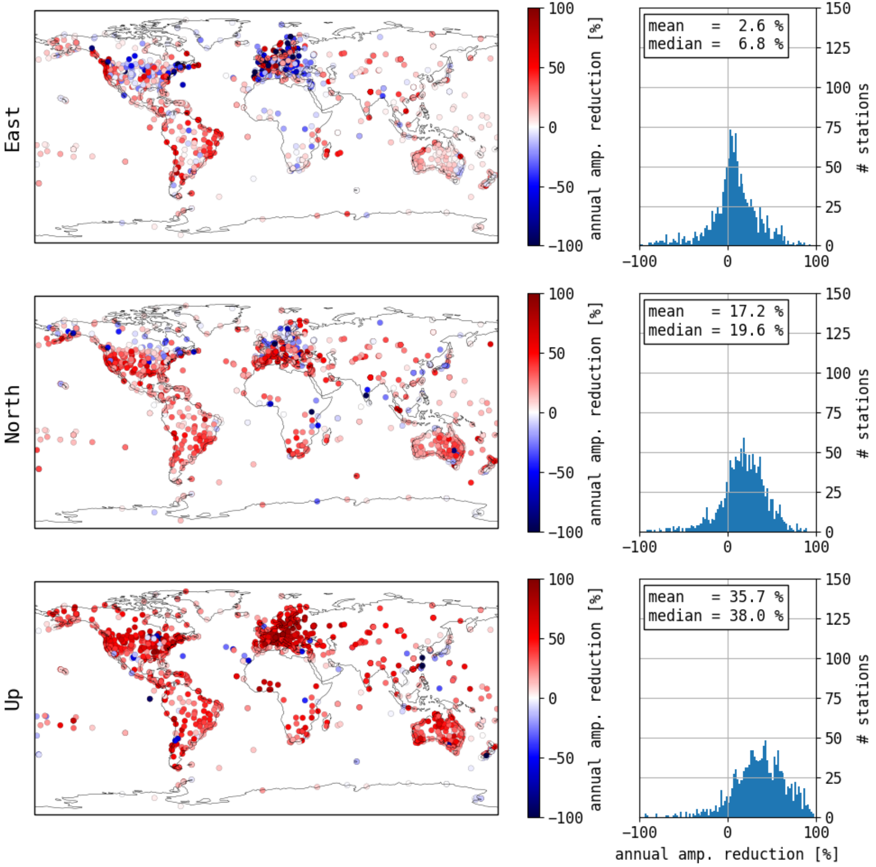


Relative reduction of non-seasonal scatter
(repro3 – ERA5-TUGO vs. repro3 – ERA5-IB)

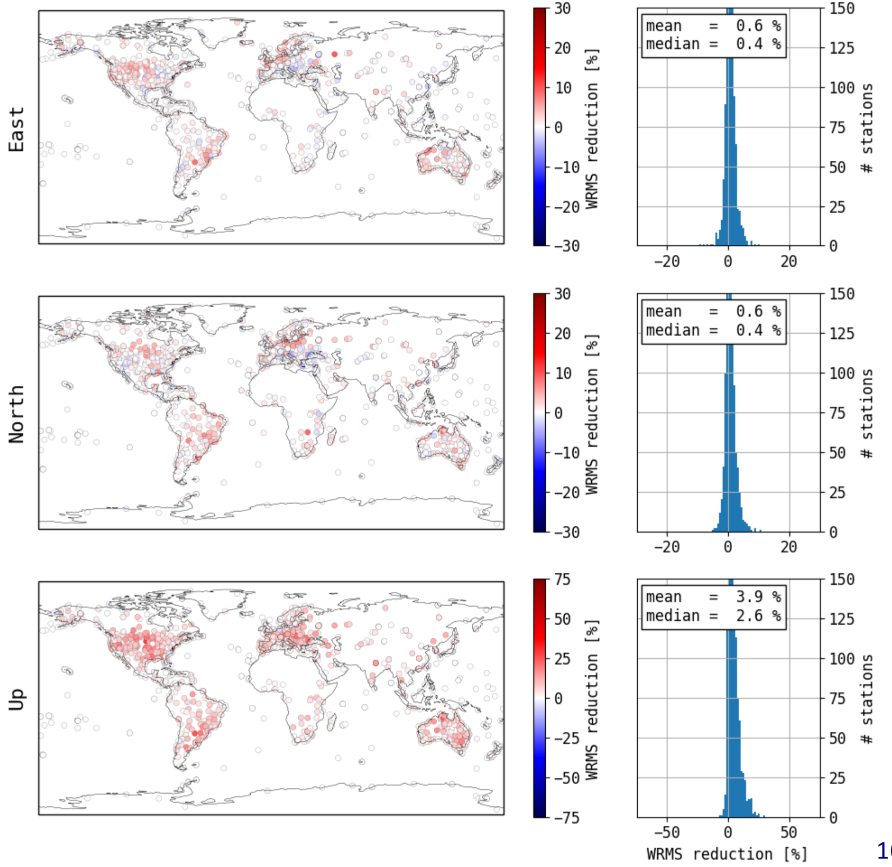


Confrontation with GGFC loading models: hydrology

Relative reduction of annual amplitudes
(repro3 – ERA5-TUGO+hydro vs. repro3 – ERA5-TUGO)

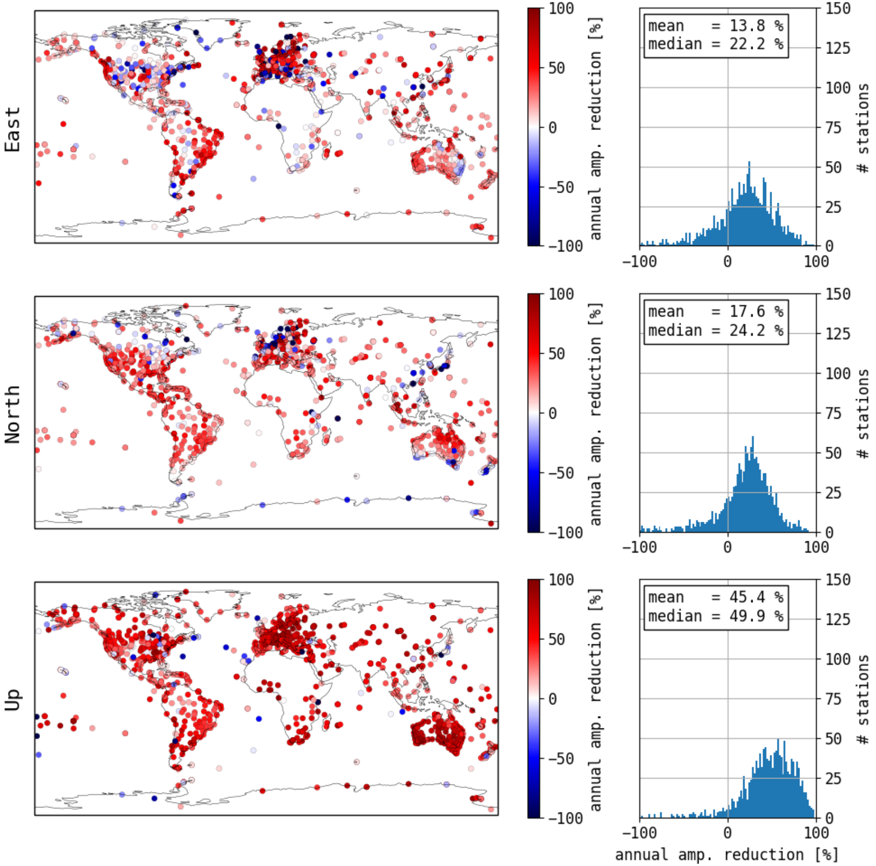


Relative reduction of non-seasonal scatter
(repro3 – ERA5-TUGO+hydro vs. repro3 – ERA5-TUGO)

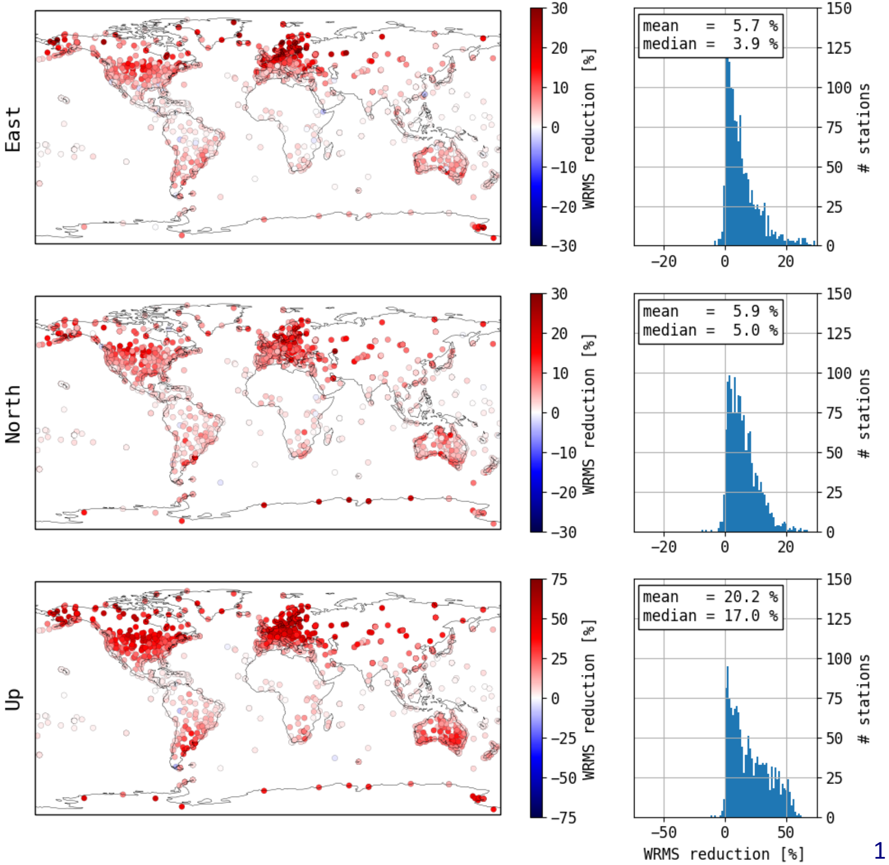


Confrontation with GGFC loading models: total load

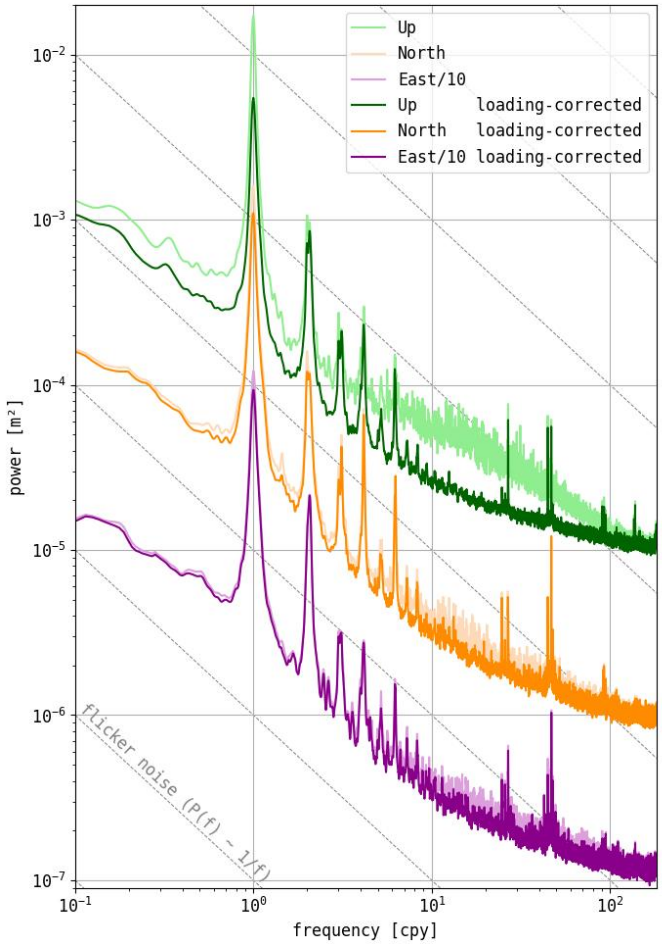
Relative reduction of annual amplitudes (repro3 – ERA5-TUGO+hydro vs. repro3)



Relative reduction of non-seasonal scatter (repro3 – ERA5-TUGO+hydro vs. repro3)



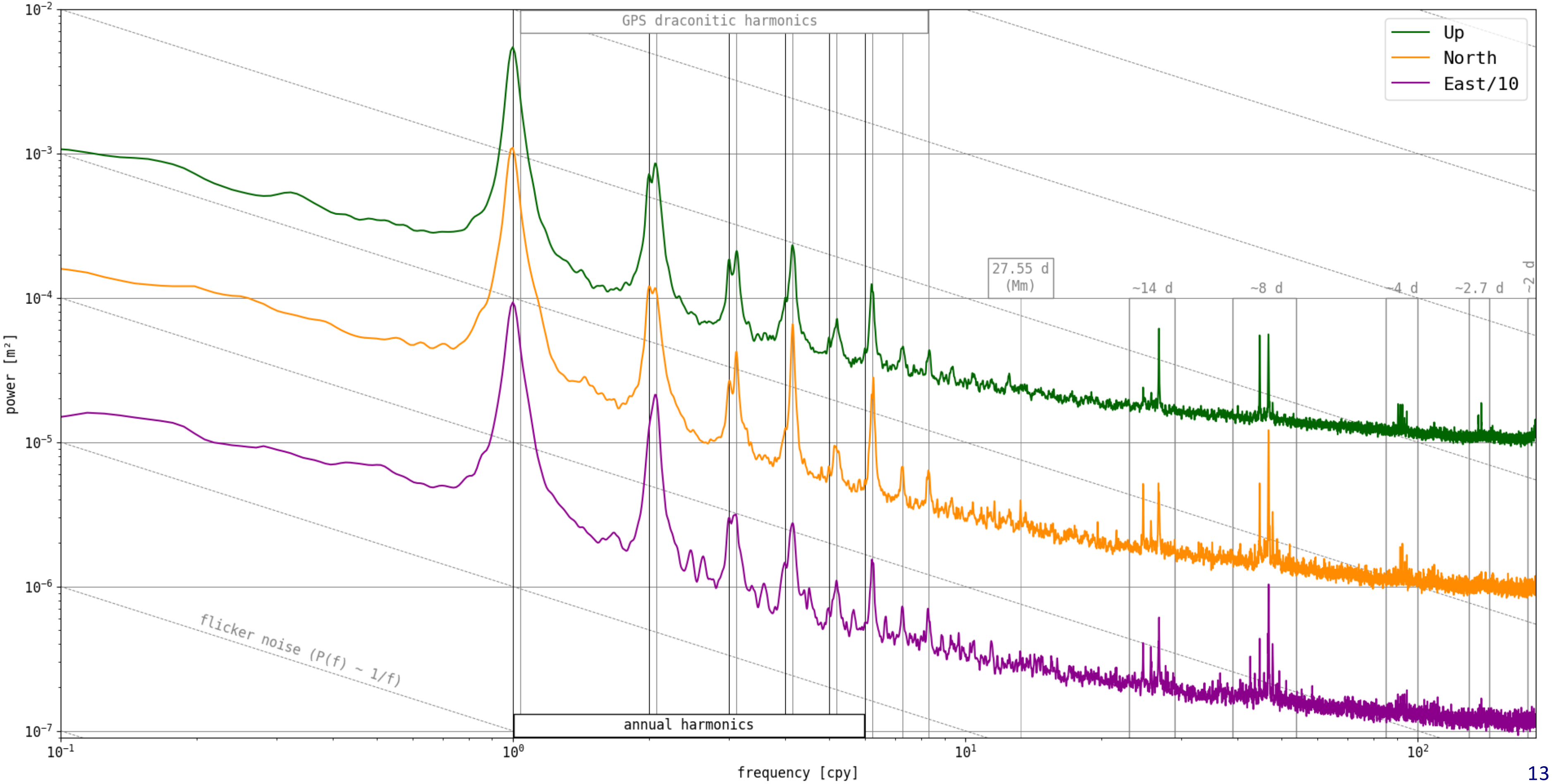
Confrontation with GGFC loading models: power spectra



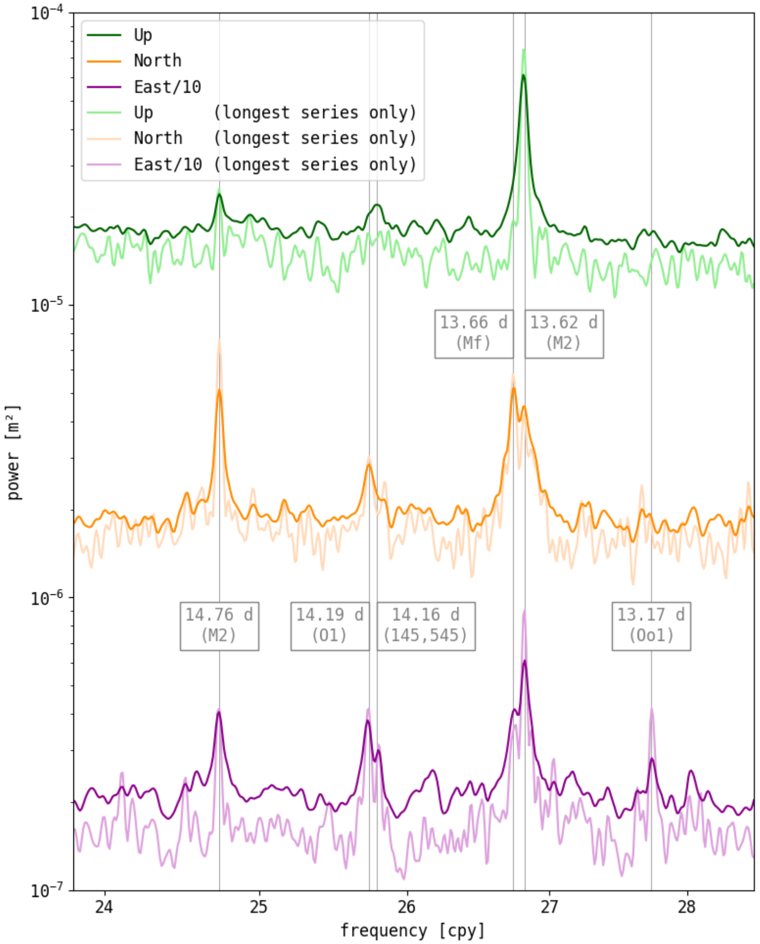
← **Average Lomb-Scargle periodograms of repro3 residuals with & without loading corrections**

- **Little impact of loading corrections in horizontal**
- **But strong impact in vertical!**
  - **Average background noise well described by white + power-law noise model after loading corrections, but not before**
  - **Fitting white + power-law noise models to GNSS height time series uncorrected for loading deformation can yield strongly biased noise parameter estimates and velocity uncertainties.**
- **See JGR paper by Gobron et al. (2021)**
  - https://doi.org/10.1029/2021JB022370
- **All following results are based on loading-corrected series.**

Average periodograms of loading-corrected residuals

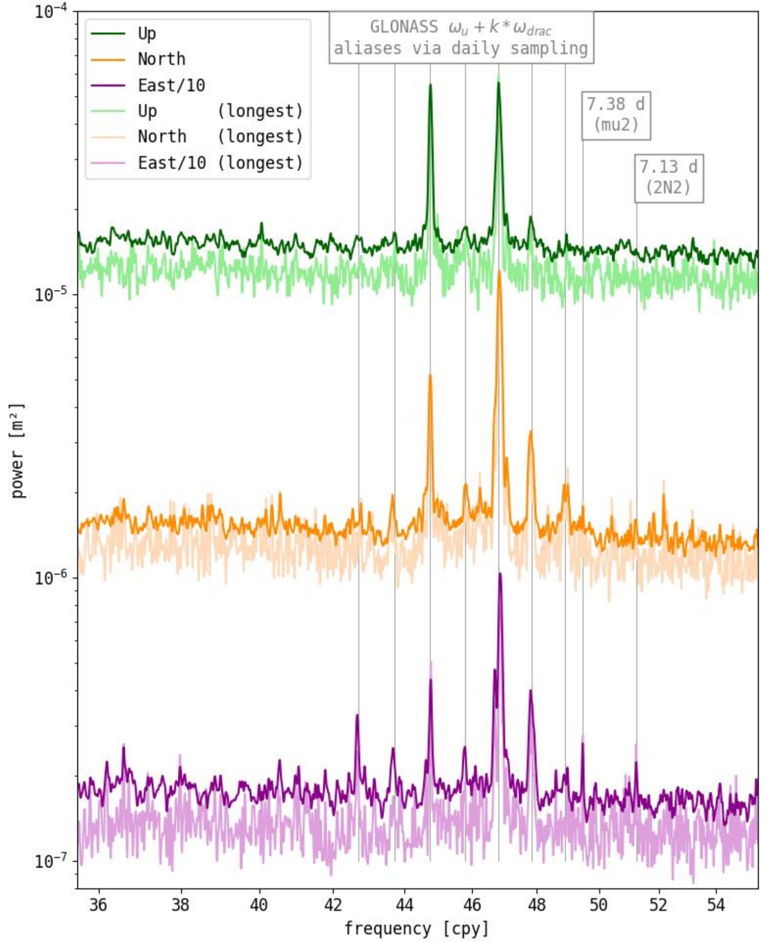


Average periodograms: zoom on ≈14 d



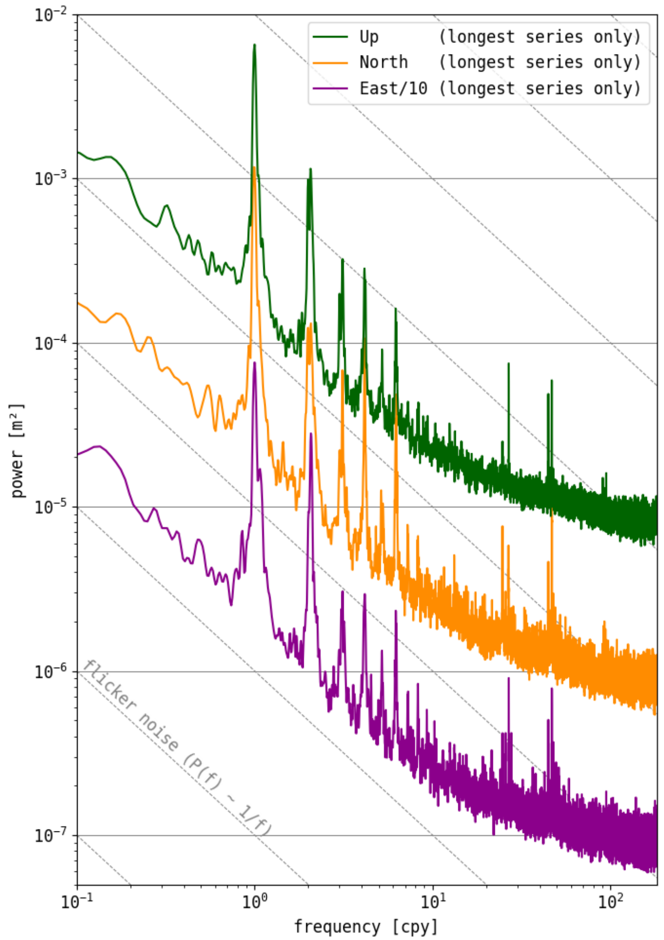
- **Direct tidal effects:**
  - **Mf (13.66 d)**
  - **See also faint Mm (27.55 d) signal in previous slide**
- **Tidal aliases via daily sampling:**
  - **M2 (14.76 d)**
  - **O1 (14.19 d)**
  - **145,545 (14.16 d)**
  - **Oo1 (13.17 d)**
- **Tidal alias via ground repeat period of GPS satellites:**
  - **M2 (13.62 d)**

Average periodograms: zoom on ≈8 d



- **Two more tidal aliases via daily sampling:**
  - **μ2 (7.38 d)**
  - **2N2 (7.13 d)**
- **GLONASS-related 'comb' at aliases of $\omega_u + k\cdot\omega_{drac}$ via daily sampling**
  - **ω_u = frequency of Sun-satellite angle in orbital plane**
  - **ω_{drac} = GLONASS draconitic frequency**
  - **$-4 \leq k \leq 2$**
- **Similar combs around:**
  - **≈4 d (aliases of $2\cdot\omega_u + k\cdot\omega_{drac}$)**
  - **≈2.7 d (aliases of $3\cdot\omega_u + k\cdot\omega_{drac}$)**
  - **≈2 d (aliases of $4\cdot\omega_u + k\cdot\omega_{drac}$)**
- **Likely explanation for GLONASS spectral combs: solar radiation pressure mis-modeling** **(see additional slides)**

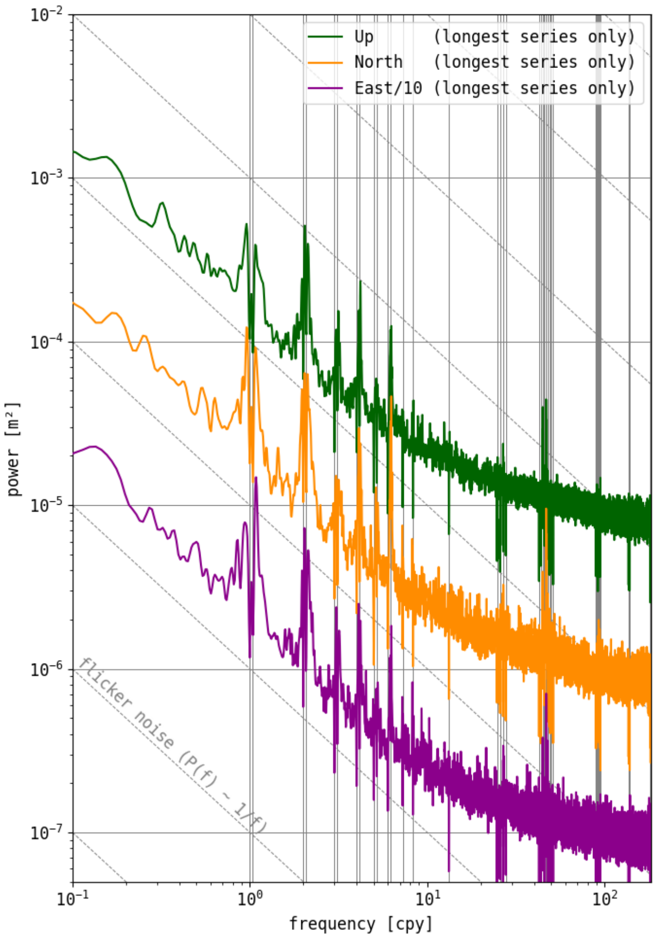
Modeling ≈periodic signals in repro3 time series



← Average periodograms of longest repro3 residual time series

1) No sine waves in trajectory models

Modeling ≈periodic signals in repro3 time series

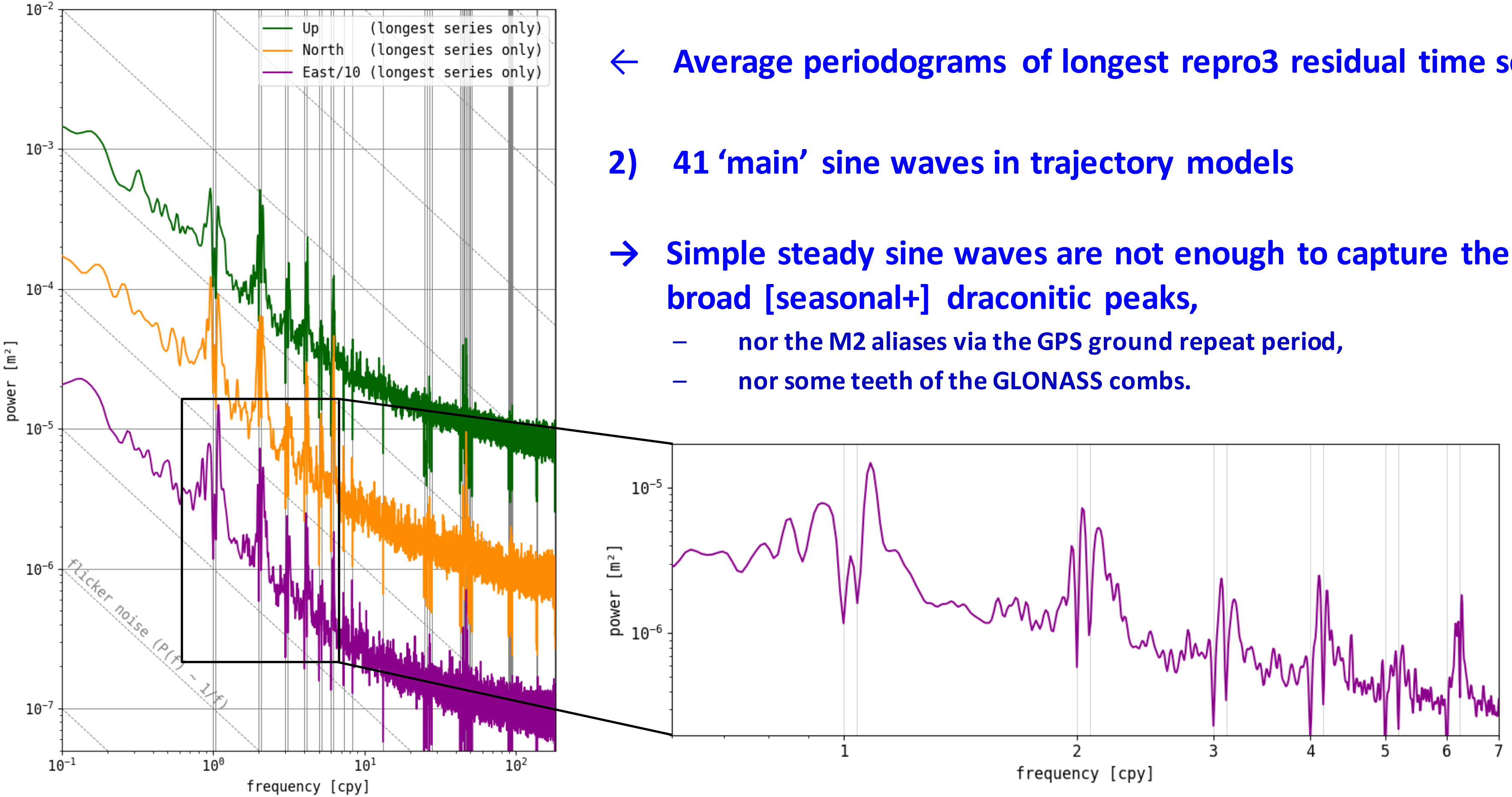


← Average periodograms of longest repro3 residual time series

2) 41 'main' sine waves in trajectory models:

- First 6 annual harmonics
- First 8 GPS draconitic harmonics
- Mm, Mf
- M2, O1, 145,545, Oo1, μ2, 2N2 aliases via daily sampling
- M2 alias via GPS ground repeat period
- GLONASS $\omega_u + k\cdot\omega_{drac}$ aliases via daily sampling $(-4 \leq k \leq 2)$
- GLONASS $2\cdot\omega_u + k\cdot\omega_{drac}$ aliases via daily sampling $(-4 \leq k \leq 1)$
- GLONASS $3\cdot\omega_u + k\cdot\omega_{drac}$ aliases via daily sampling $(-4 \leq k \leq -2)$
- GLONASS $4\cdot\omega_u + k\cdot\omega_{drac}$ aliases via daily sampling $(-6 \leq k \leq -5)$

Modeling ≈periodic signals in repro3 time series



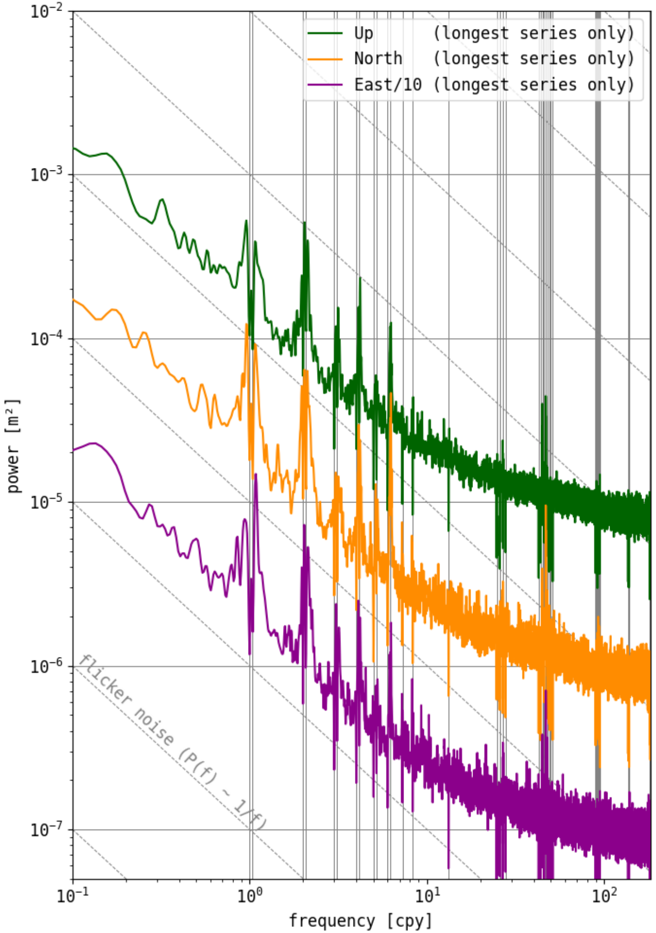
← Average periodograms of longest repro3 residual time series

2) 41 ‘main’ sine waves in trajectory models

→ Simple steady sine waves are not enough to capture the broad [seasonal+] draconitic peaks,

- nor the M2 aliases via the GPS ground repeat period,
- nor some teeth of the GLONASS combs.

Modeling ≈periodic signals in repro3 time series



← Average periodograms of longest repro3 residual time series

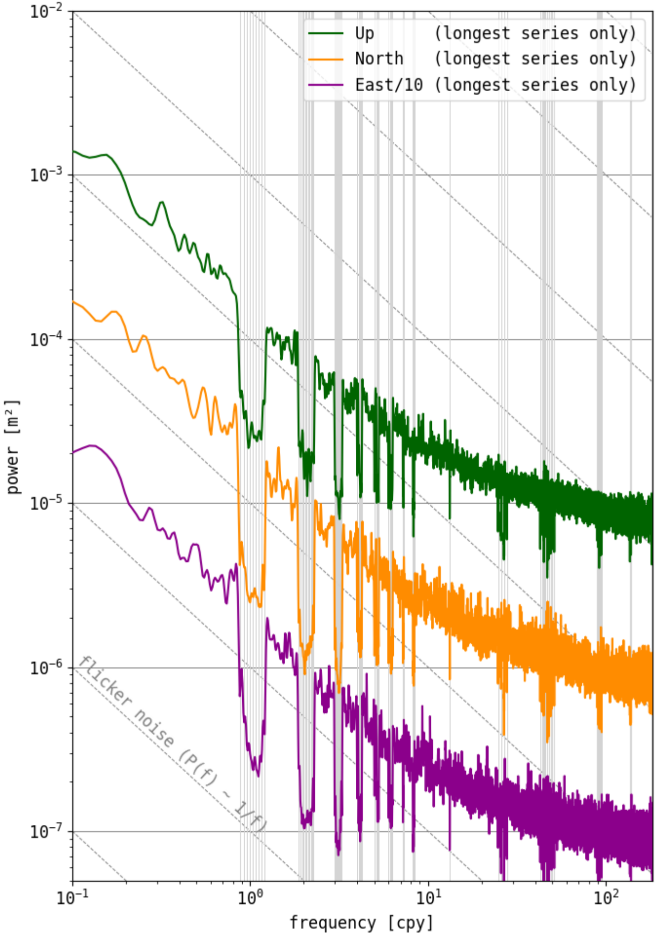
2) 41 'main' sine waves in trajectory models

→ Simple steady sine waves are not enough to capture the broad [seasonal+] draconitic peaks,

- nor the M2 aliases via the GPS ground repeat period,
- nor some teeth of the GLONASS combs.

- Why?
  - Solar radiation pressure modeling errors likely vary with the evolution of the GNSS constellations, as well as with long-term variations of β.
  - GPS draconitic peaks may actually be a superposition of combs with slightly offset frequencies (see additional slides).
  - Non-loading, non-stationary seasonal deformation may also contribute, though only to the ≈annual and ≈semi-annual (?) peaks.

Modeling ≈periodic signals in repro3 time series



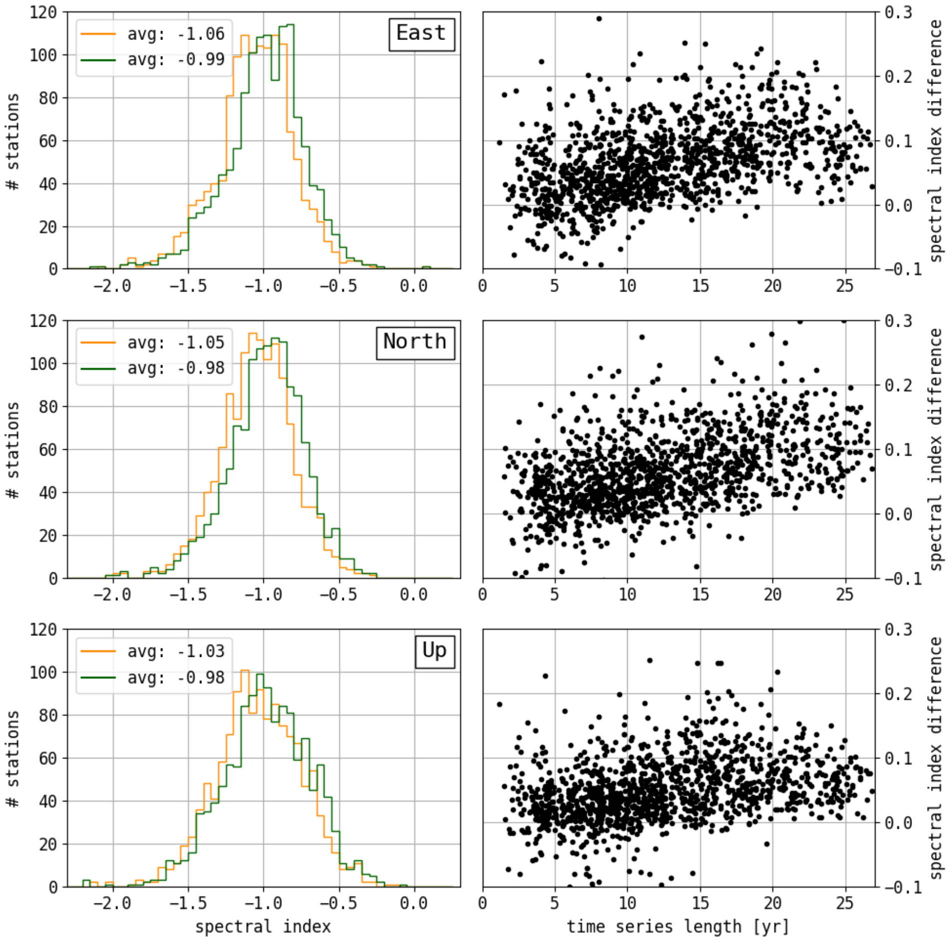
← Average periodograms of longest repro3 residual time series

3) 41 'main' sine waves + 60 'adjacent' sine waves

- 'Adjacent' waves separated from each other and from 'main' waves by: $\omega_{prec,GPS}$ ≈ 1/25.5 cpy ≈ spectral resolution of longest repro3 series
- In order to allow adjustment to shorter series as well, the amplitudes of all sine waves (except annual and semi-annual) are constrained to zero ± appropriate levels.

→ The residuals can finally be considered as an image of the background noise (with some frequency bands filtered out).

Noise analysis of repro3 time series

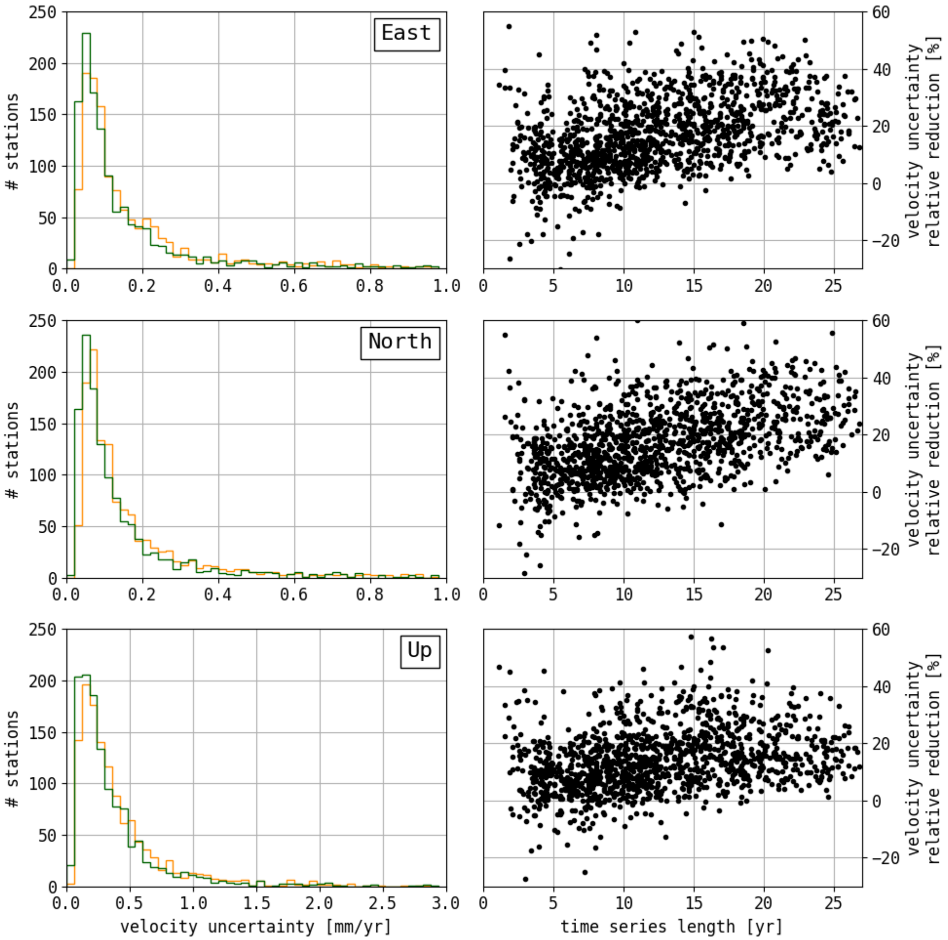


- Adjust variable white + power-law noise models together with different trajectory models to repro3 time series
  – Estimation method: restricted maximum likelihood

← Impact of accounting or not for non-stationary periodic signals on estimated spectral indices
  – Only 'main' sine waves in trajectory models
  – 'Main' + 'adjacent' sine waves in trajectory models

- Accounting for non-stationary periodic signals slightly shifts spectral indices towards white noise.
  – Especially for long time series (for which spectral peaks stand higher above background noise)

Noise analysis of repro3 time series



- Adjust variable white + power-law noise models together with different trajectory models to repro3 time series
  - Estimation method: restricted maximum likelihood

← Impact of accounting or not for non-stationary periodic signals on velocity uncertainties
  - Only 'main' sine waves in trajectory models
  - 'Main' + 'adjacent' sine waves in trajectory models

- Accounting for non-stationary periodic signals reduces velocity uncertainties.
  - Average relative reductions: 17% in horizontal / 14% in vertical
  - For series longer than 15 years: 24% in horizontal / 18% in vertical

Summary

- **Manual offset detection and PSD modeling, aided by statistical tests**
  - repro3 discontinuity list and PSD models published along with ITRF2020P

- **GGFC loading models reduce annual signals and non-seasonal scatter of repro3 time series in expected proportions.**
  - Note strong change in vertical background noise spectrum with loading corrections.
  - → Background noise in GNSS height time series uncorrected for loading deformation does not follow usual white + power-law model (Gobron et al., 2021).

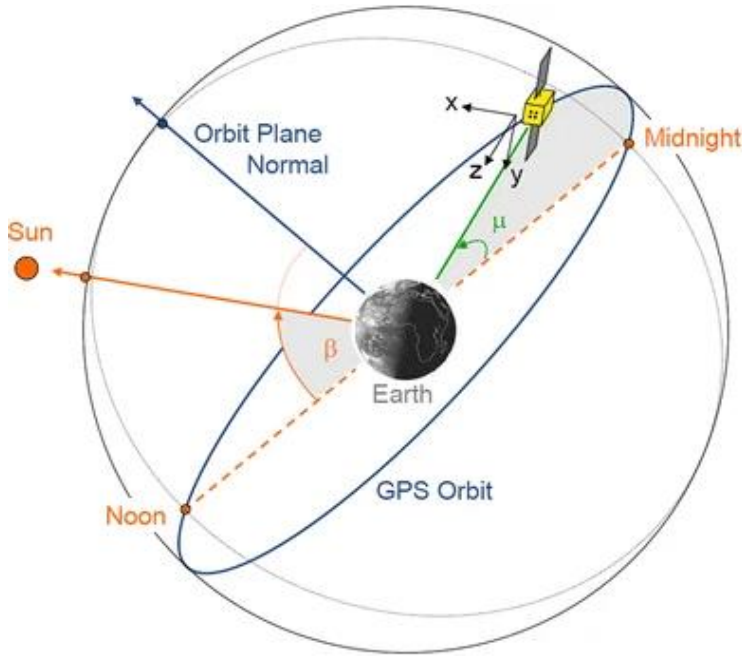
- **repro3 time series include 'usual' spurious draconitic and tide-related signals, but also:**
  - Previously undetected tide-related signals (Mm, 145,545, Oo1, μ2, 2N2),
  - GLONASS-related combs around harmonics of ≈8 d, likely due to solar radiation pressure modeling errors.

- **repro3 time series show evidence of non-stationary [seasonal+] draconitic signals.**
  - Modelled here by means of 'adjacent' sine waves
  - Failure to account for this non-stationarity results in biased noise parameter estimates and velocity uncertainties.
  - Velocity uncertainties obtained with 'standard' trajectory models and white + power-law noise models are likely to be over-estimated by ≈20% in average for long time series.

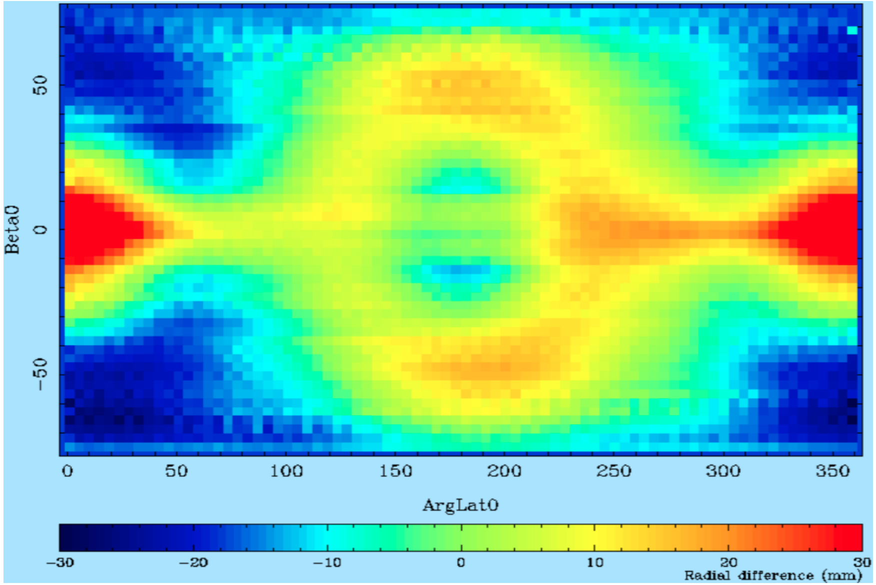
Additional slides

Possible explanation for GLONASS spectral combs

- Solar radiation pressure and thermal re-radiation mis-modeling induces coherent orbit error patterns in the (u,β) frame.



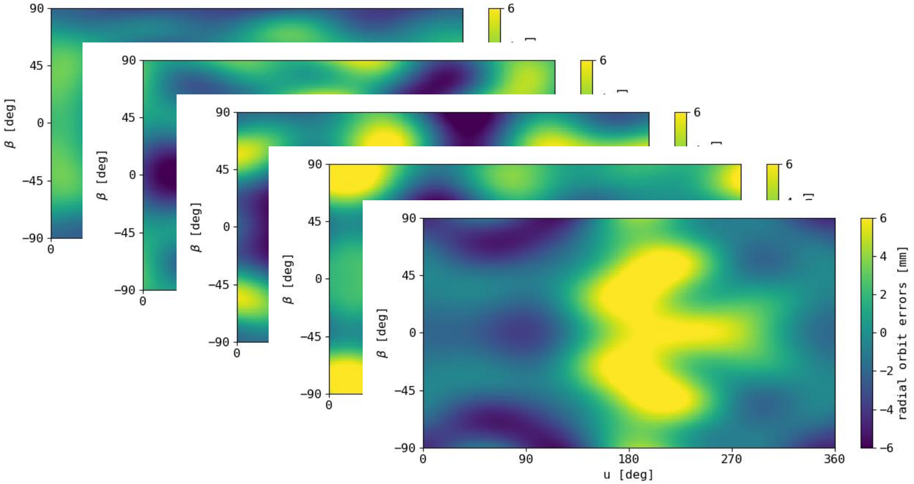
Montenbruck et al. (2011)   Note: $u = \mu + 180°$



Springer et al. (2019): 'JPL-ESA' GPS IIF radial orbit differences
(just one example of such a pattern among many in the literature)

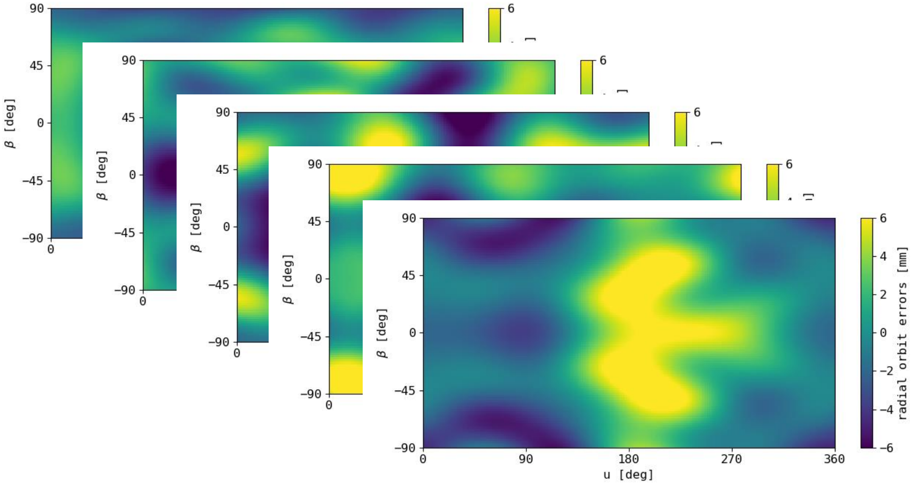
Possible explanation for GLONASS spectral combs

1) Generate random (radial) orbit error patterns for individual GLONASS satellites

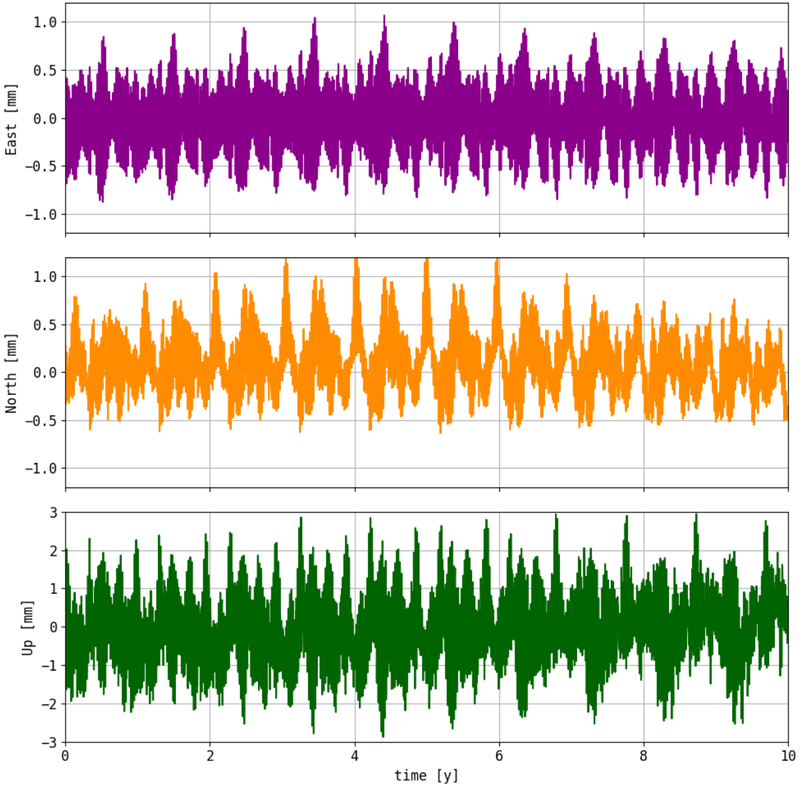


Possible explanation for GLONASS spectral combs

1) Generate random (radial) orbit error patterns for individual GLONASS satellites



2) Simulate impact on daily PPP positions for a fictitious station in New Orleans



Simulated range observations

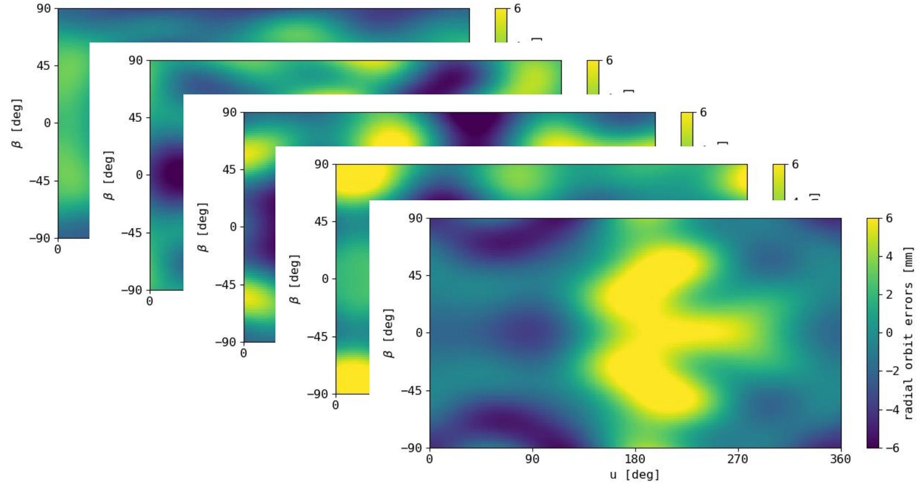
- Nominal GPS & GLONASS constellations
- Keplerian orbits + preceding ascending nodes
- 15 min sampling
- 10° cutoff angle
- sin²(elevation) weighting

Estimated parameters

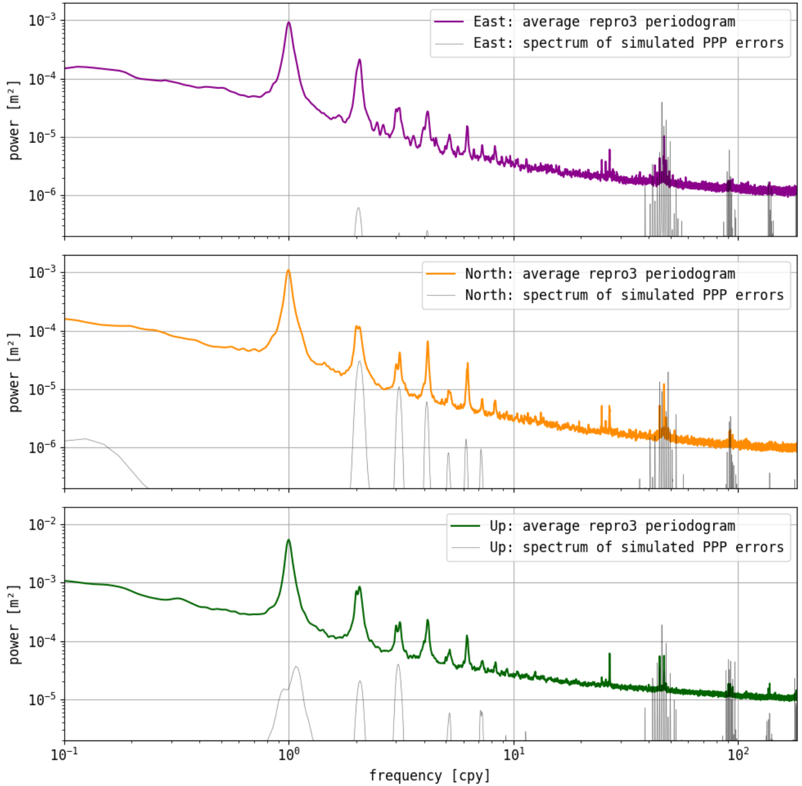
- Daily station positions
- Hourly ZWD + daily gradients
- Epoch-wise clock offsets
- Pass-wise GLONASS ambiguities
- (GPS ambiguities assumed fixed)

Possible explanation for GLONASS spectral combs

1) Generate random (radial) orbit error patterns for individual GLONASS satellites



3) Compare spectra of simulated PPP errors with average repro3 periodograms

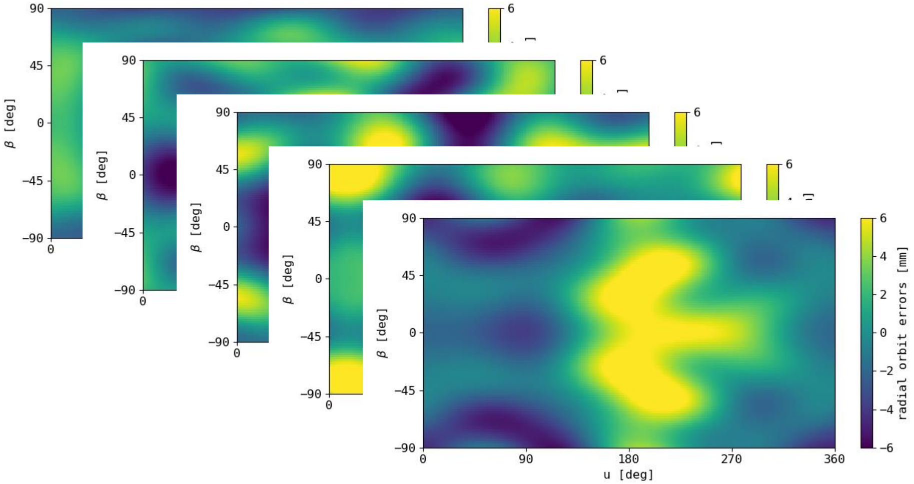


Notes

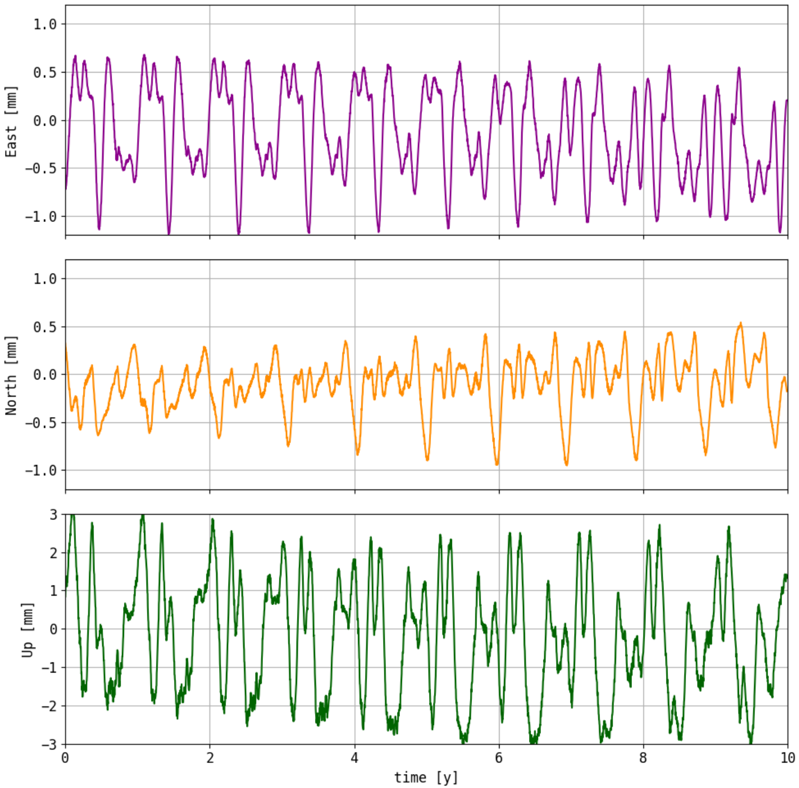
- The heights of the individual peaks in the spectra of simulated PPP errors are not to be interpreted. They are highly dependent on the particular set of random orbit error patterns used in the simulation, as well as on various other simulation settings.
- Similar results are obtained for along-track and cross-track orbit errors.

What about GPS?

1) Generate random (radial) orbit error patterns for individual GPS satellites

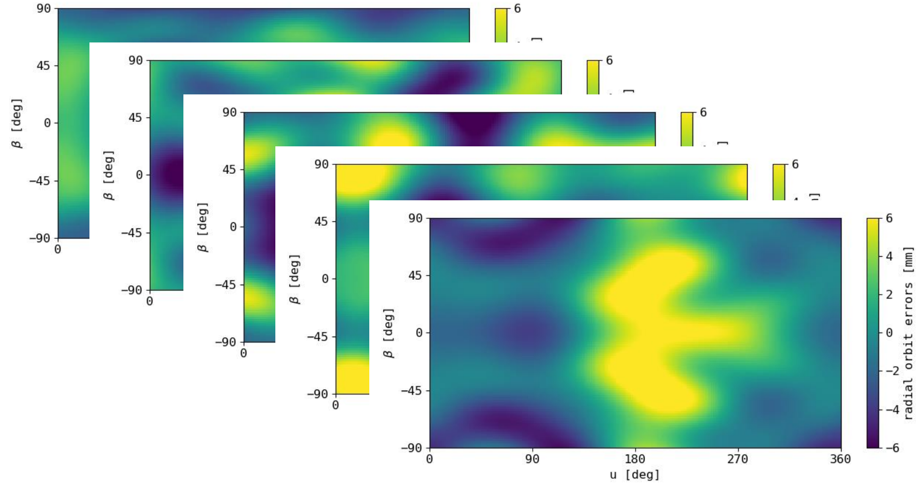


2) Simulate impact on daily PPP positions for a fictitious station in New Orleans

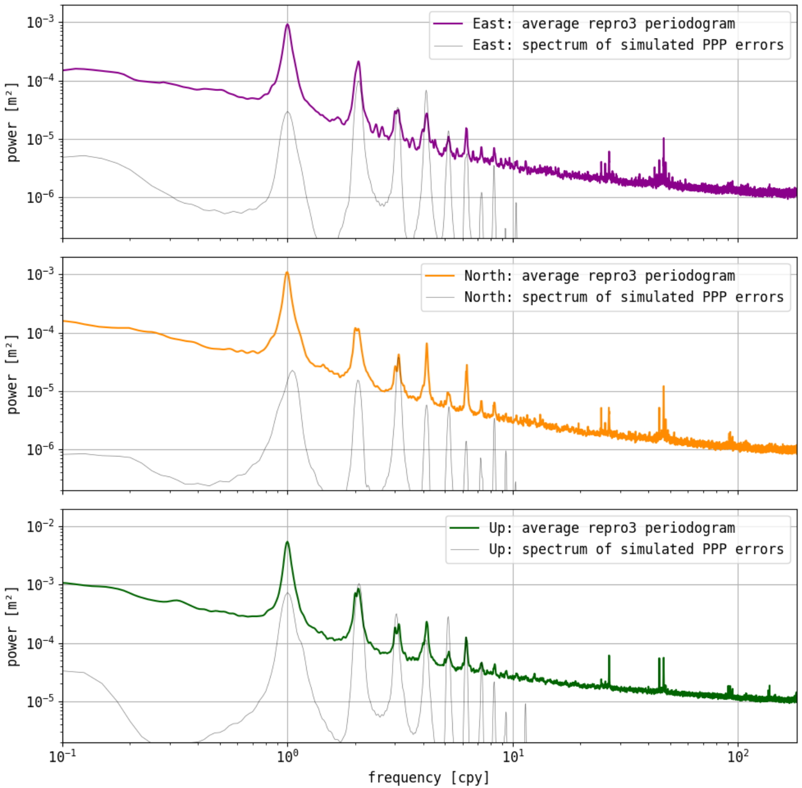


What about GPS?

1) Generate random (radial) orbit error patterns for individual GPS satellites



3) Compare spectra of simulated PPP errors with average repro3 periodograms



Notes

- In case of GPS, only ≈draconitic harmonics are generated.
- This is because, by 'coincidence', $k{\cdot}\omega_u$ signals alias close to (but not exactly at) the k^{th} draconitic harmonic via daily sampling.
- For GLONASS on the other hand, $k{\cdot}\omega_u$ signals alias at periods of ≈8 d / k.