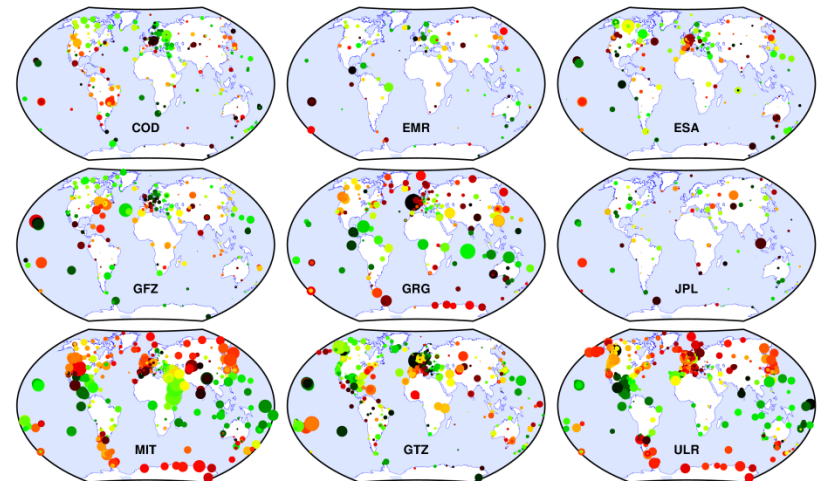
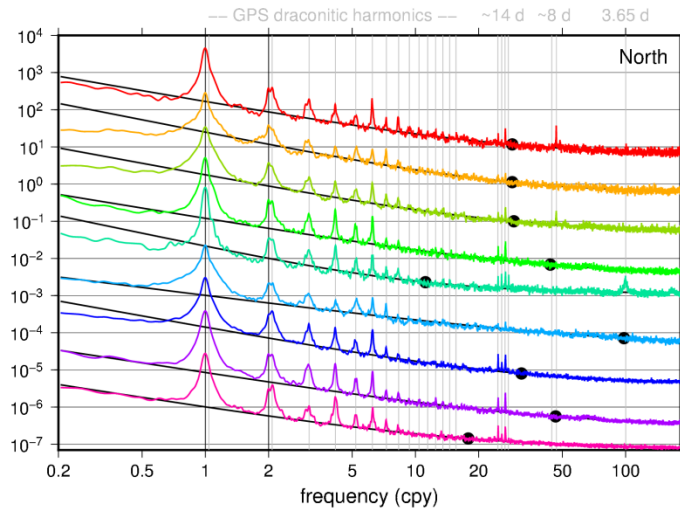


# Error analysis of the IGS repro2 station position time series

Paul Rebischung, Zuheir Altamimi, Jim Ray, Bruno Garayt

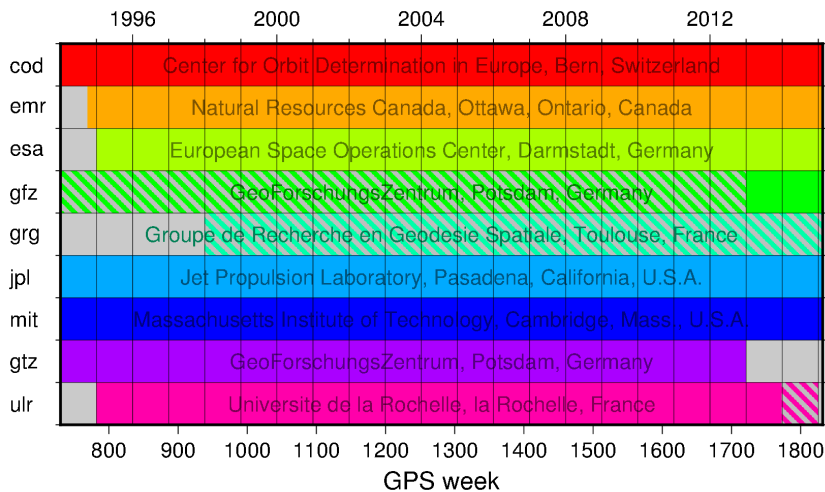


# Outline

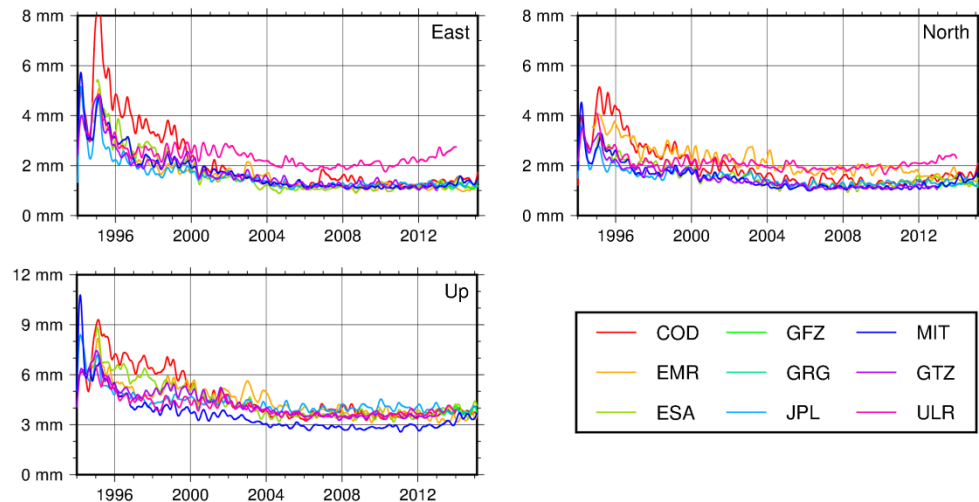
- **Daily repro2 SINEX combinations**
  - Main results
  - Spectral analysis of AC station position residuals
- **AC-specific long-term stackings**
  - Purpose: study "absolute" AC station position time series
  - Background noise
  - Spurious periodic signals

# Daily repro2 SINEX combinations

## AC contributions to the repro2 campaign



## Smoothed, unbiased daily WRMS of the « AC – combined » station position residuals



## Overall levels of inter-AC agreement

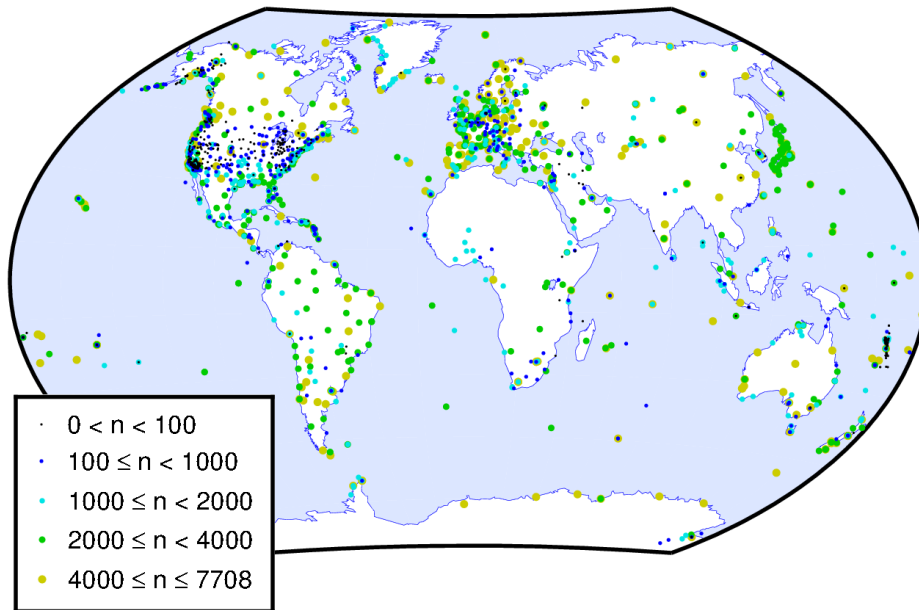
STATION POSITIONS	
Horizontal	Vertical
≈ 1.5 mm	≈ 4 mm

EOPs		
$x_p, y_p$	$\dot{x}_p, \dot{y}_p$	LOD
25-40 $\mu$ s	140-200 $\mu$ s/d	8-20 $\mu$ s/d

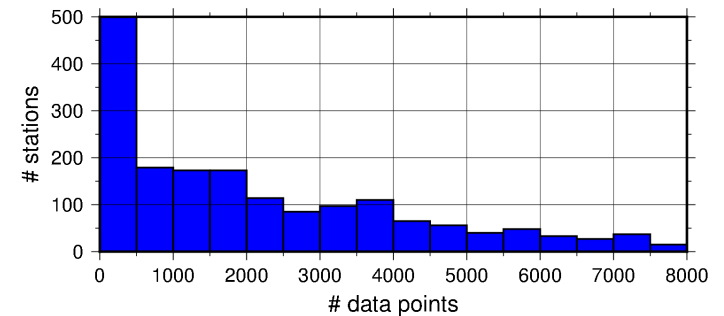
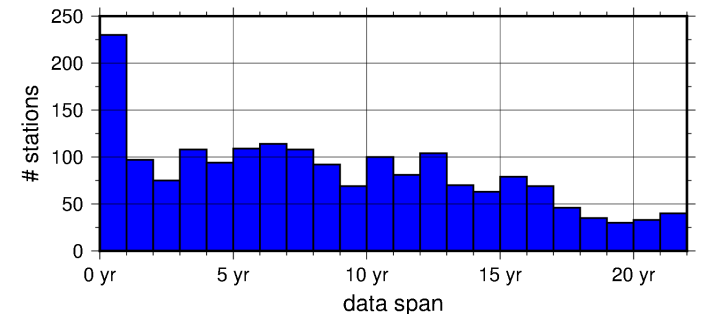
	APPARENT GEOCENTER		SCALE
	X/Y	Z	
Long-term trends	± 3 mm ± 0.3 mm/yr		± 1 mm ± 0.1 mm/yr
Non-linear	≈ 4 mm	≈ 8 mm	< 1 mm

# Combined IGS repro2 dataset

- **7714 daily SINEX files**
  - Daily station positions, geocenter coordinates and EOPs
  - January 2, 1994 → February 14, 2015
  - **1848 stations**



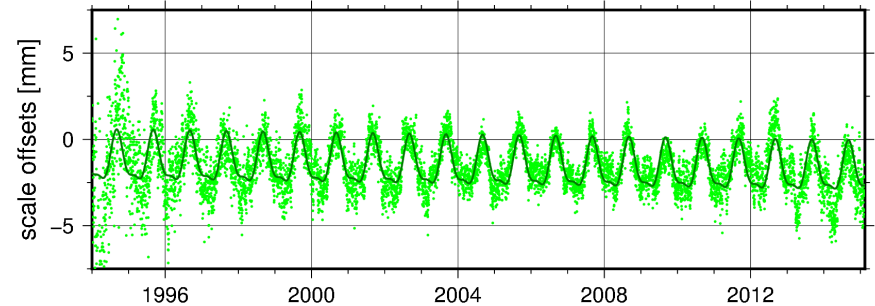
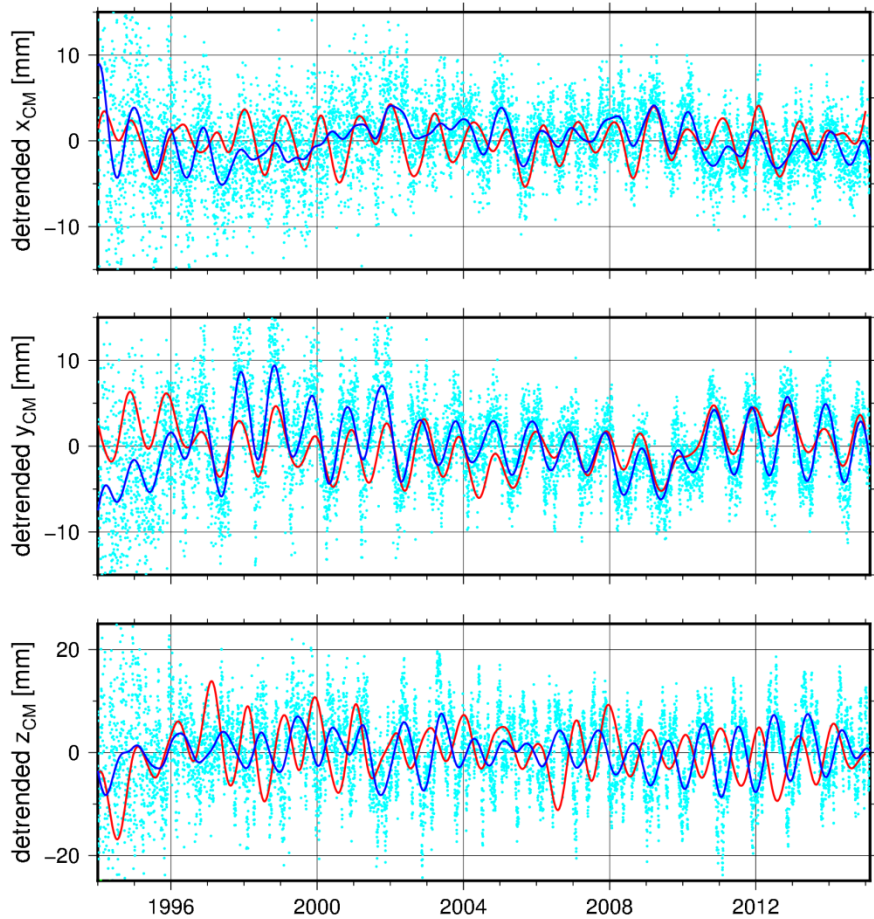
Stations included in the daily repro2 combined solutions.  
The size and color of each dot is function of  
the number of days  $n$  each station is present.



Histograms of the lengths (top)  
and numbers of data points (bottom)  
of the repro2 station position time series



# Geocenter & terrestrial scale



.... Scale factors estimated between the daily repro2 combined solutions and IGB08  
 — Trend + annual + semi-annual fit

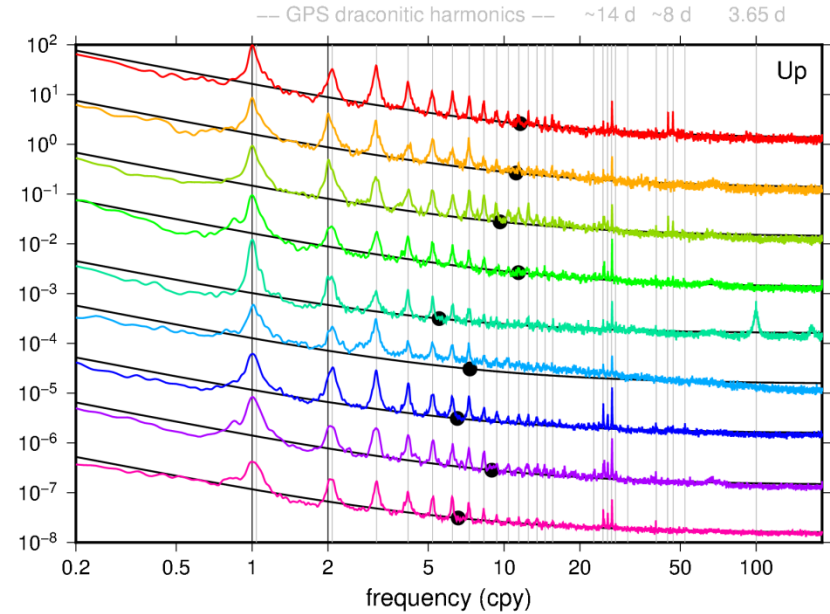
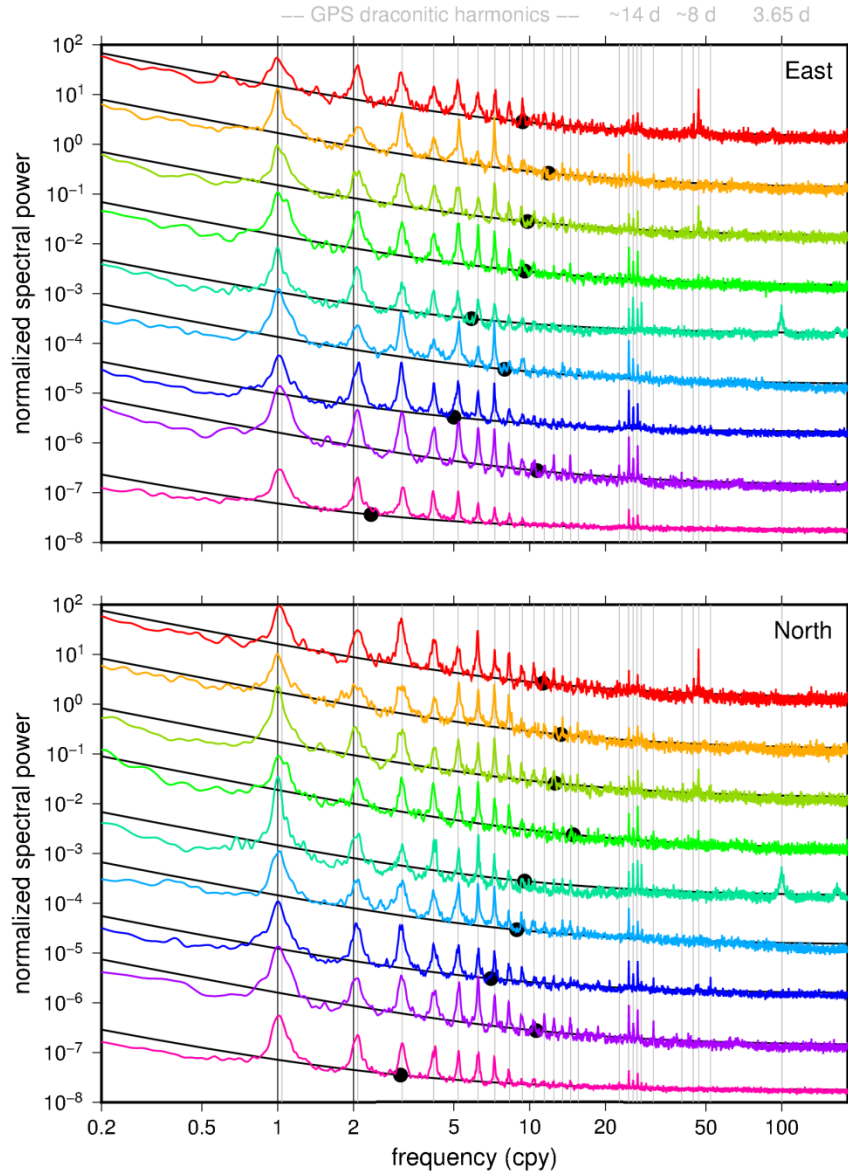
	Offset at 2005. [mm]	Rate [mm/yr]	Annual amp [mm]	Annual phi [deg]
$x_{CM}$	1.6	0.28	1.5 / 2.6	41 / 48
$y_{CM}$	2.6	-0.40	3.6 / 2.8	310 / 320
$z_{CM}$	7.0	-0.18	3.8 / 5.9	181 / 26
scale	-1.5	-0.03	1.4	-114

Results from linear trends + annual fits to:

- a) the daily repro2 combined geocenter coordinate time series
- b) geocenter coordinate time series derived from the SLR contribution to ITRF2014
- c) time series of scale offsets estimated between the daily repro2 combined solutions and IGB08

.... Detrended daily repro2 combined geocenter coordinates  
 — Detrended & smoothed repro2 geocenter coordinates  
 — Detrended & smoothed geocenter coordinates derived from the SLR contribution to ITRF2014

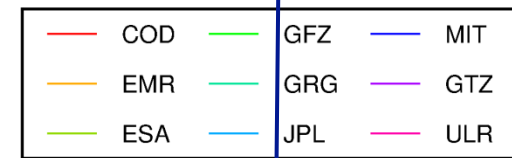
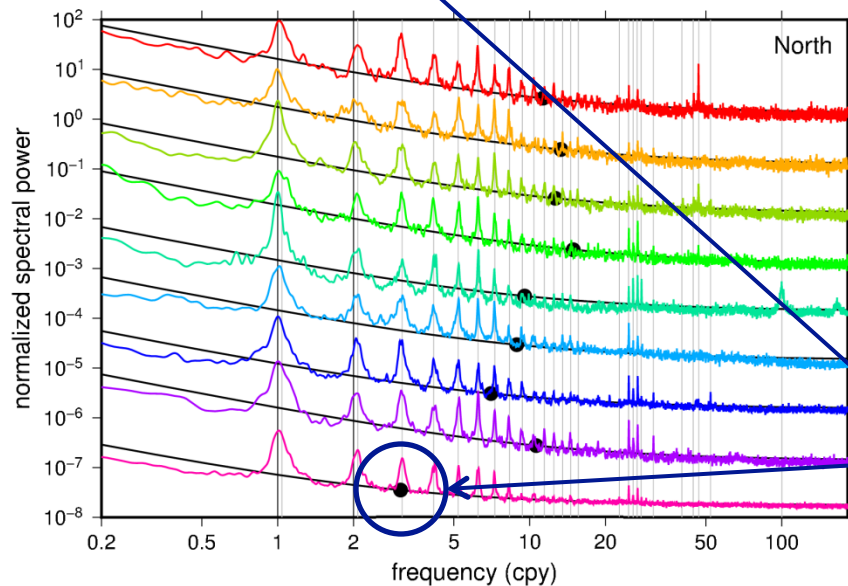
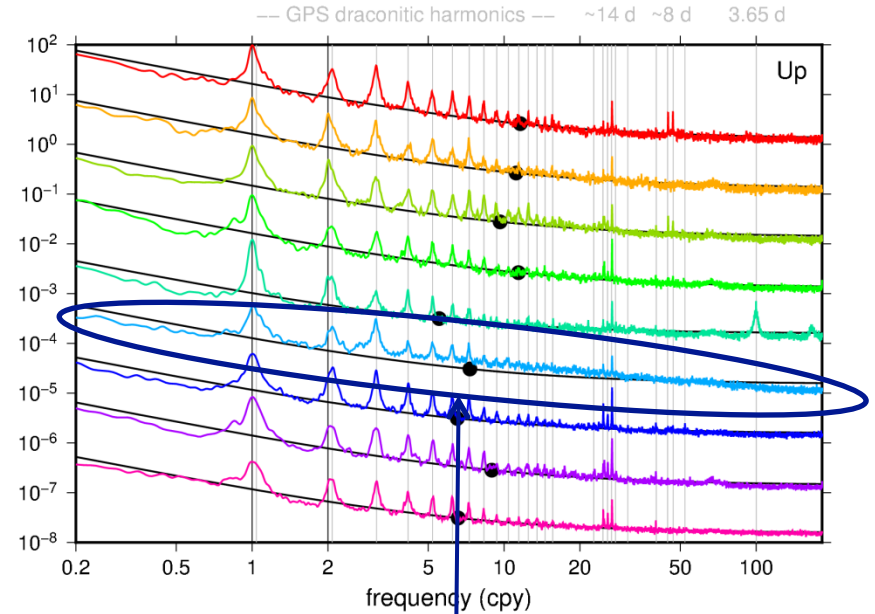
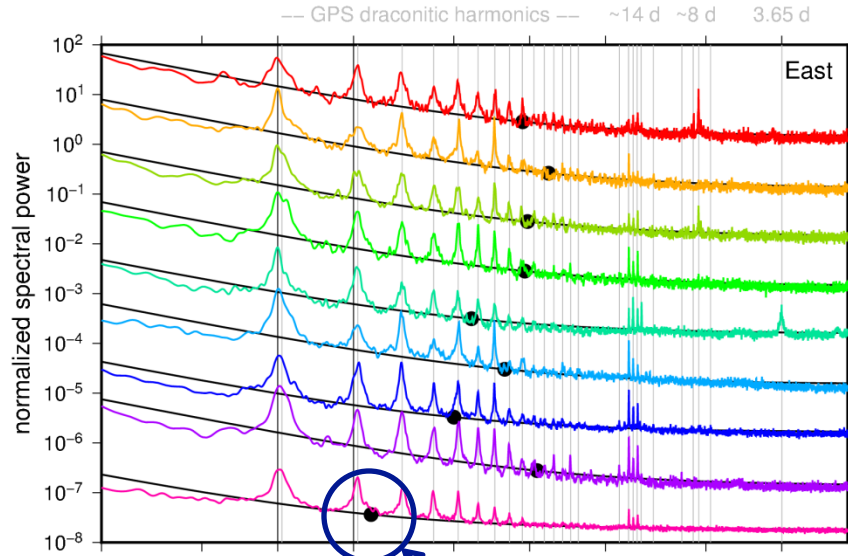
# Spectra of AC station position residuals



**Averaged normalized Lomb-Scargle periodograms of the AC station position residual time series from the daily repro2 combinations**

- results from white + flicker noise (i.e.,  $a + b/f$ ) fits
- crossover frequencies between white & flicker noises

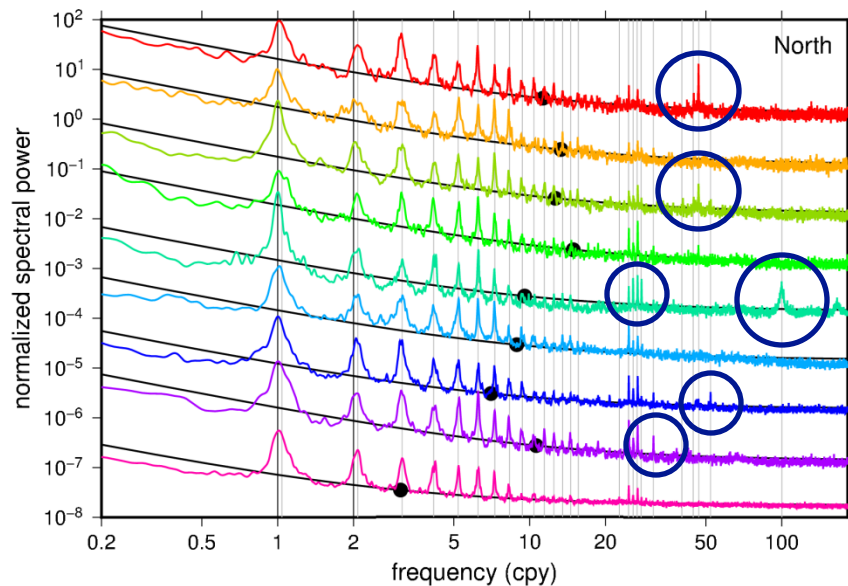
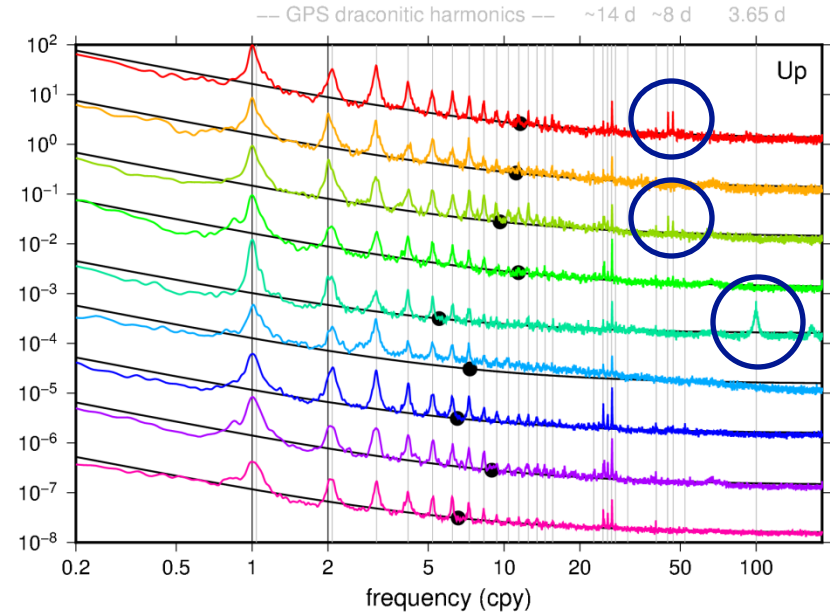
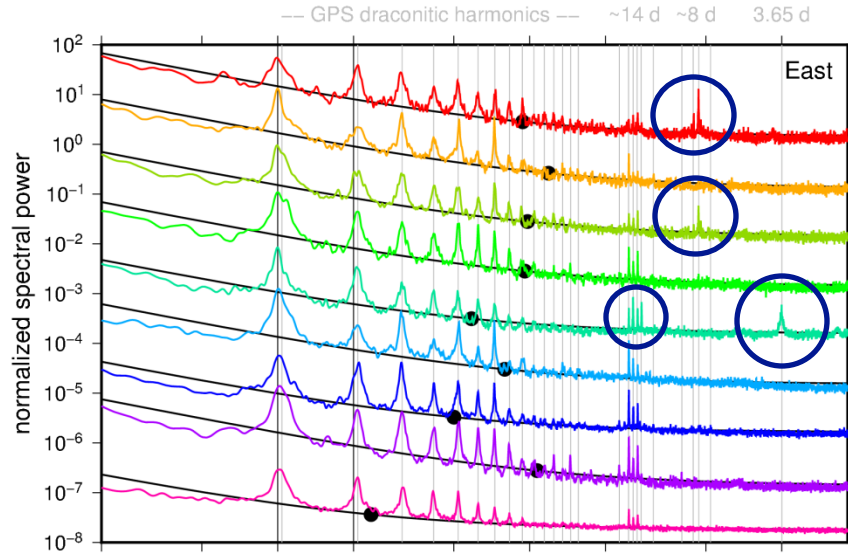
# Spectra of AC station position residuals



Departure of JPL's residuals from the white + flicker noise model, particularly in Up (unknown reason)

Higher level of white noise in ULR's horizontal residuals (sub-optimal combination of station clusters)

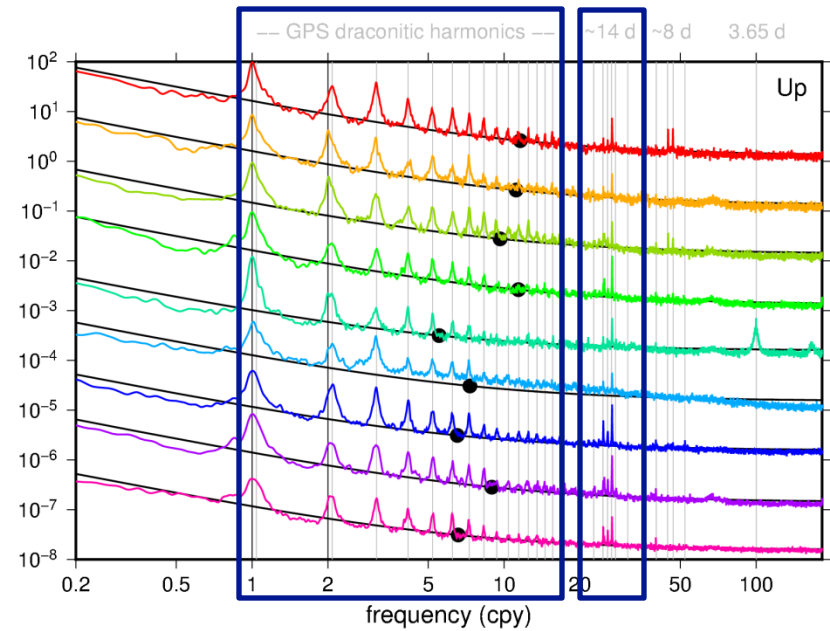
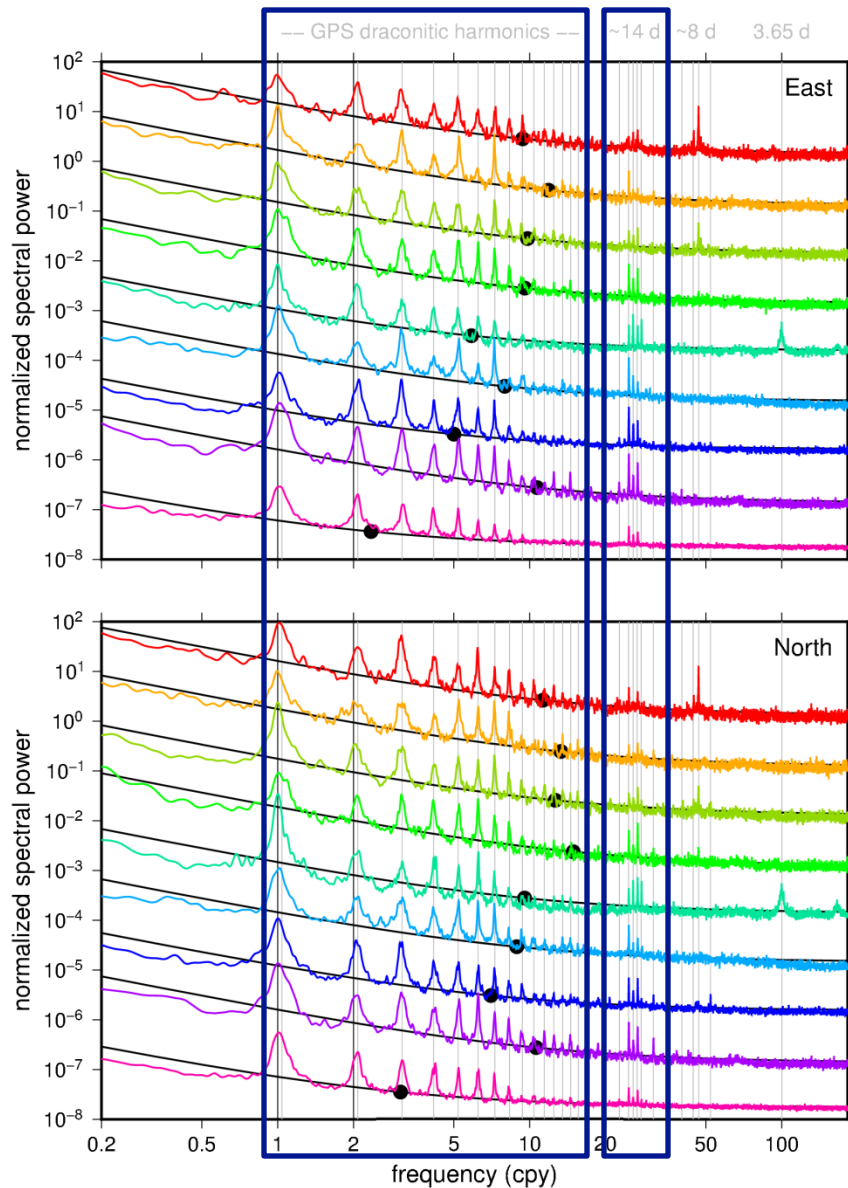
# Spectra of AC station position residuals



- $\approx 3.65$  day peaks in **GRG's** residuals (date rounding issue?)
- 7.0 day line in **MIT's** North residuals (orbit constraints?)
- 7.8 & 8.2 day lines in **COD's** & **ESA's** residuals (GLONASS)
- 11.8 day line in **GTZ's** North residuals (?)
- 13.2 day lines in **GRG's** horizontal residuals (?)



# Spectra of AC station position residuals



Harmonics of the GPS draconitic year (1.04 cpy)

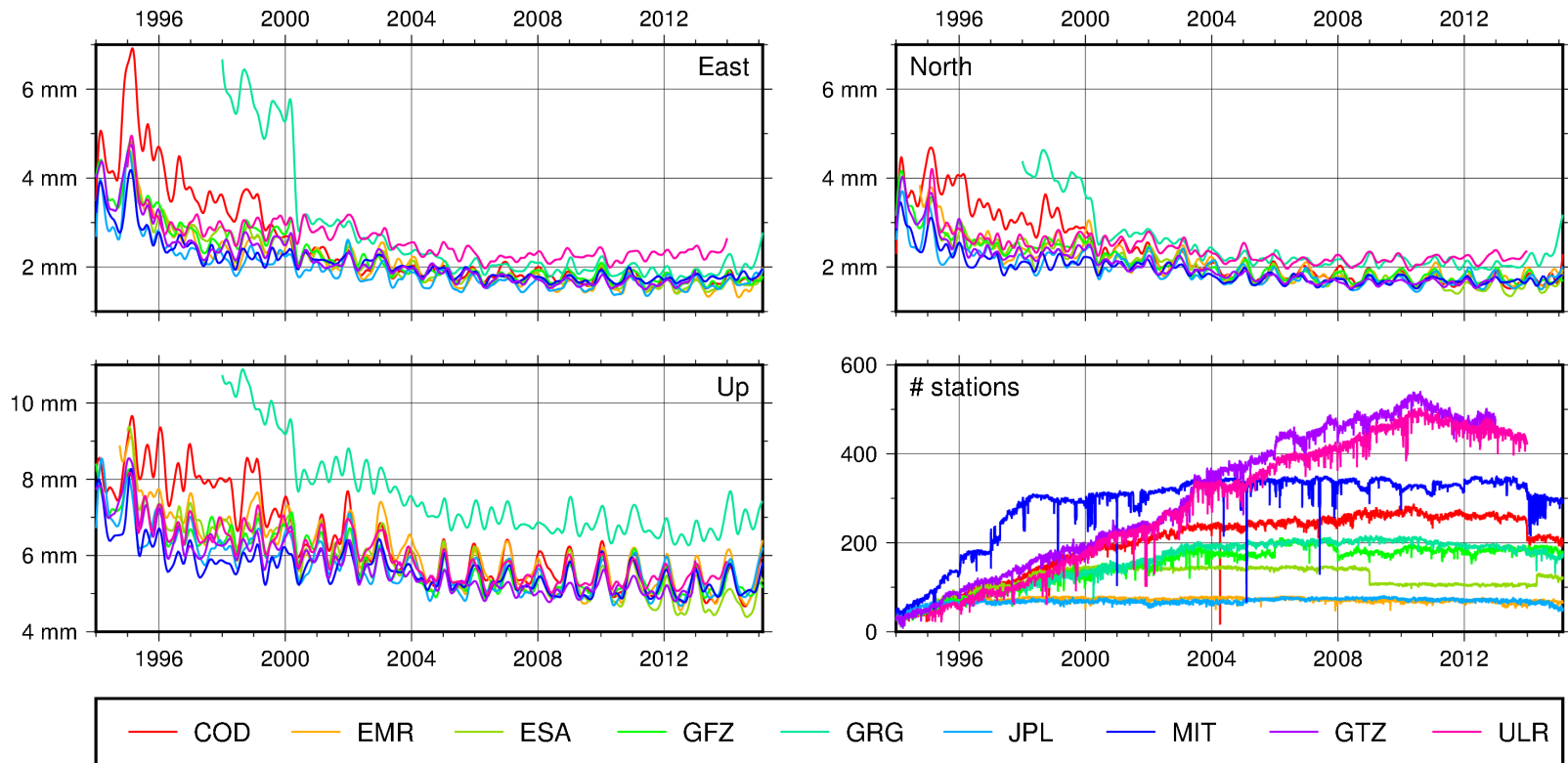
Fortnightly tidal lines

- 13.6 days ( $M_f$  tide)
- 14.2 days ( $O_1$  alias through 24h sampling)
- 14.8 days ( $M_2$  alias through 24h sampling)

# AC-specific long-term stackings

- **Purpose:**
  - Study "absolute" AC station position time series (rather than the differences to their mean)
  - Contribute to trace sources of spurious periodic signals (especially GPS draconitic harmonics & fortnightly lines)
- **Strategy:**
  - Pre-process daily AC solutions as for the daily SINEX combinations
  - Reject stations with time series < 500 days or large non-linear motions
  - Correct post-seismic deformations using ITRF2014 models
  - Use ITRF2014 discontinuity list (with marginal AC-specific adjustments)
  - Jointly estimate long-term positions & velocities + annual & semi-annual signals
  - Iterate until < 0.01% of observations have normalized residuals > 5

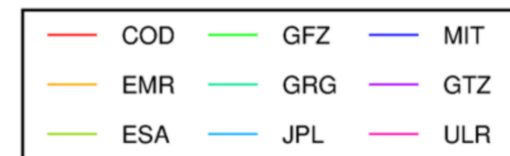
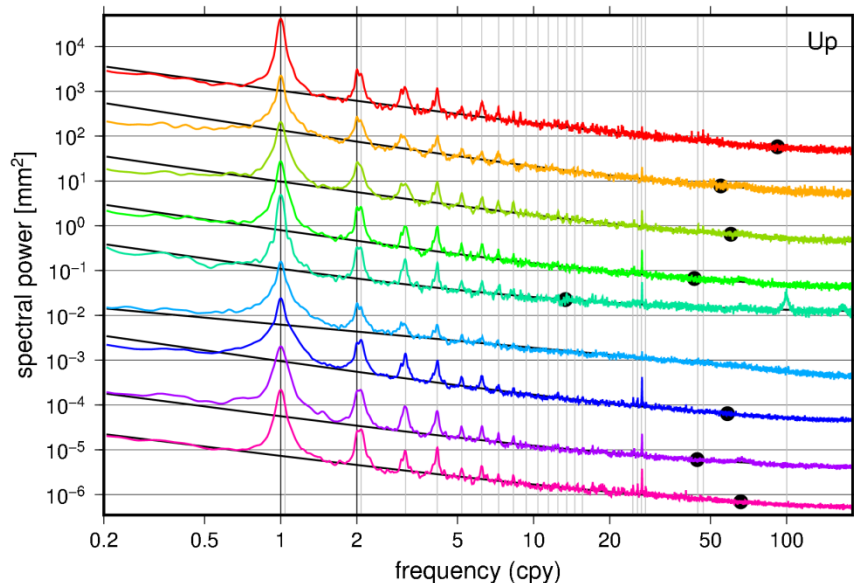
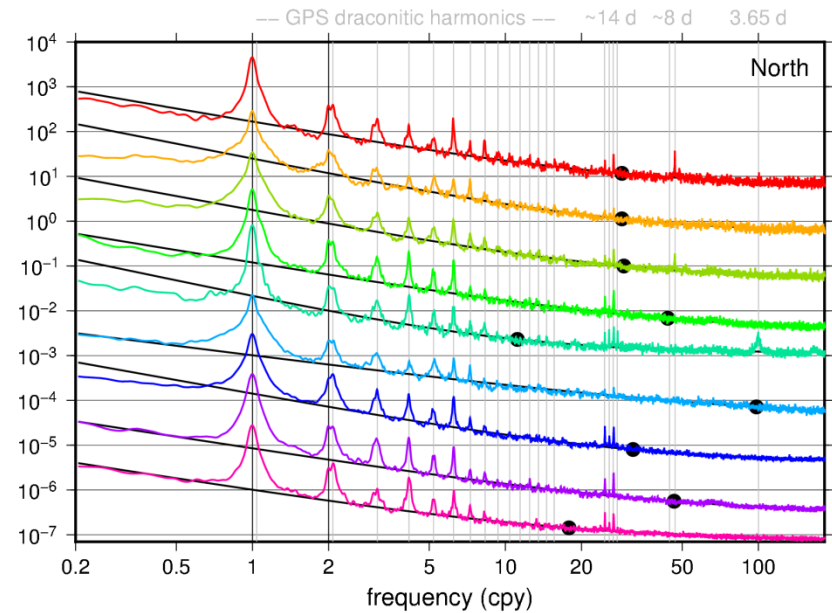
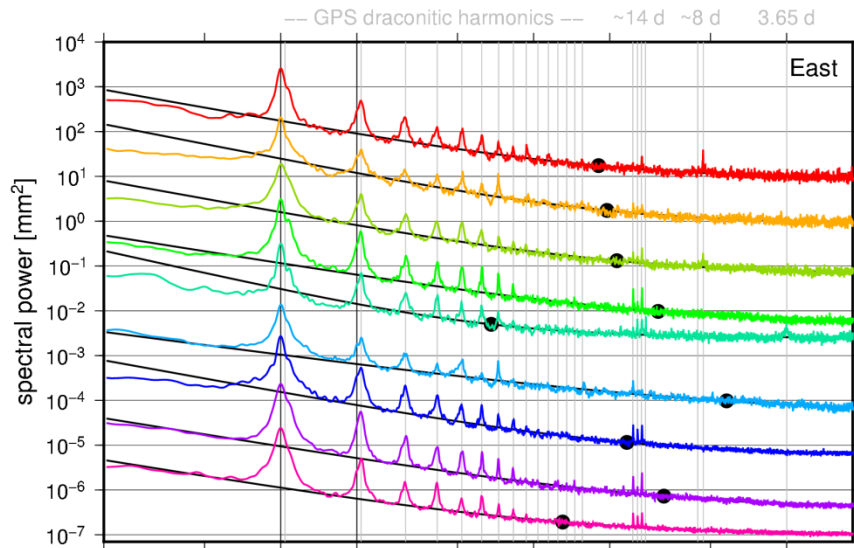
# Stacking residuals: temporal domain



Daily WRMS of the stacking residuals / Number of stations in the cleaned daily AC solutions

- **COD:** higher noise level before 1999, especially in East (ambiguity resolution?)
- **GRG:** higher noise level before 2000 (phase ambiguities not fixed)
- **GRG:** substantially higher WRMS in Up ( $\approx 7$  mm after 2004) (?)
- **ULR:** higher noise level in horizontal (sub-optimal combination of station clusters)

# Stacking residuals: spectral domain



**Averaged Lomb-Scargle periodograms of the station position residual time series from the AC-specific stackings (with annual & semi-annual signals restored)**

- results from white + power-law noise (i.e.,  $a + b/f^\alpha$ ) fits
- crossover frequencies between white & power-law noises



# Stacking residuals: background noise

	EAST			NORTH			UP		
	$\sigma_{WN}$ [mm]	$\alpha$	$\sigma$ (1 cpy) [mm]	$\sigma_{WN}$ [mm]	$\alpha$	$\sigma$ (1 cpy) [mm]	$\sigma_{WN}$ [mm]	$\alpha$	$\sigma$ (1 cpy) [mm]
COD	2.9	1.02	13	2.4	0.99	13	5.4	0.79	32
EMR	2.9	1.12	16	2.4	1.12	16	6.2	0.88	37
ESA	2.6	1.03	13	2.2	1.05	13	5.7	0.82	31
GFZ	2.2	0.91	11	1.8	0.94	11	5.8	0.83	28
GRG	5.0	1.27	18	3.4	1.19	15	10.6	0.84	33
JPL	2.2	0.74	10	1.9	0.72	10	0.8	0.52	25
MIT	2.4	1.03	12	2.0	1.02	12	5.7	0.83	31
GTZ	1.9	0.92	10	1.7	0.88	10	5.5	0.76	24
ULR	3.1	0.93	11	2.7	0.90	11	5.9	0.72	27

Parameters of the white + power-law noise models represented in the previous slide:

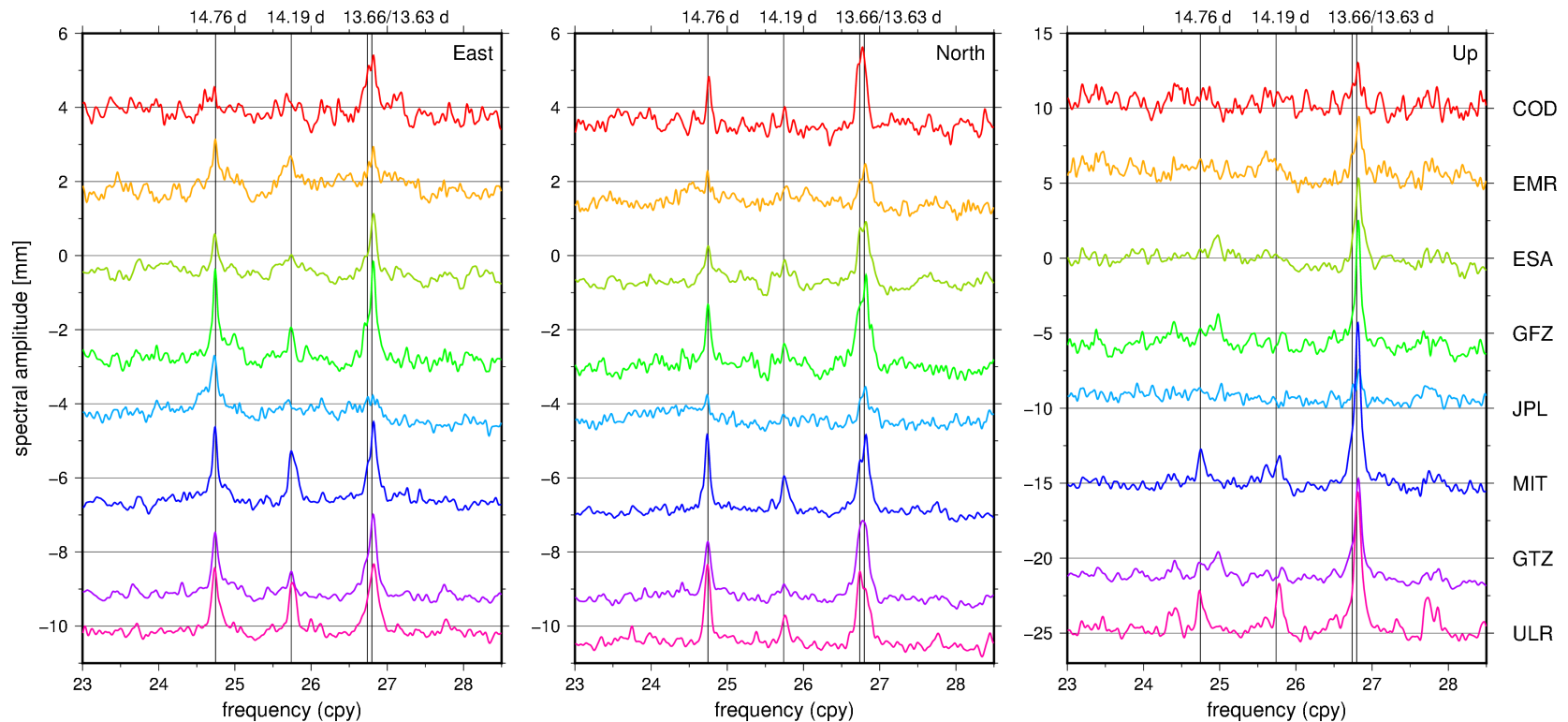
$\sigma_{WN}$  = white noise amplitude

$\alpha$  = spectral index

$\sigma$  (1 cpy) = total noise amplitude at 1 cpy

- **GRG:** higher level of white noise
- **JPL:** lower spectral indices; hardly trace of white noise flattening (especially in Up)
- **All:** more colored noise in horizontal than in vertical

# Stacking residuals: fortnightly band

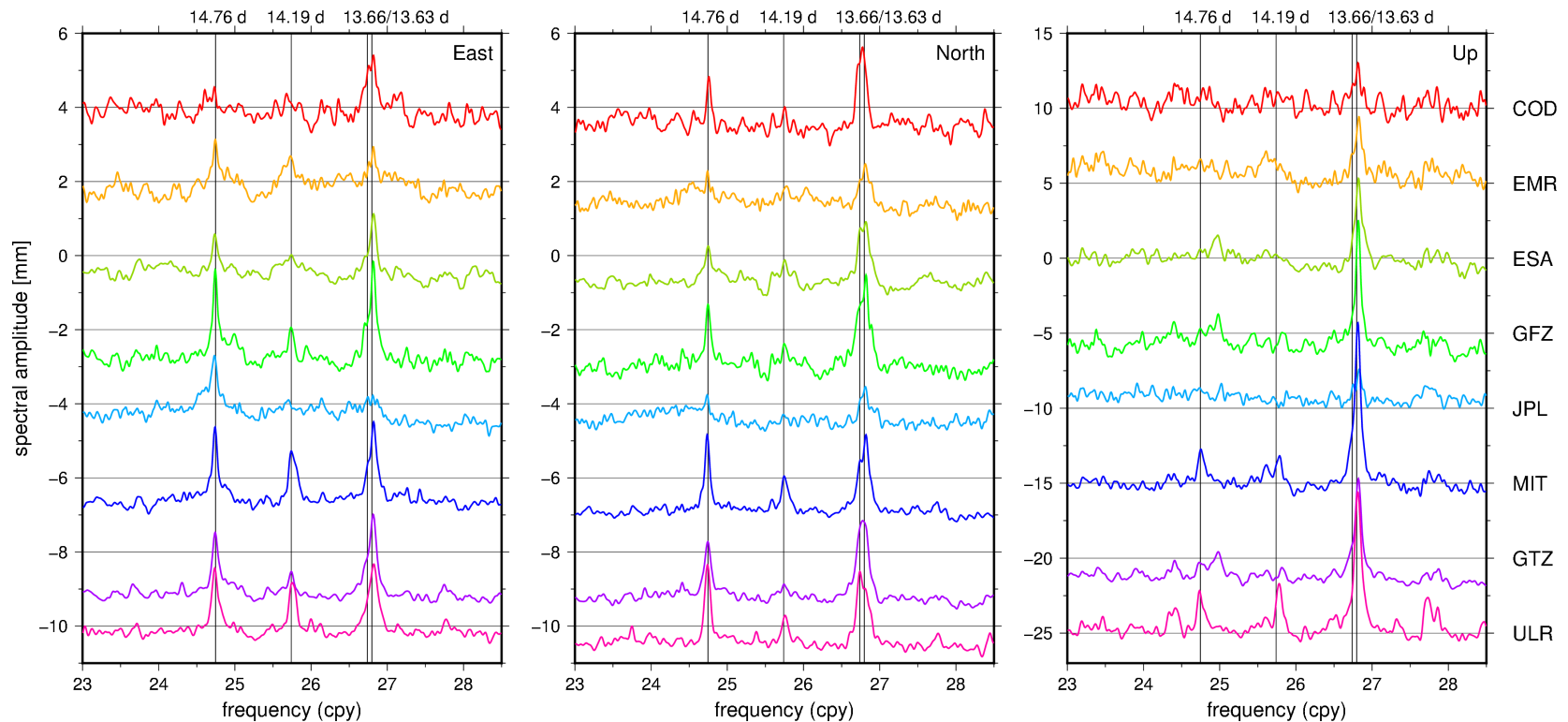


Square-root of the averaged Lomb-Scargle periodograms shown in slide 12: zoom on the fortnightly band

## 14.76 days ( $M_2$ alias):

- Spectral peaks visible in the horizontal residuals of all ACs
  - ↳ consistent with a rotational origin (e.g. error in the IERS subdaily EOP tide model)
- Seem more pronounced for **GFZ/GTZ** and **MIT/ULR**
- Spectral peaks visible in the vertical residuals of **MIT/ULR**

# Stacking residuals: fortnightly band

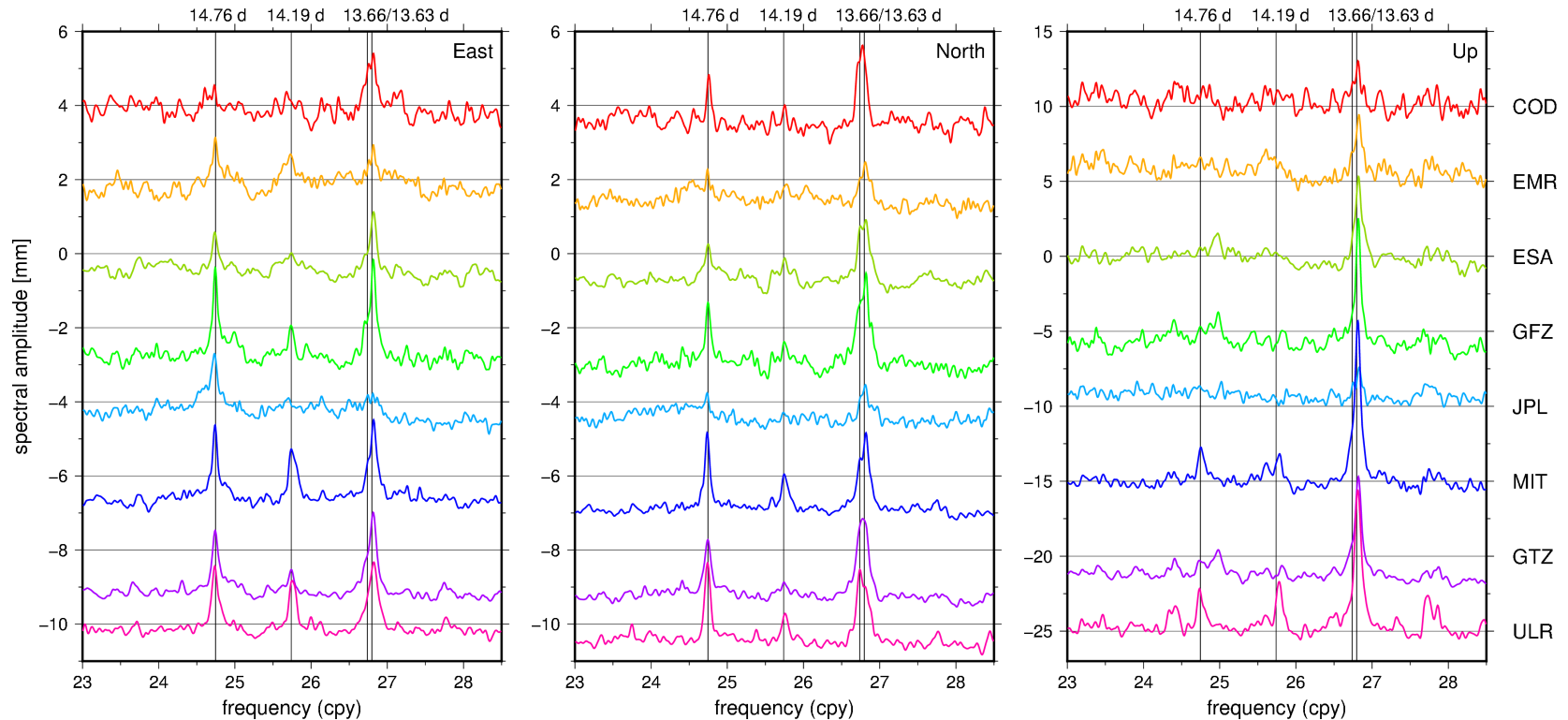


Square-root of the averaged Lomb-Scargle periodograms shown in slide 12: zoom on the fortnightly band

## 14.19 days ( $O_1$ alias):

- Small spectral peaks discernable in the horizontal residuals of some ACs
  - ↳ consistent with a rotational origin (e.g. error in the IERS subdaily EOP tide model)
- Clearer for MIT/ULR
- Spectral peaks visible in the vertical residuals of MIT/ULR

# Stacking residuals: fortnightly band



Square-root of the averaged Lomb-Scargle periodograms shown in slide 12: zoom on the fortnightly band

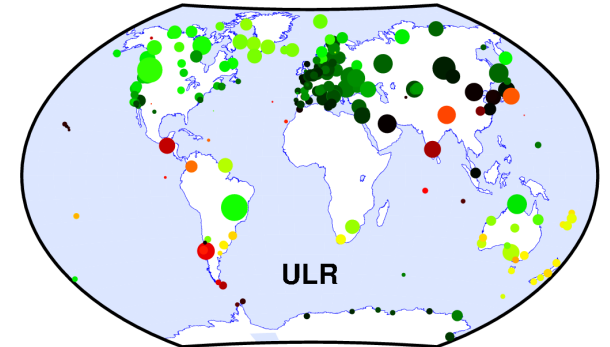
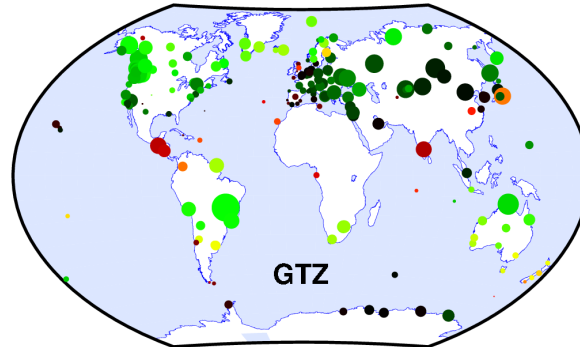
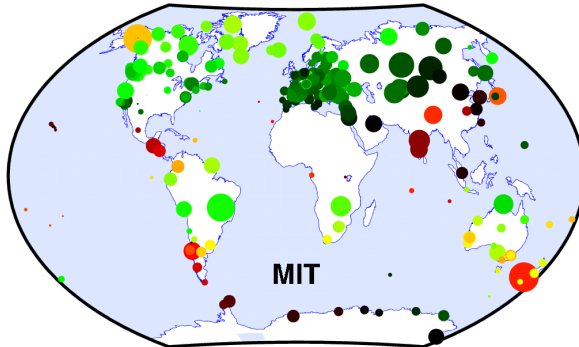
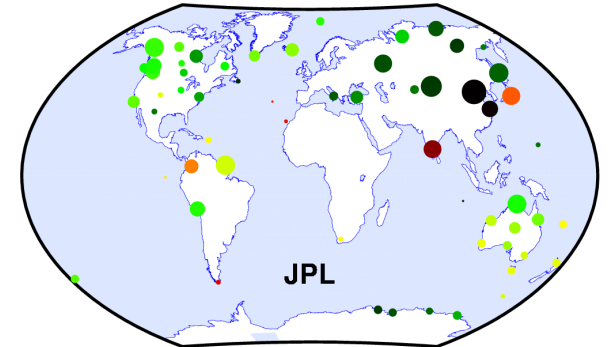
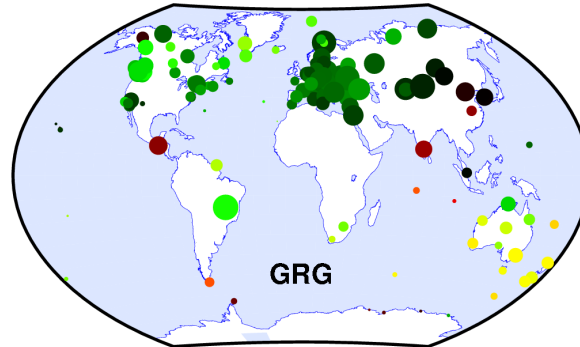
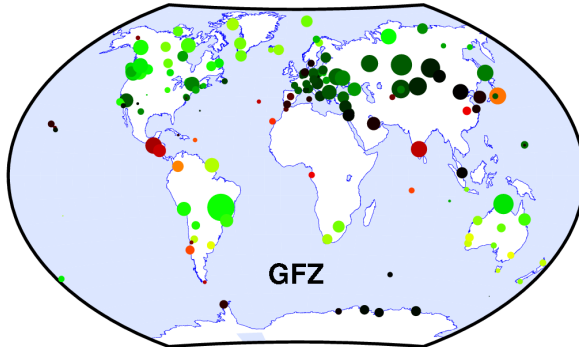
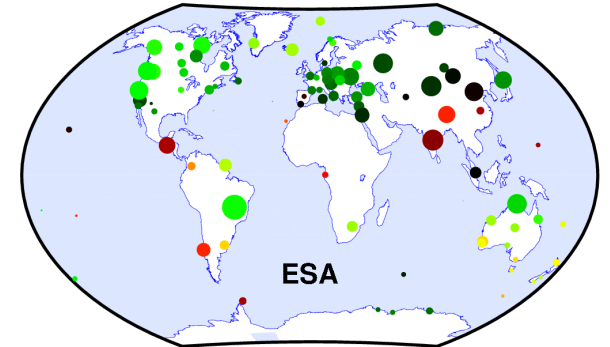
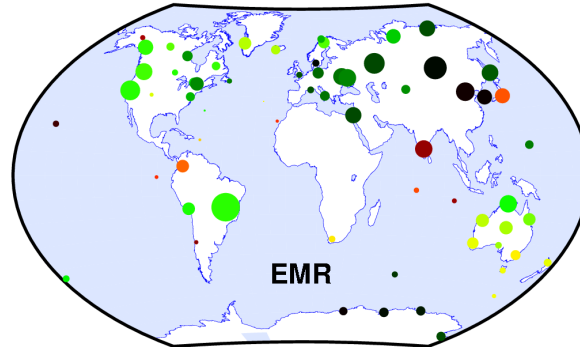
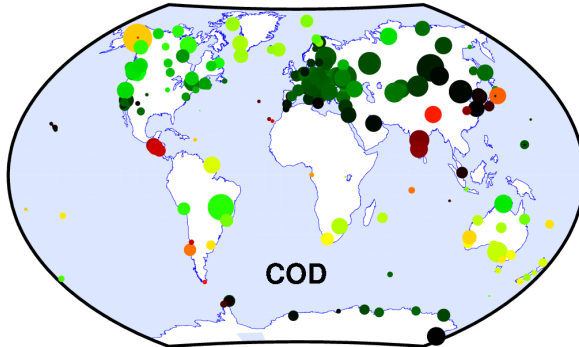
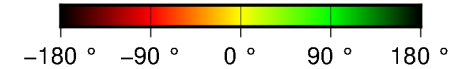
## 13.66 days ( $M_f$ tide) / 13.63 days (75,565 tide):

- Both lines visible in (almost) all 3 components of all ACs
- 13.63 day lines generally larger, although they correspond to a minor tide!?
- Much lower peaks for **JPL**: low-frequency error absorbed by **JPL**'s stochastic orbit parameters?
- Vertical peaks larger for **MIT/ULR**

# Spatial distribution of periodic signals

• 2.0 mm • 4.0 mm ● 10.0 mm

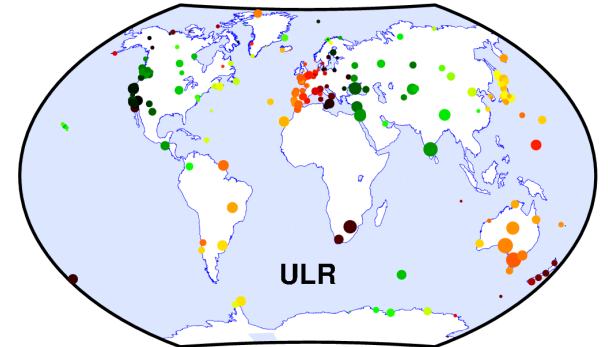
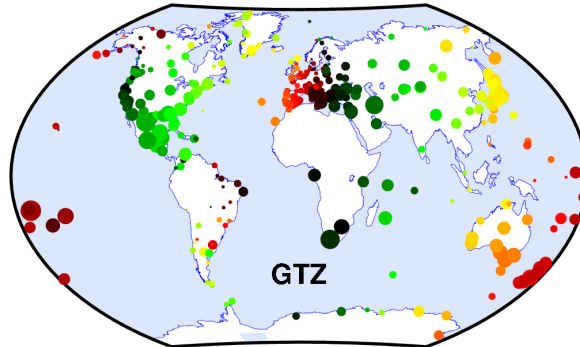
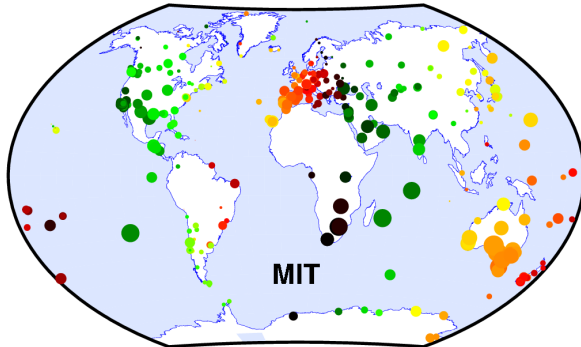
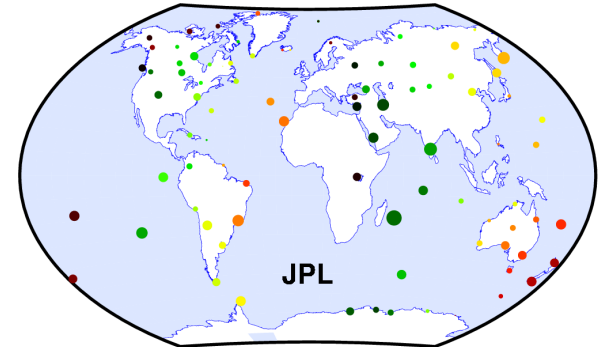
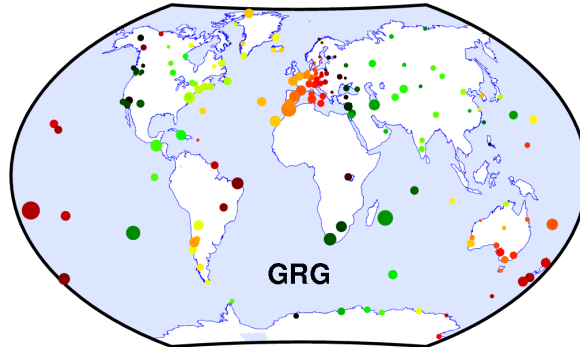
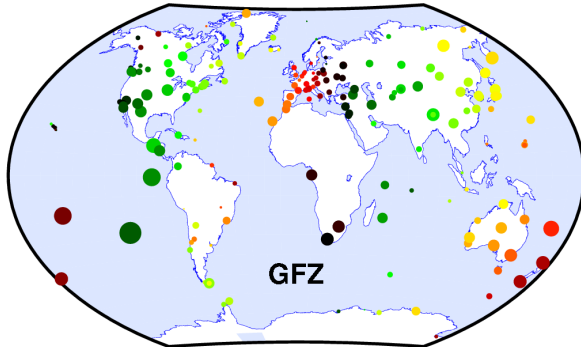
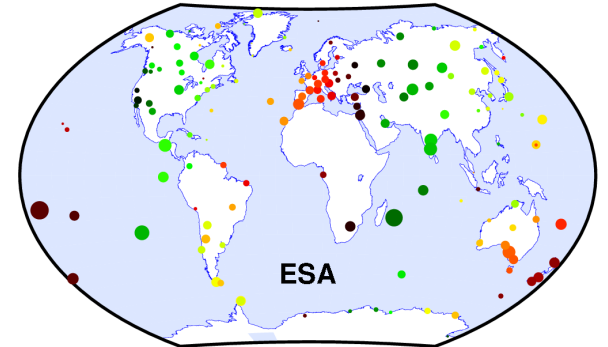
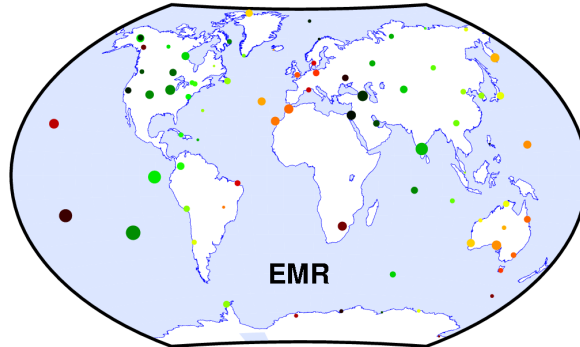
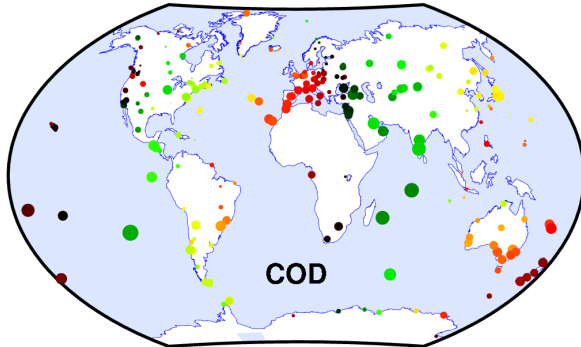
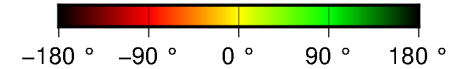
Annual – Height



# Spatial distribution of periodic signals

• 0.4 mm   • 0.8 mm   ● 2.0 mm

2<sup>nd</sup> draconitic harmonic – East

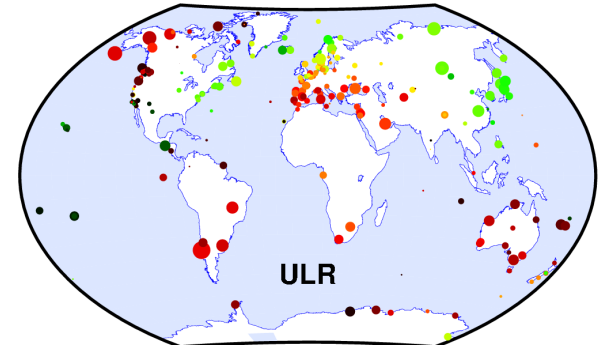
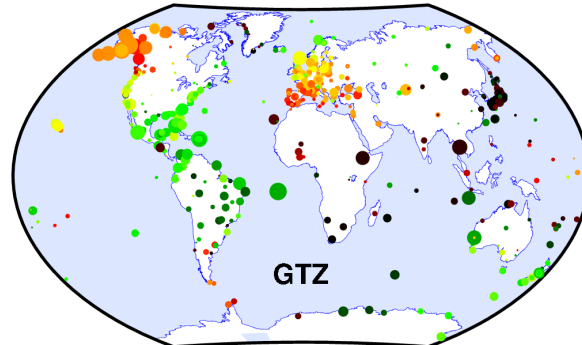
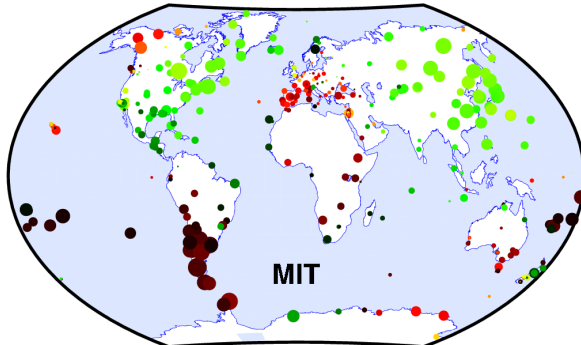
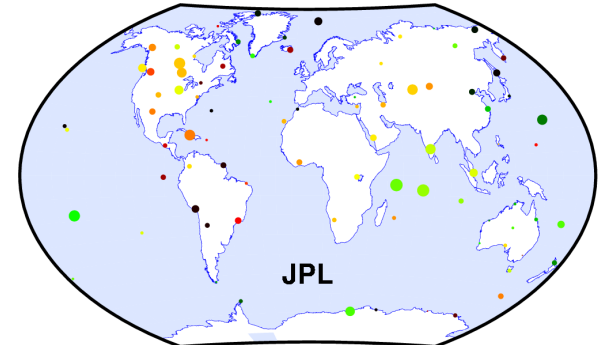
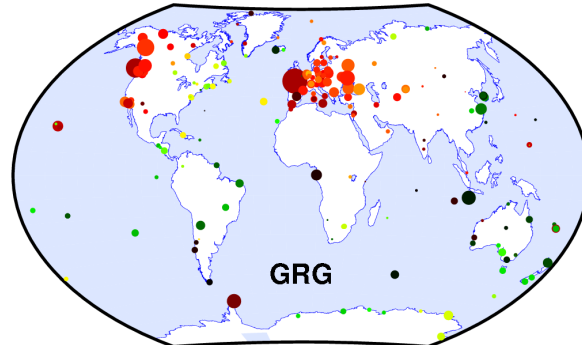
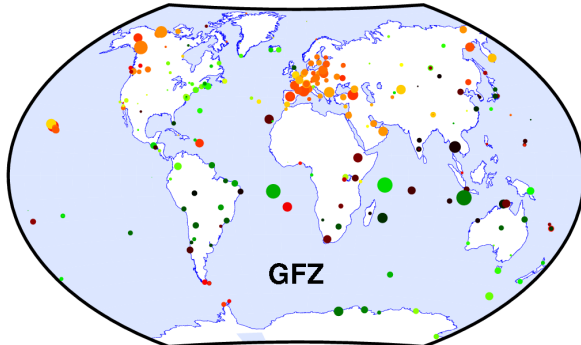
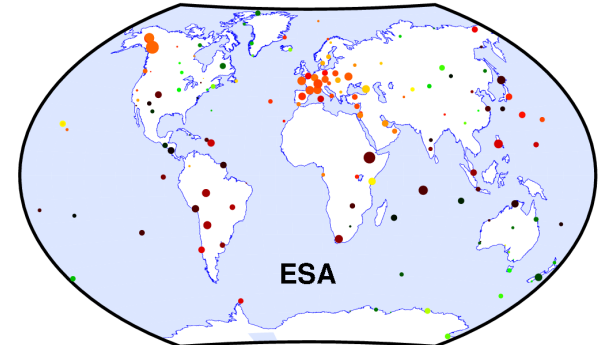
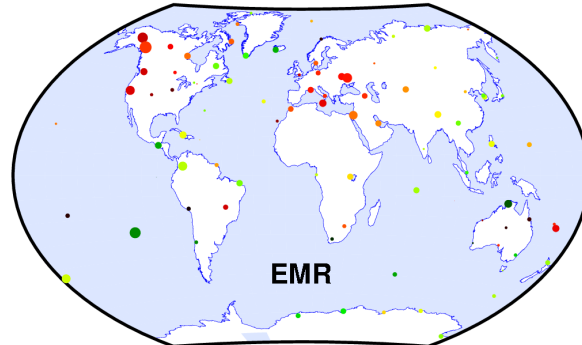
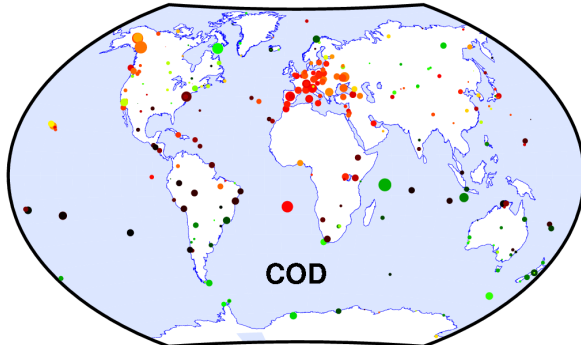
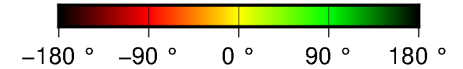




# Spatial distribution of periodic signals

• 0.1 mm • 0.2 mm ● 0.5 mm

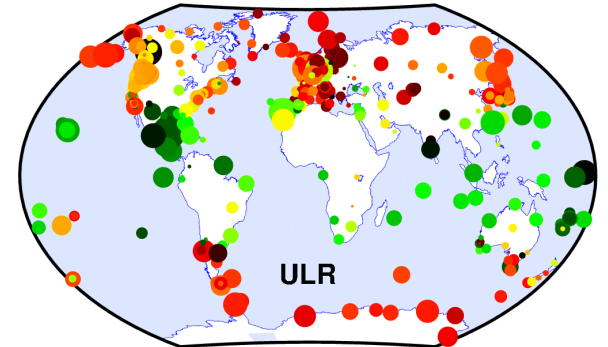
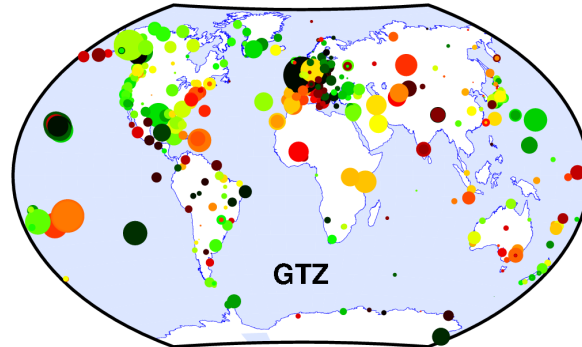
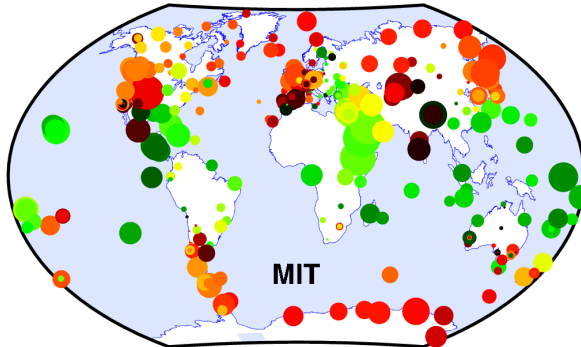
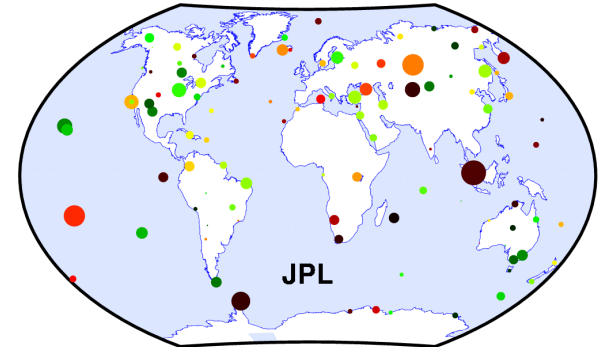
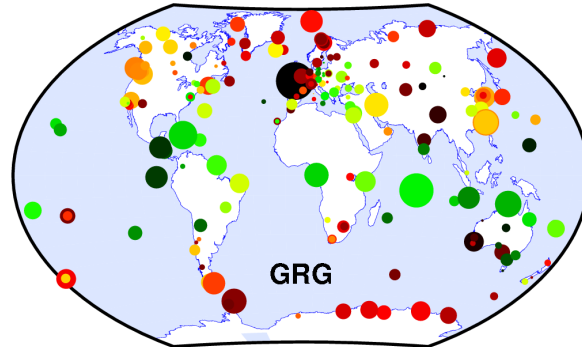
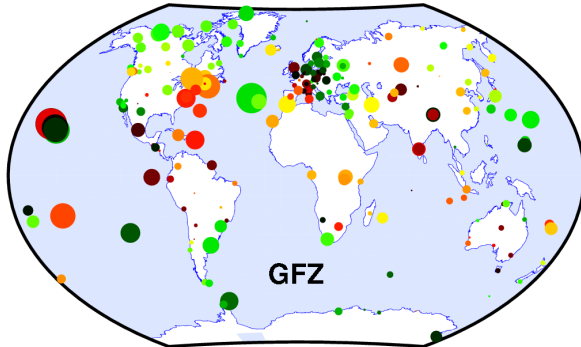
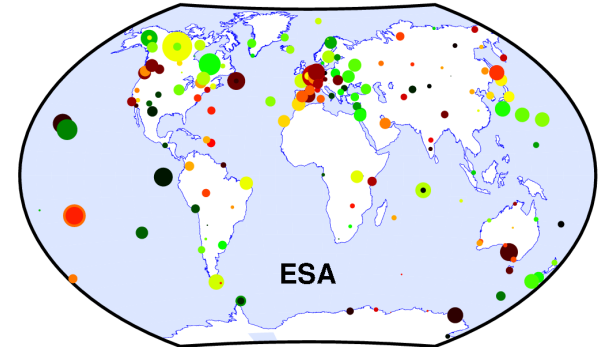
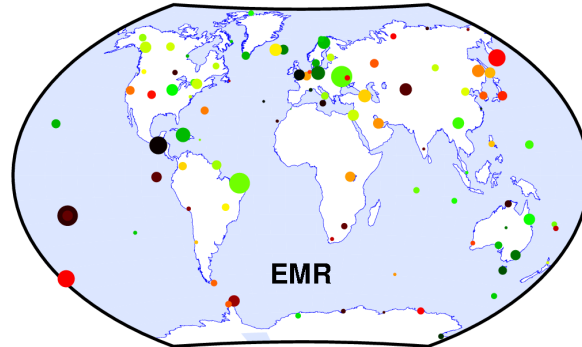
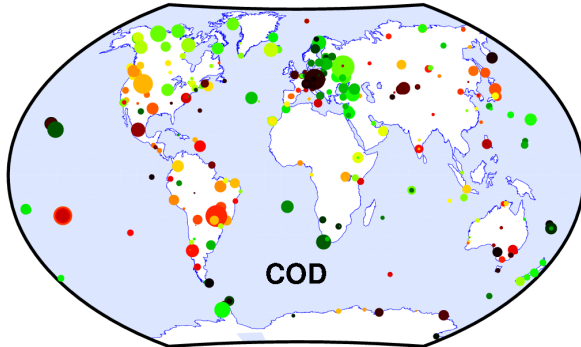
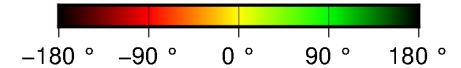
14.77 days – North



# Spatial distribution of periodic signals

• 0.2 mm • 0.4 mm ● 1.0 mm

13.63 days – Height





# Spatial distribution: summary

- **Annual / semi-annual:**
  - Visually good inter-AC consistency
- **Draconitics:**
  - Strong spatial correlations for low harmonics
    - Main orbit-related source
  - Maps generally similar amongst ACs up to the 4<sup>th</sup> harmonic
    - Possibly common modeling errors
- **Fortnightly band:**
  - 14.76 & 14.19 days (aliases): large-scale correlations in horizontal signals, with some phase shifts between ACs
  - 13.63 days (direct): large-scale correlations, phase shifts between ACs, strong latitude-dependence for MIT/ULR and GRG's vertical signals

# Next steps

- **Analyze repro2 orbit and ERP discontinuities**
  - To better constrain the sources of draconitic and fortnightly signals
- **Analyze short baselines**
  - To help separating/quantifying local and global errors
- **Revisit consistency of repro2 time series with loading models**

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**Thank you for your attention!**