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NAVISP EL1-047 Final Presentation:

"An Innovative concept for the Risk Assessment of Geologic Hazards using GNSS and Solid Earth Tides"

Tidal Interplate Lithospheric Deformation of Earth



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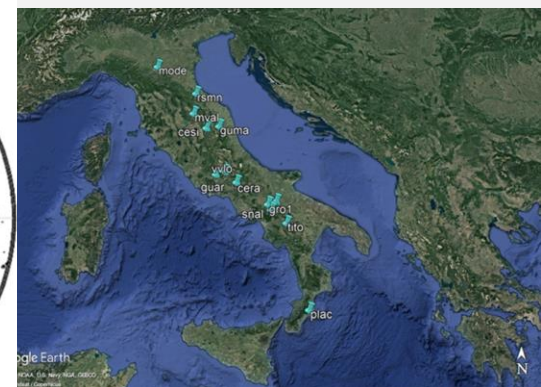
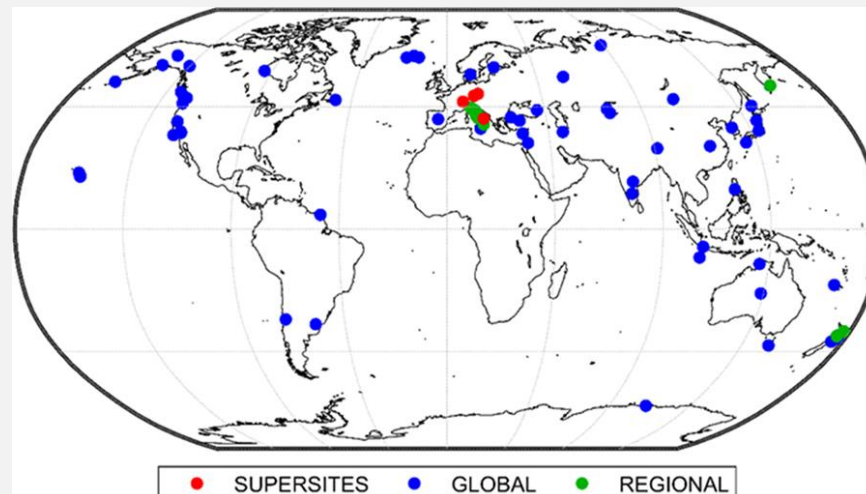
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1. Brief Introduction (Francesco)
2. GNSS PPP data processing strategies (JD)
3. Data filtering and LSET estimation (FV)
4. LSET vs GSET geodetic comparison (JD)
5. Scripts to prepare tectonic & EQ dataset (GN)
6. Geophysics framework: Tectonics & Tides (CD)
7. Results of LSET for Tectonics (FV)
8. Seismicity framework (CD)
9. Geophysics framework: Earthquakes & Tides (CD);
10. Results of LSET & Earthquakes Hazard (FV);
11. Volcanoes framework & Results (GN, FV);
12. Conclusions, Recommendations and Perspectives (FV, All);
13. Final Discussion (All)

1. Opportunity to estimate coordinates of GNSS by using PPP absolute approach;
2. Investigate if it can be defined a Local behaviour of SET which depend on position over Earth. In geodesy is currently applied IERS-2010 SET global model;
3. Understand if there is a correlation between LSET and Tectonics, Seismicity and Volcanic activities/hazards



- **GNSS processing preparation**

- Network & site selection, data & metadata download, quality control
- Testing and optimizing the processing strategy
- Testing and comparing potential precise products

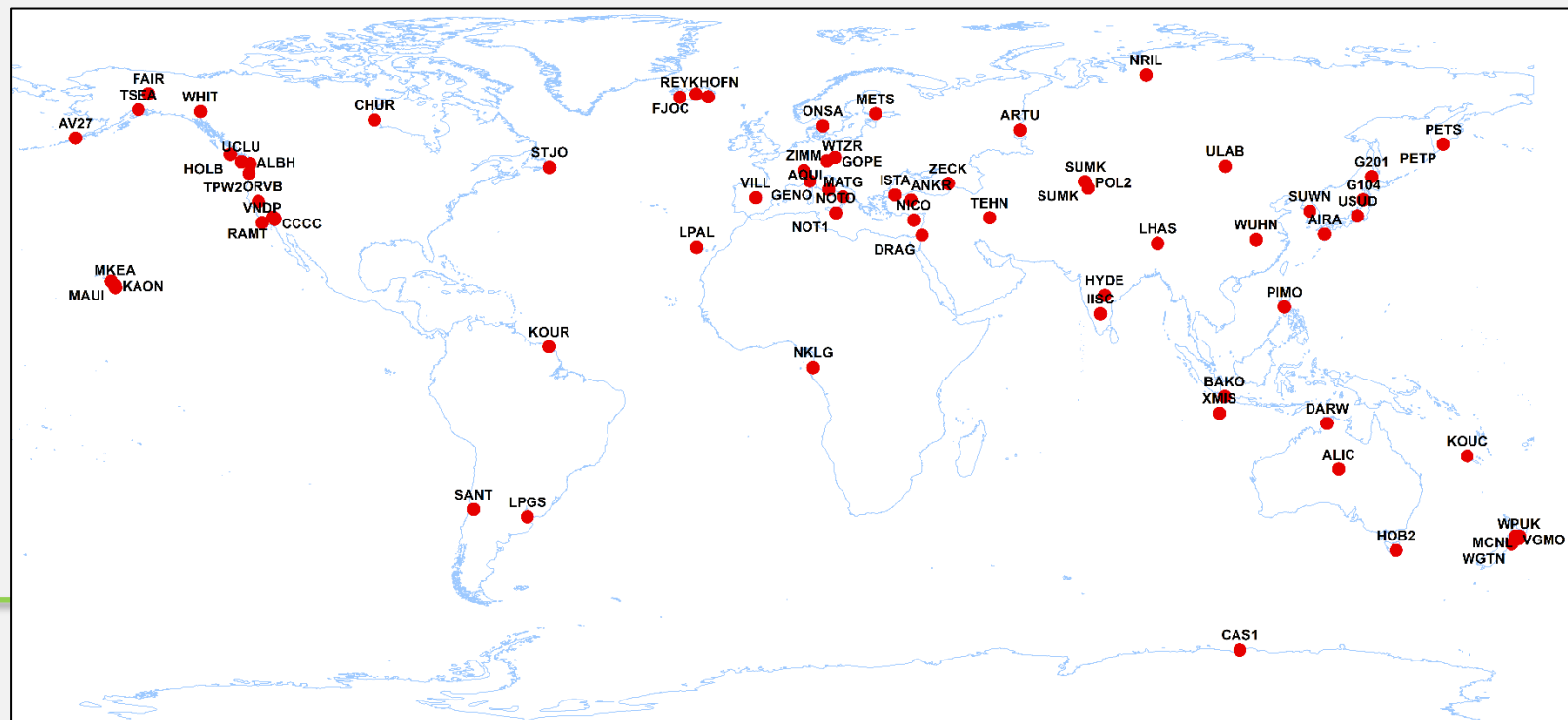
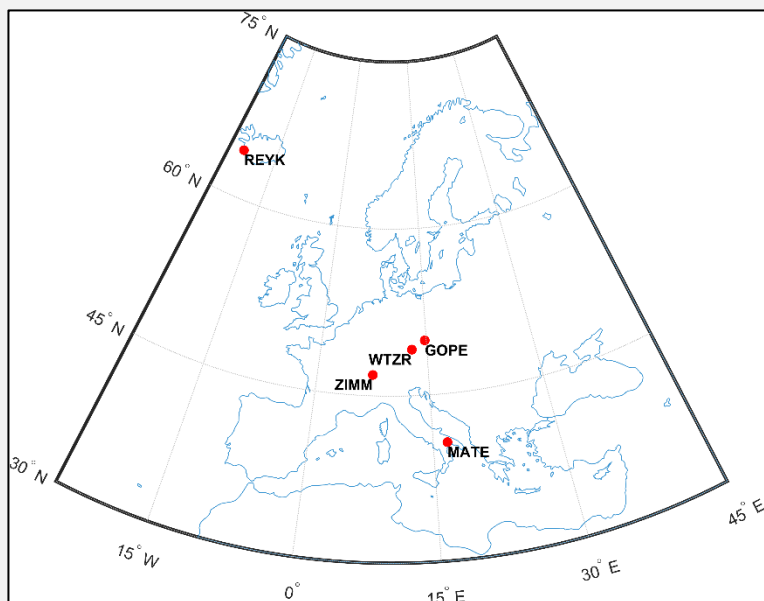
- **GNSS processing design (initial testing)**

- Checking coordinates residuals and repeatability
- Specific processing variants (sub-daily/weekly solutions)
- Defining exchange format, data filtering

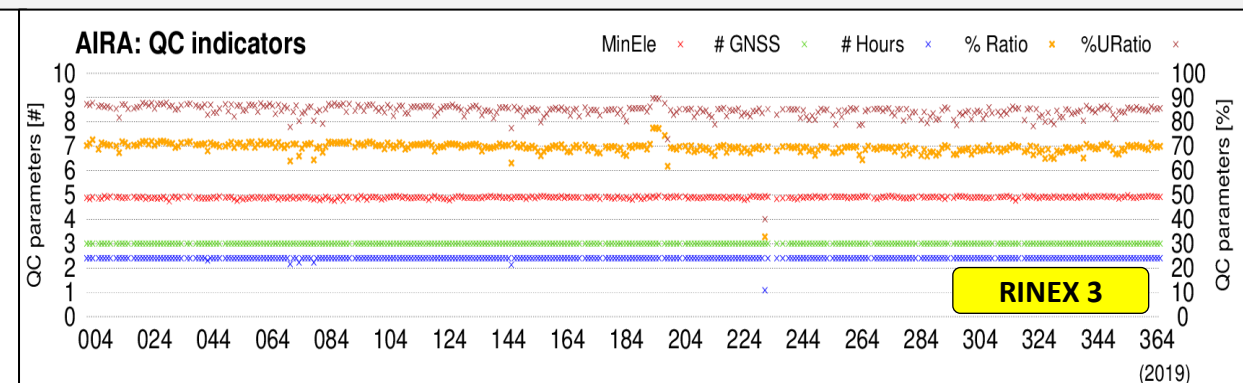
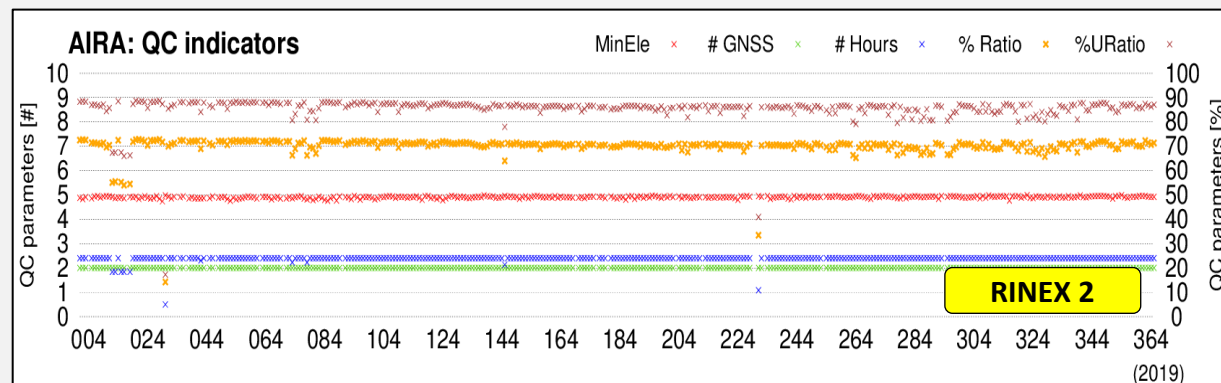
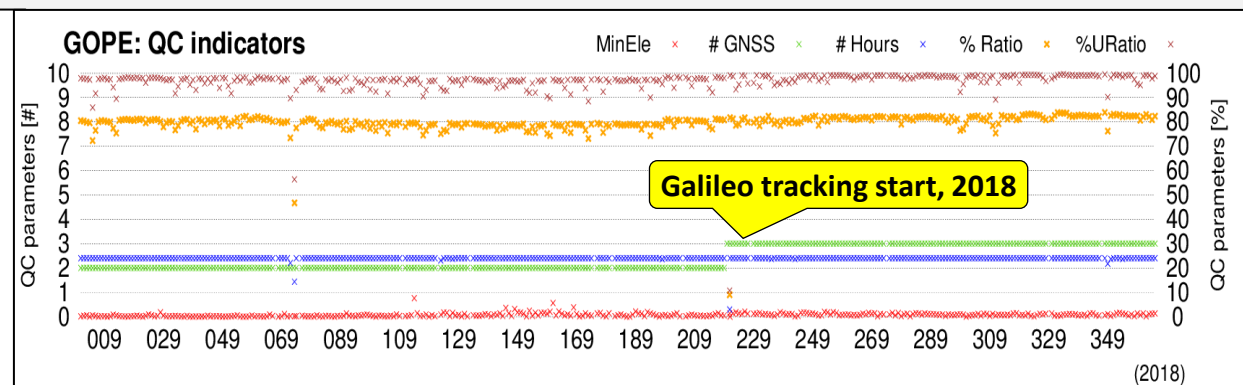
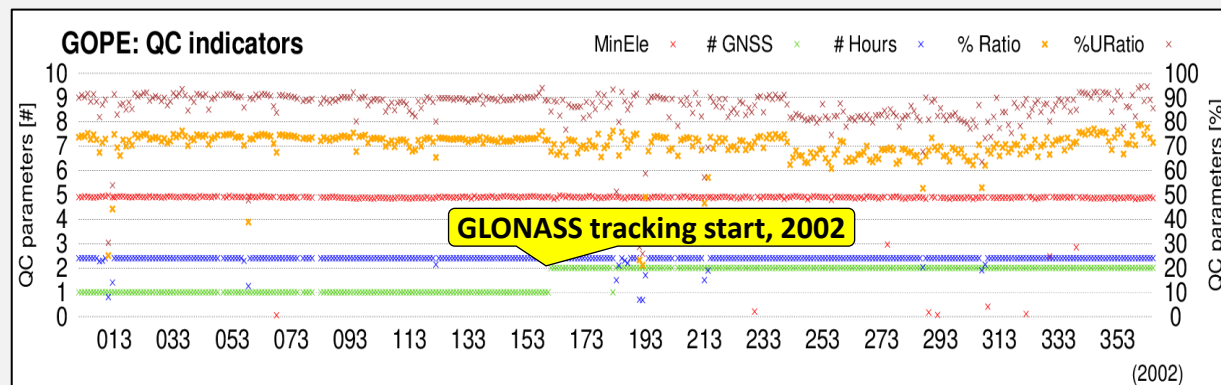
- **GNSS processing results (1st and 2nd run)**

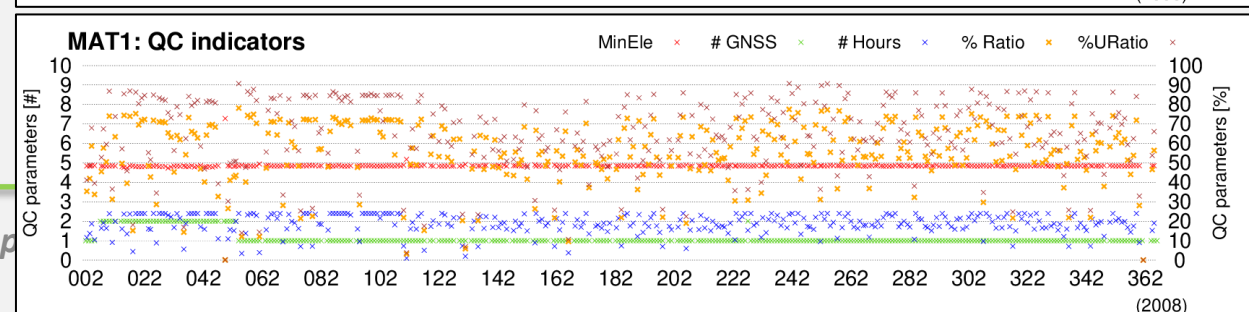
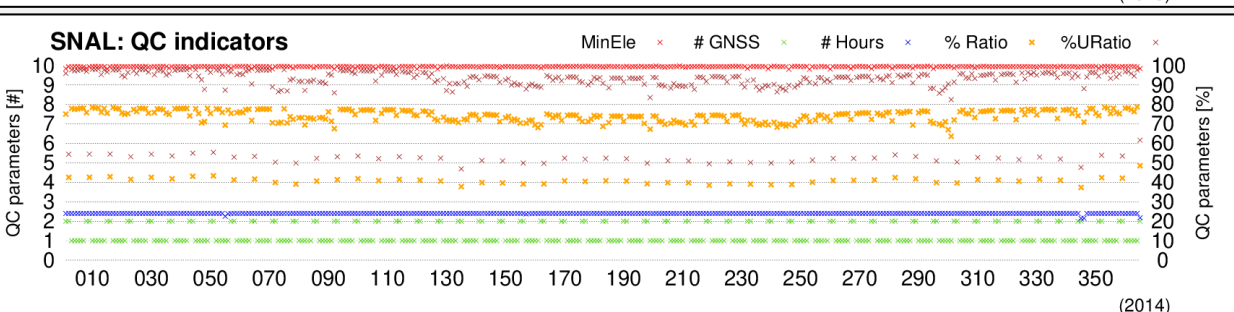
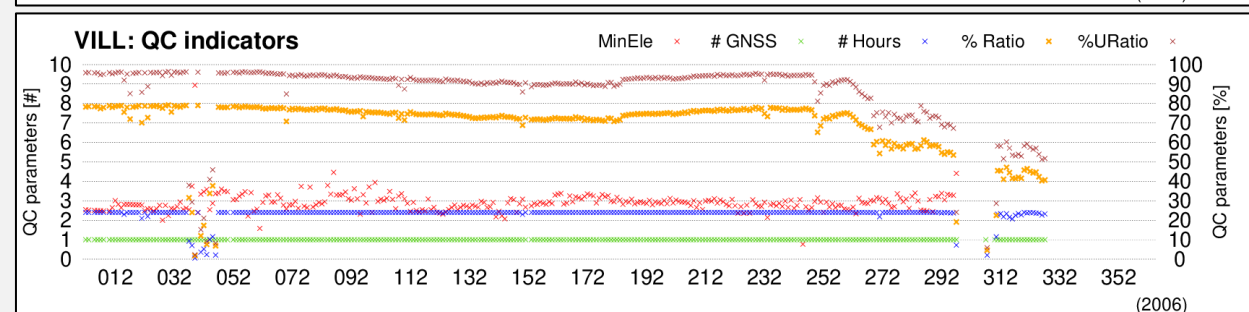
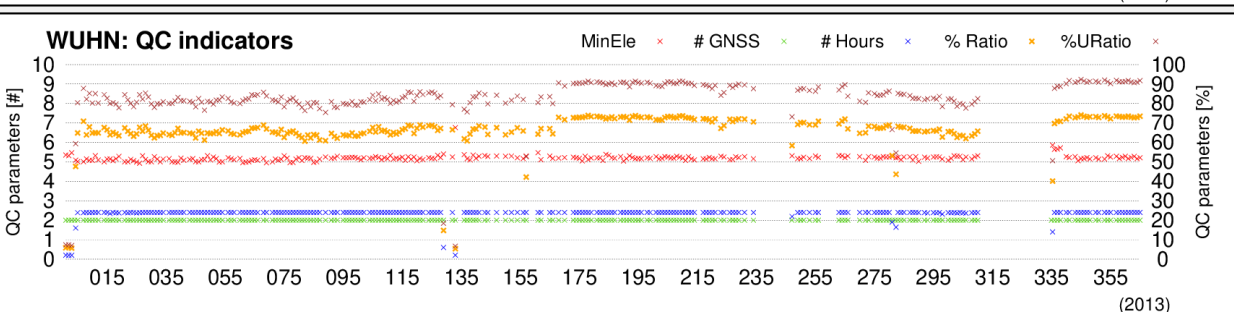
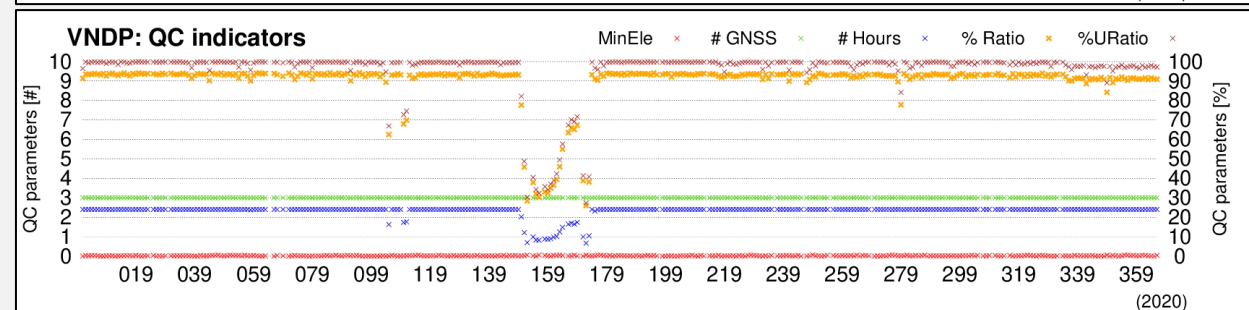
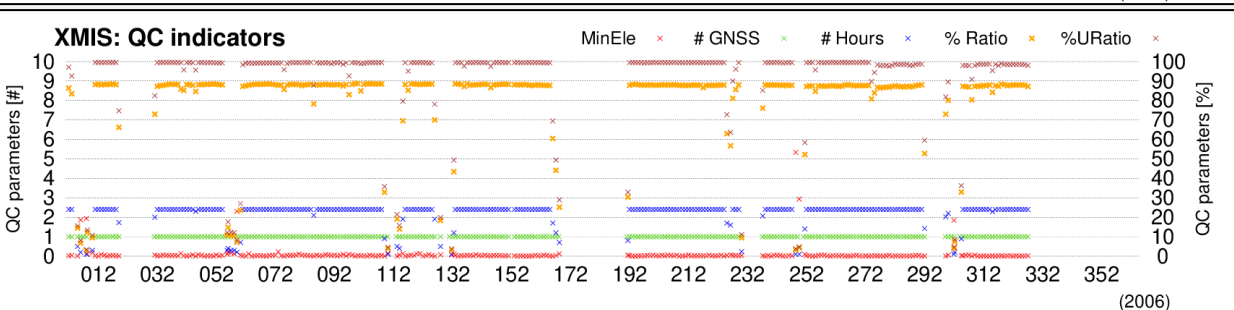
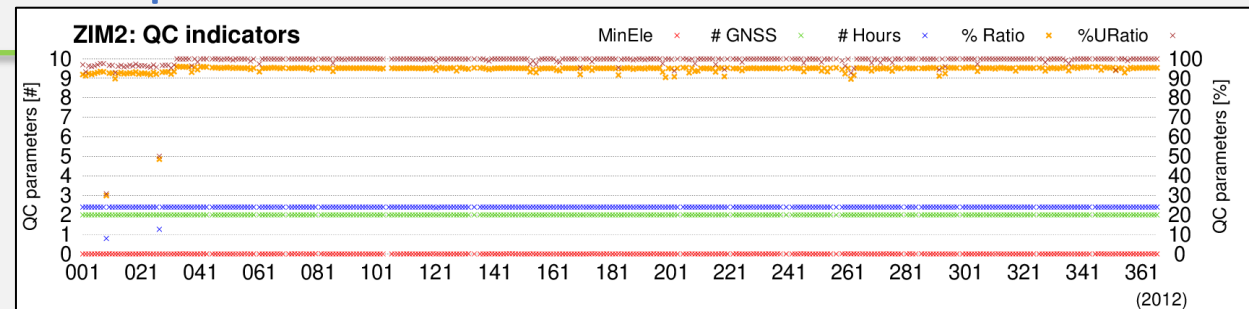
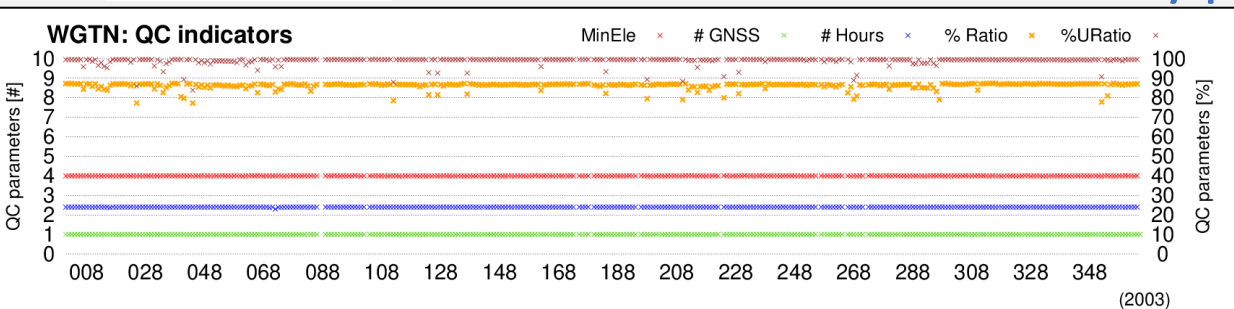
- Long-term global vs. high-resolution regional production
- Specific variants for the solid earth tide modelling
- Evaluation of the results

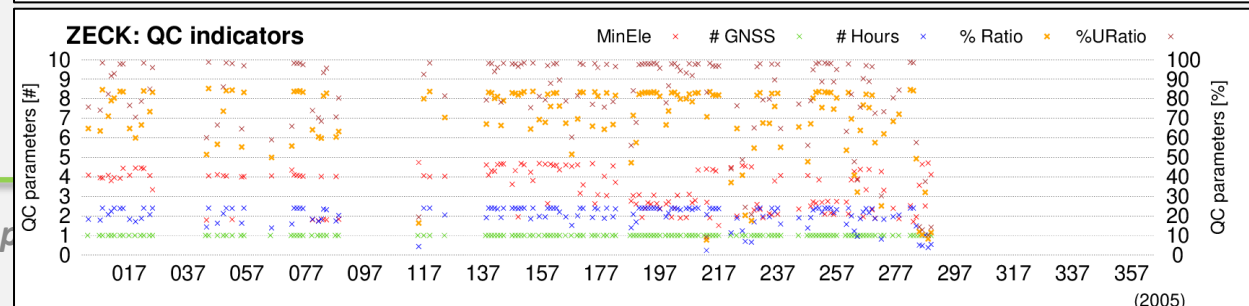
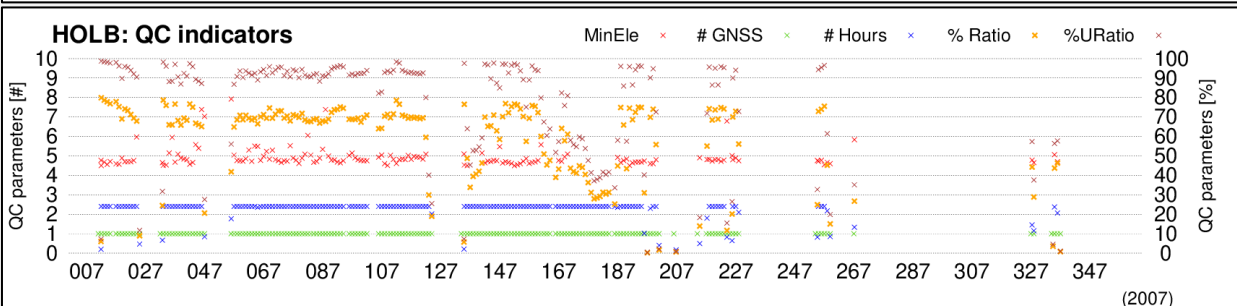
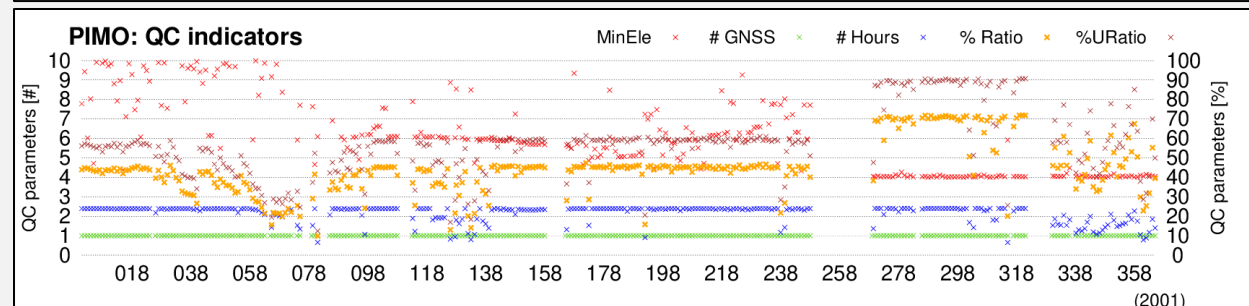
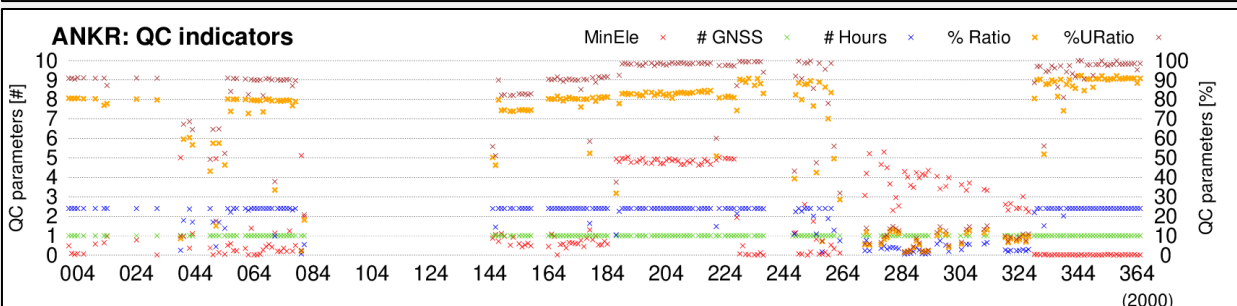
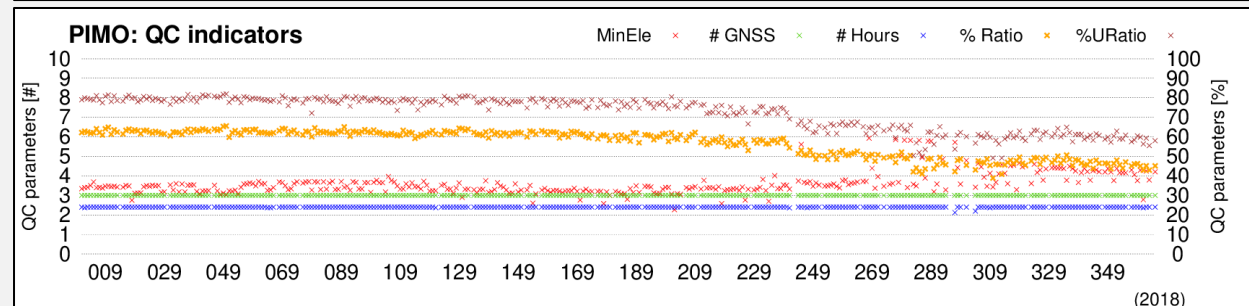
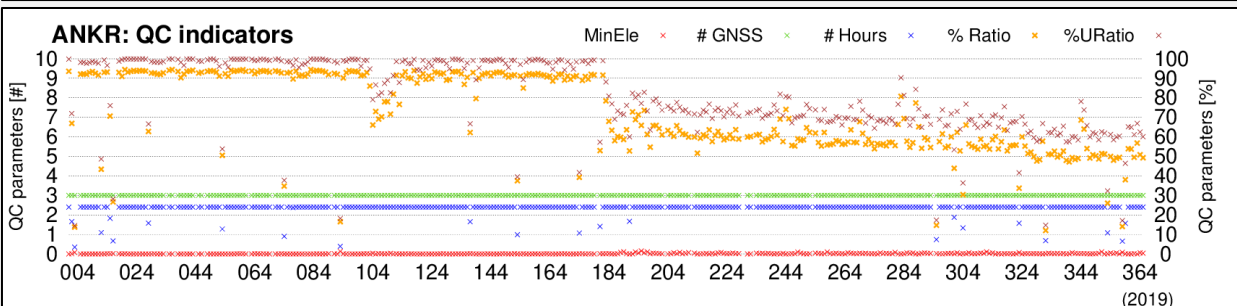
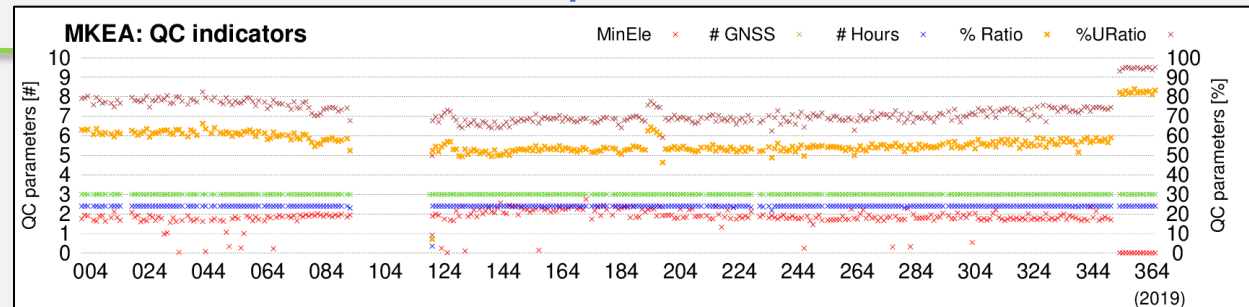
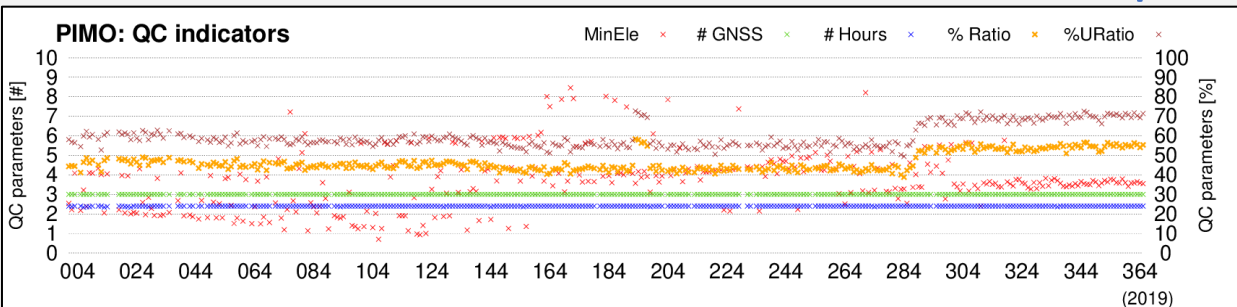
- Station selection: global data, hazard area, super-sites, long-time series,
- Data centers: IGS, UNAVCO, EUREF, RING, GEONET (NZ), USCD/SOPAC
- Metadata: site-log files
- Data: RINEX 2 (GPS+GLO) + RINEX 3 (+ Galileo)
- Period: as long as possible (optimally 2000-2020)



- Software: **G-Nut/Anubis Pro 3**
- Processing all collected RINEX v2 and v3 for quantitative, qualitative and complex control
- Visualizing key parameters for minimalistic plots (to easy cross-check with PPP solutions)
 - # GNSS, Data length, Have/Exp observations (0deg/15deg), minimum elevation angle
- Collecting key info on sites, evolution of data (observation/system availability, data quality, quantity)







SUPERSITE solution (as long as possible)

few selected stations (or dual-stations)

→ Essential for strategy testing and validation

GLOBAL solution (2000-2020, or as long as possible)

as many as possible stations (optimally all)

basic solution variants (GPS+GLONASS all the time, +Galileo)

→ Essential for generating long-term homogeneous coordinate time-series worldwide

REGIONAL solution (2015-2020, or longer if possible)

specific areas/stations for geohazard monitoring

additional solution variants (focus on multi-constellation, sub-daily sampling, etc.)

→ Essential for correlation to geohazard assessment

Optimizing the processing strategy:

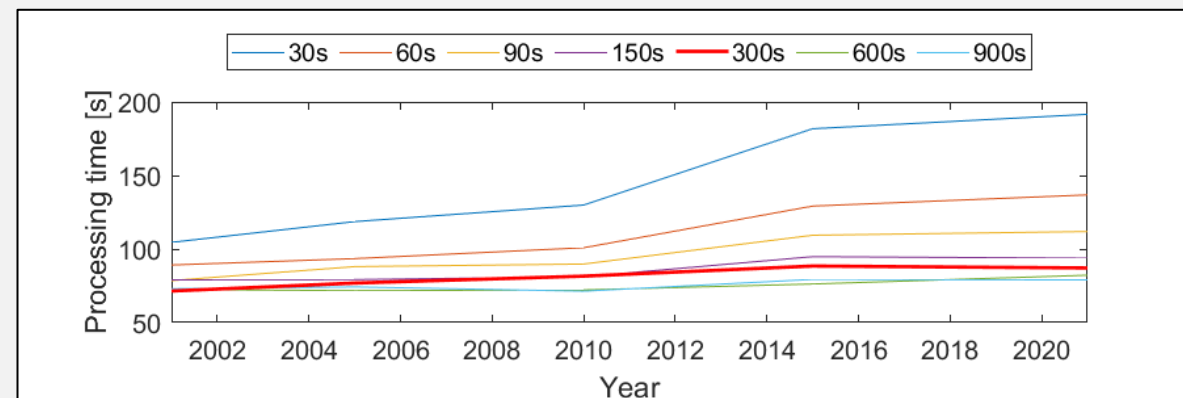
Sampling: observation data, resulting coordinates

Strategy: window, observations, parameter setup, models, multi-constellation etc.

Inputs : RINEX 2/3, precise products, precise models

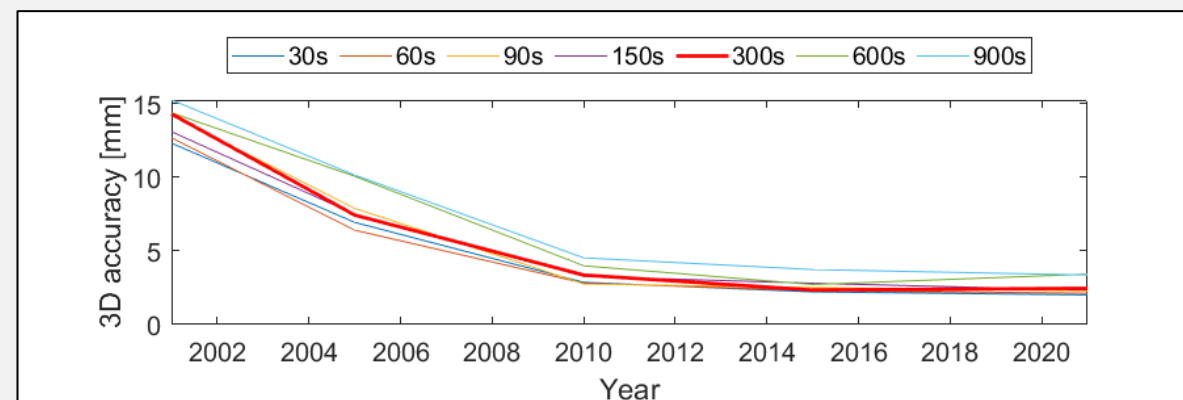
Processing time vs. processing sampling rate:

- The mean processing time of daily solutions at each site over the years.
- 30/60/90/150/300/600/900s data sampling
→ **300s interval accepted**



Accuracy vs. processing sampling rate:

- 30/60/90/150/300/600/900s data sampling
→ **300s interval accepted**

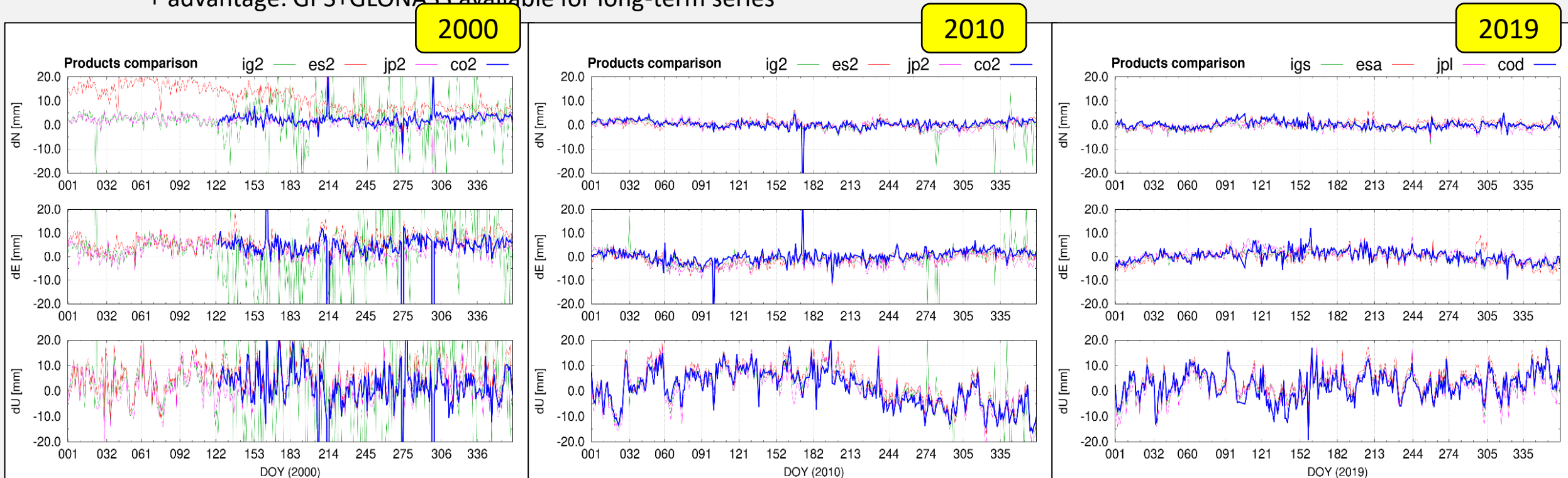


Candidates: IGS, individual ACs Repro2 (<2013, <2015) and operational production

- Comparison of precise products from IGS and selected ACs: ESA, JPL, EMR, GRG, CODE
 - GPS-only solution
- Worse performance of the IGS products, namely due to satellites clock corrections
 - robustness of the combination process, AC systematic errors, clock alignment, etc.

➔ **CODE Repro2 & operational products accepted at that time**

+ advantage: GPS+GLONASS available for long-term series



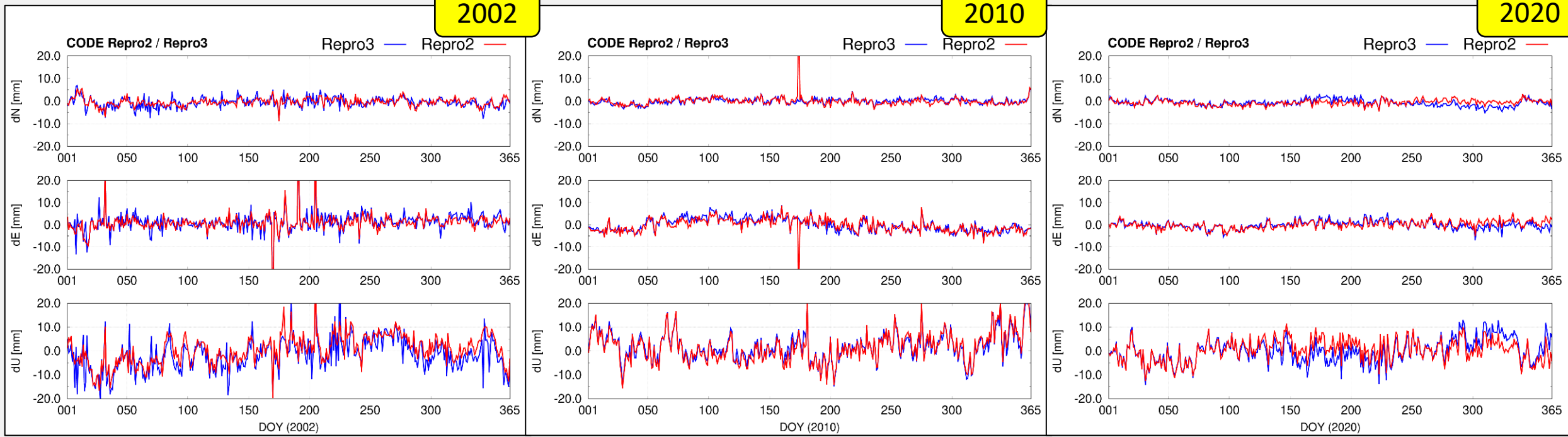
Repro3 has been finished by several IGS ACs (we contacted CODE and ESA ACs)

- **Comparison: CODE Repro2/oper × CODE Repro3 (2000–2020)**

- Initial test of the CODE Repro2 (CODE_2015) precise products with the new CODE Repro3
- CODE R3 is consistent throughout the entire period (2000-2020), **but for the first year the clock files (still missing)**
we also observed offset in height compared to existing solution (e.g. IGS, EUREF), probably due to new scale & scale rate in ITRF2020!
- No IGS combination, just first (external) validation of the CODE R3 product (few issues in 2000-2001)

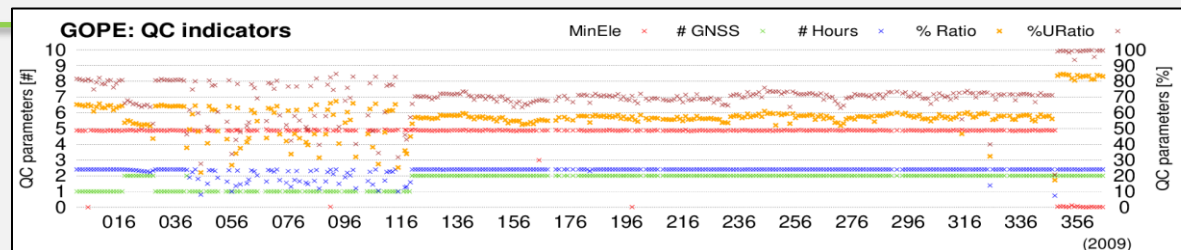
➔ **CODE Repro3 selected for the final solution** (no need for operational products)

further advantage: GPS+GLONASS+Galileo support, ATX with Galileo PCV, high-resolution products, attitude models, phase+code biases ...



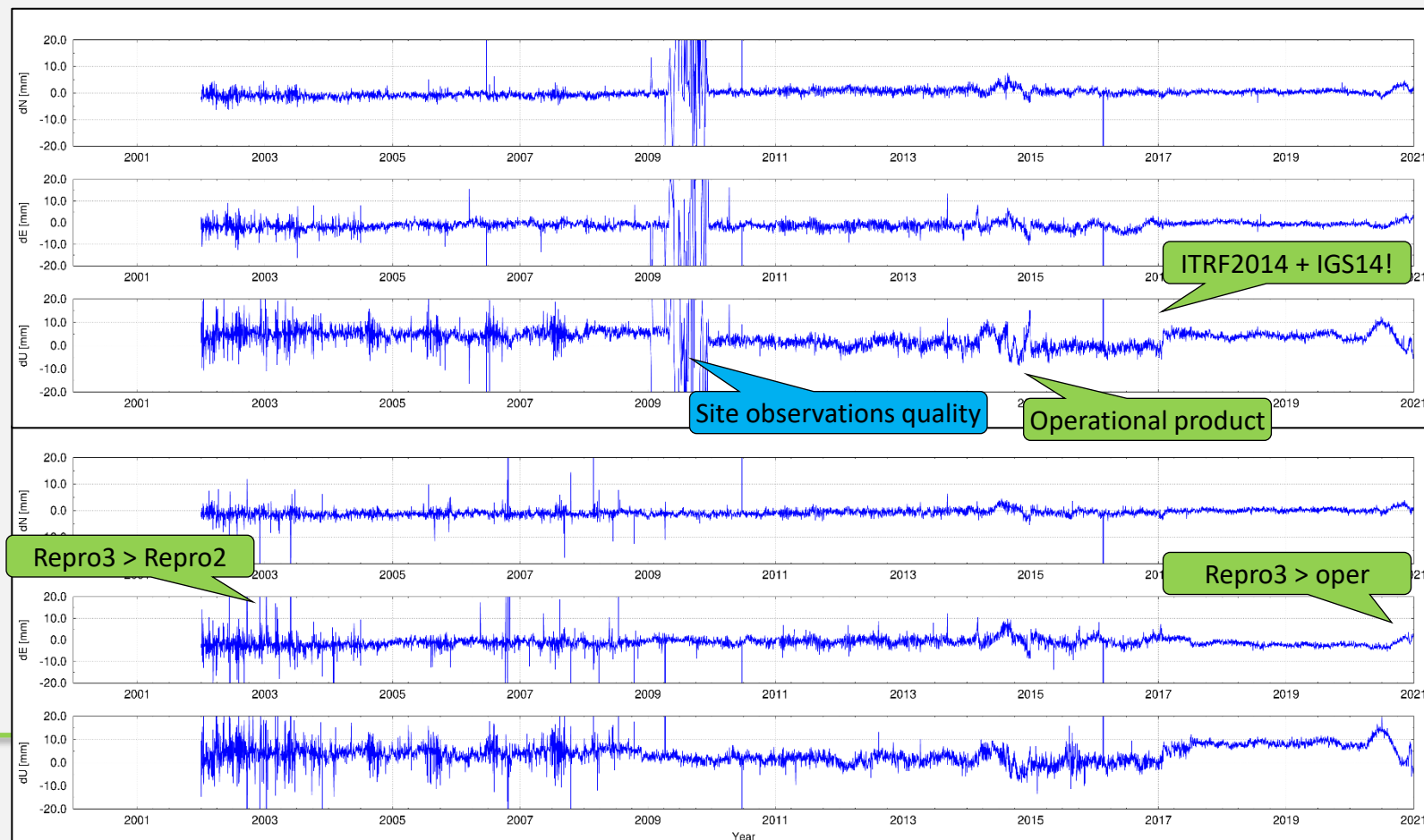
Supersites:

Repro2 – Repro3 differences:



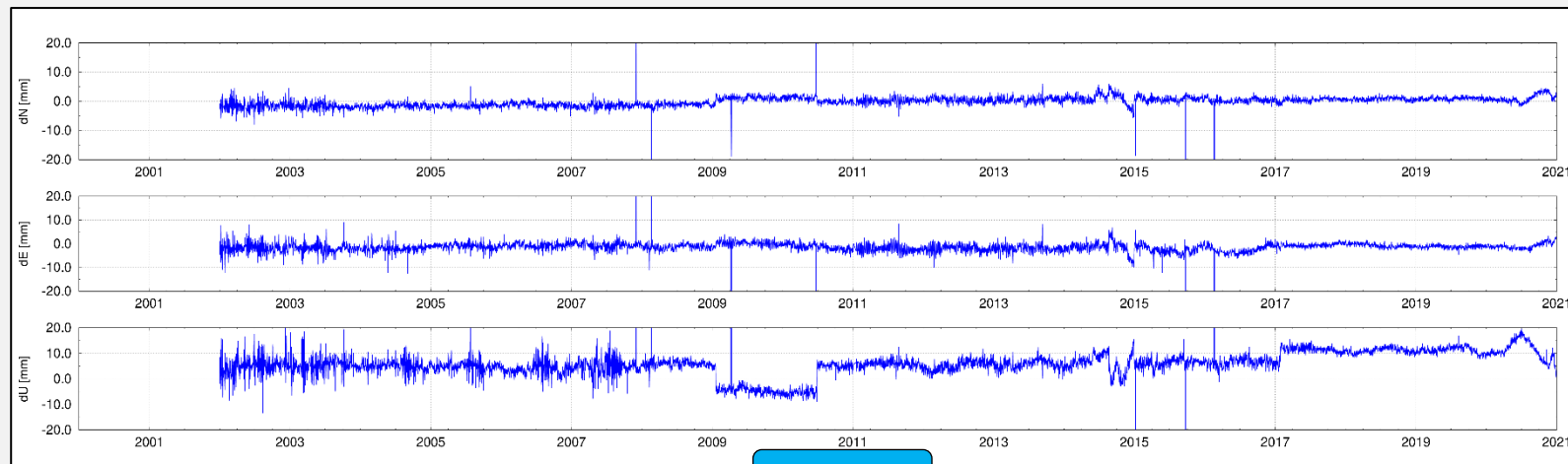
GOPE

MATE



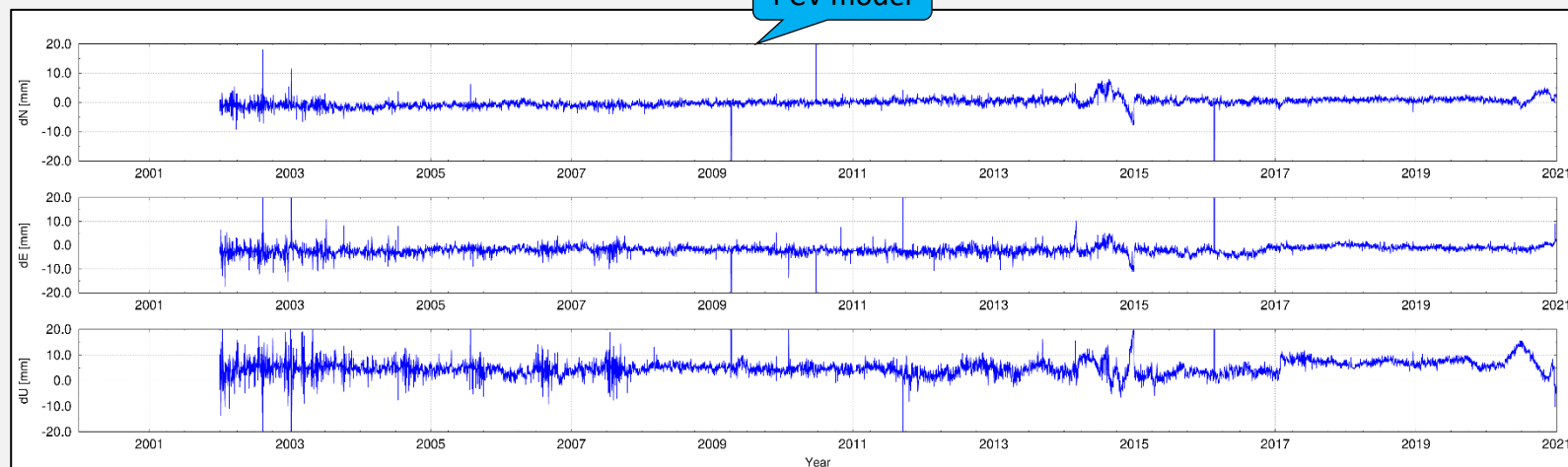
**Supersites:
Repro2 – Repro3 differences:**

WTZR



PCV model

ZIMM

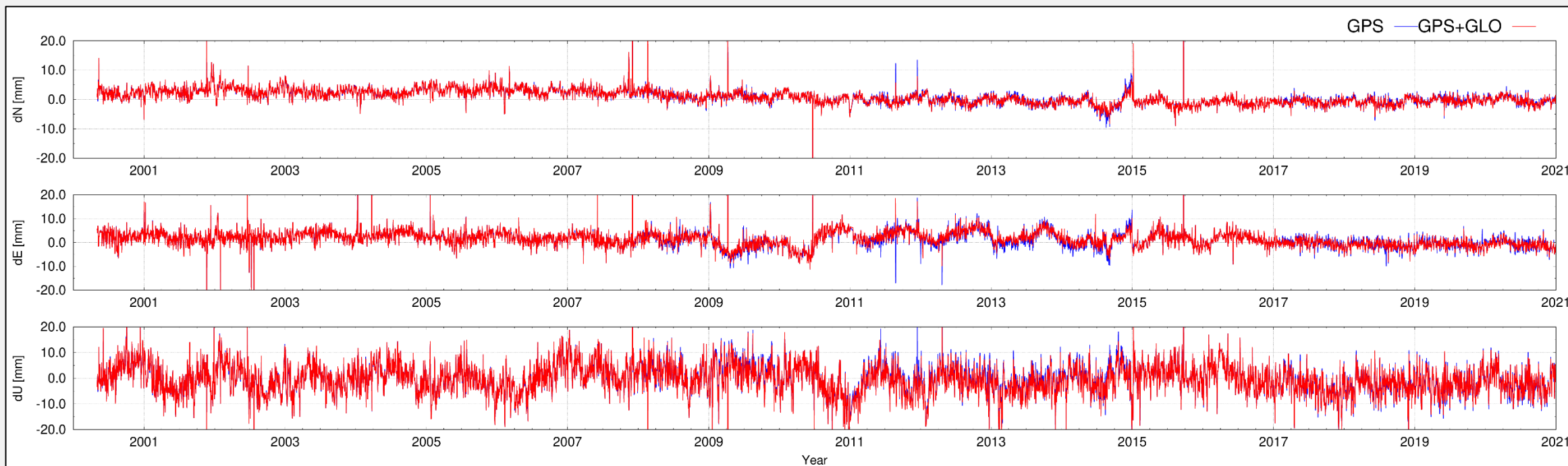


GNSS/PPP:

- Software: **G-Nut/Geb software**
- Ionosphere-free linear combination (*+testing raw-model*)
- float ambiguity resolution (*+testing ambiguity fixing*)
- CODE Repro3 satellite orbits & clocks
- GOP's consolidated multi-GNSS broadcast orbits (*identify healthy satellites*)
- IERS Conventions 2010 solid Earth tides and ocean tide loading (**+ enabling on/off settings**)
- ATX for Repro3 (incl. Galileo satellite models)
- OTL model for selected stations – FES2014b
- **Estimated parameters:**
 - Station coordinates
 - Receiver clock + inter-system biases (*+ inter-frequency biases*)
 - Initial carrier-phase ambiguities as float numbers (*+ initial ambiguities resolved to integers*)
 - Zenith tropospheric delays + horizontal linear tropospheric gradients

GPS only / GPS + GLONASS

- Combined GPS + GLONASS solution provides better results compared to GPS-only
- Combination of GPS + GLONASS used for the SUPERSITE and GLOBAL variants for the period 2000-2020



Optimizing processing strategy:

GPS only / GPS + GLONASS / GPS + GLONASS + Galileo

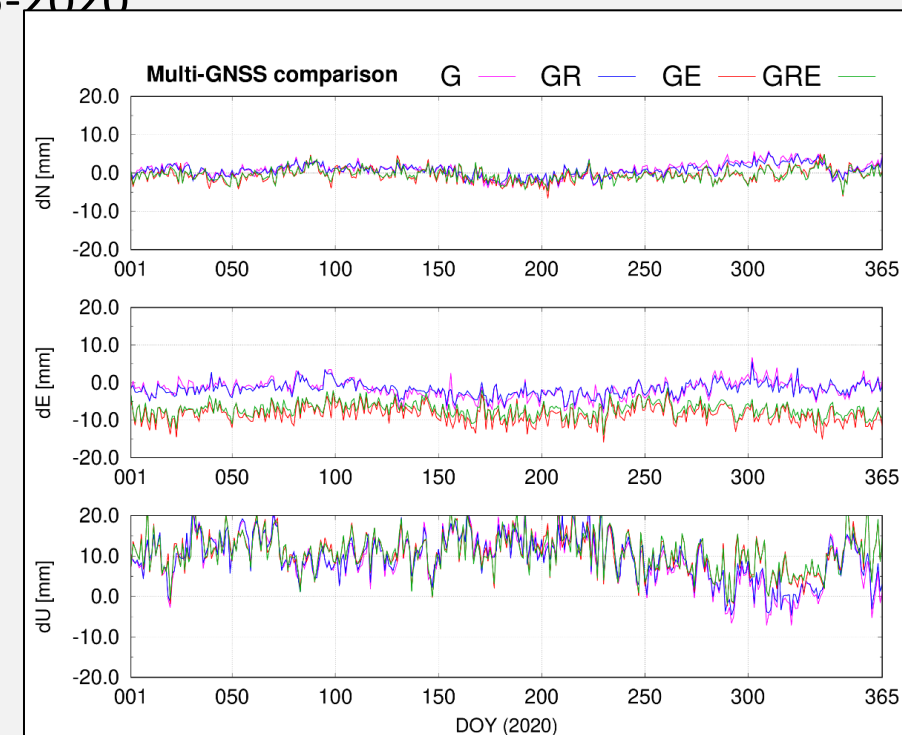
Inclusion of multi-GNSS observations improves the solution accuracy

Combination of GPS + GLONASS + Galileo used for the period 2015-2020

Galileo used only from RINEX 3 data

WTZR

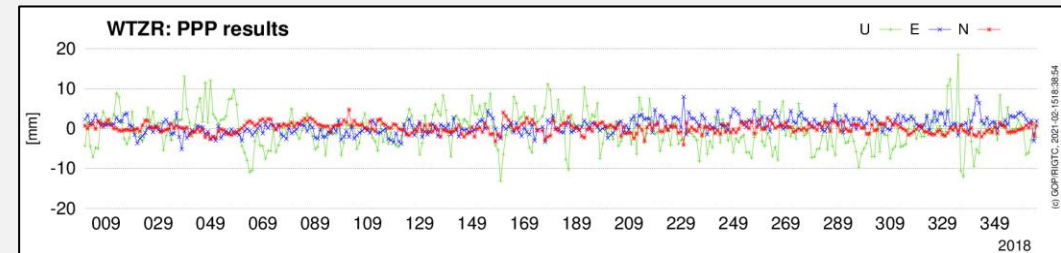
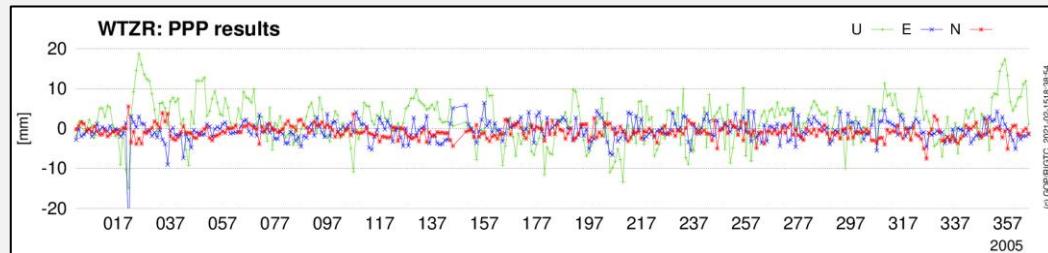
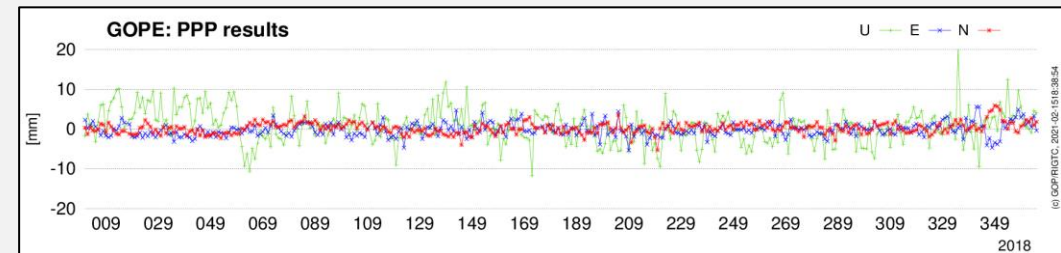
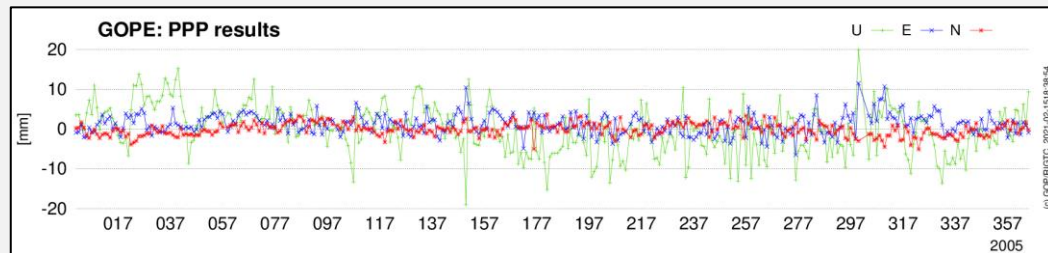
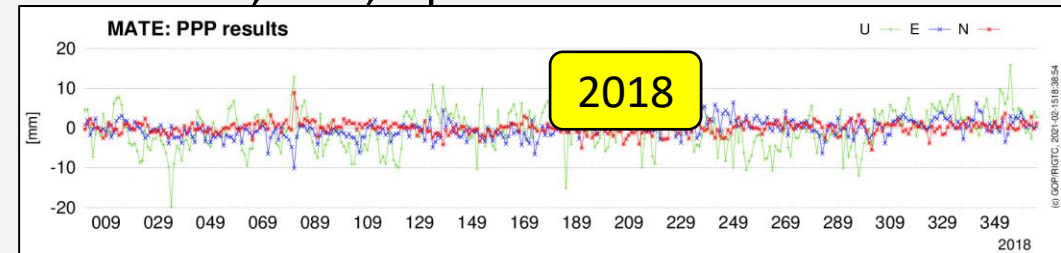
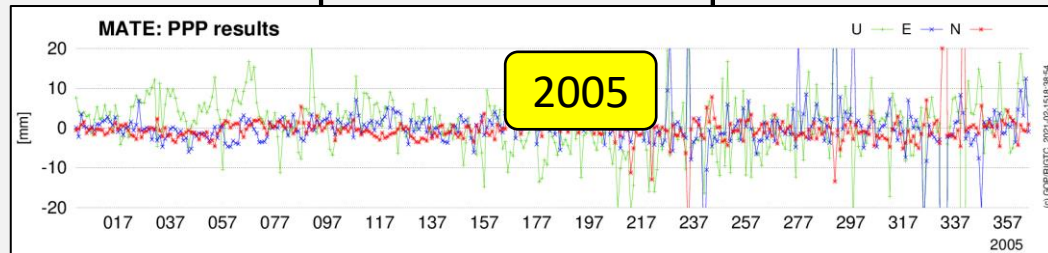
GNSS	s_N [mm]	s_E [mm]	s_U [mm]	s_{3D} [mm]
GPS	1.8	2.4	6.8	7.4
GPS + GLO	1.6	1.9	6.3	6.7
GPS + GAL	1.6	2.7	5.2	6.1
GPS + GLO + GAL	1.4	2.3	4.9	5.6



Resulted coordinates compared to an internal LSM model

Internal LSM model applies a coordinate offset, linear trend, annual + semi-annual harmonic and steps (receiver antenna changes, earthquakes, ...)

Residuals expressed in local topocentric coordinates in North, East, Up directions

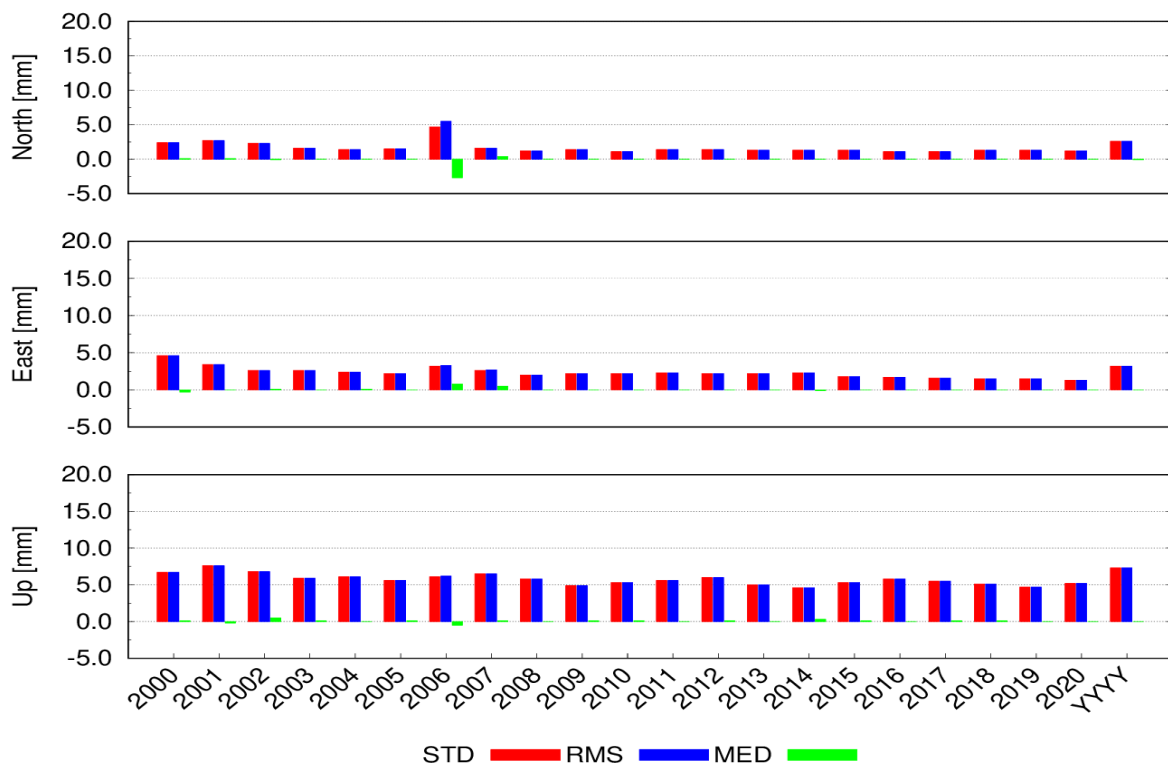


East component less accurate than North component due to the float ambiguity estimation

For CODE Repro3, the accuracy is more consistent over the full processing interval

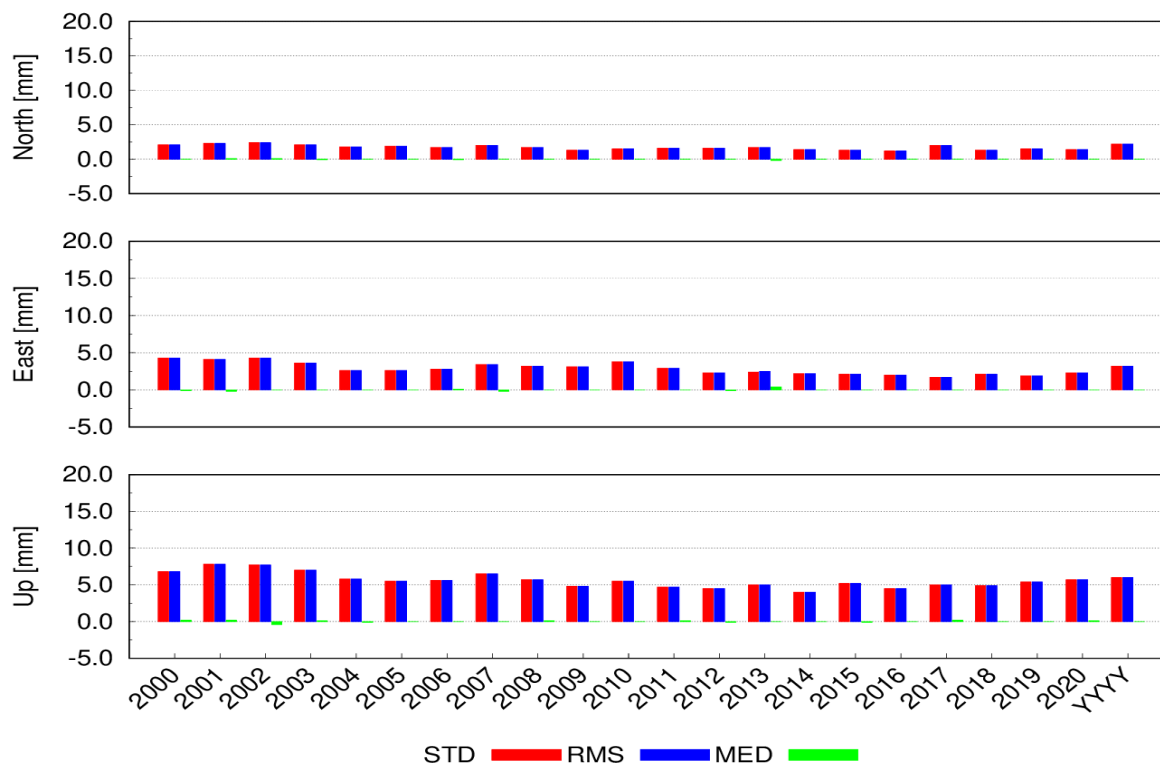
Degradations exists due to individual station data (the contribution from the product well reduced)

GOPE00CZE - SUP2 - 1D - IERS2010



(c) GOP/RIGTC, 2023-07-24 14:31:34

MATE00ITA - SUP2 - 1D - IERS2010



(c) GOP/RIGTC, 2023-07-24 14:31:36

Processing on daily basis (a standard strategy):

daily analysis = daily data and precise product, no reset of any parameters (reference solution)

Processing on weekly basis (a combined strategy):

weekly analysis = daily data and precise product, reset coordinates on a daily basis (reset of coordinates and/or ambiguities)

weekly combination = either a rigorous variance-covariance combination or a pure statistical weighted mean

Processing on sub-daily basis (an optimized strategy):

sub-daily analysis = daily data and products, reset coordinates (only!) on a sub-hourly basis

hourly solution significantly improved (by a factor of 1-3) → thanks to exploiting 'continuity' in estimated AMB, ZTD, GRD

Original solution (actual processing window)

Interval	s_N [mm]	s_E [mm]	s_U [mm]
24 h	2.0	2.3	5.0
12 h	2.9	3.7	7.5
6 h	3.7	4.8	8.9
3 h	4.5	6.9	10.3
1 h	16.3	21.2	19.3

Weekly solution with a sub-daily coordinates reset

Interval	s_N [mm]	s_E [mm]	s_U [mm]
24 h	2.1	2.4	5.2
12 h	3.0	3.7	8.2
6 h	4.0	4.8	10.6
3 h	5.3	6.2	13.1
1 h	6.9	7.9	14.1



- **GNSS processing**

- for Solid Earth Tide modelling (TECT)
- for tectonic hazards (TECT)
- for volcanic hazards (VOLC)

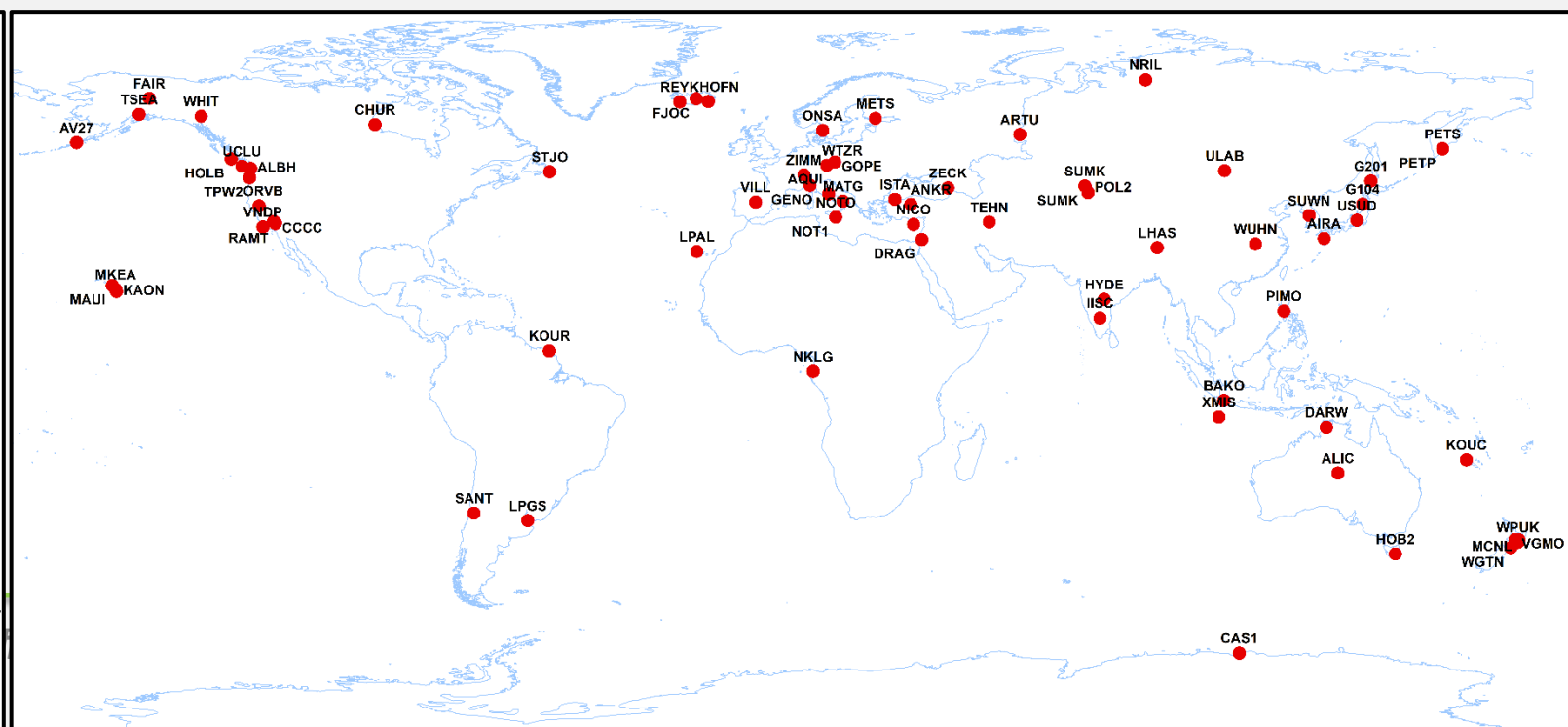
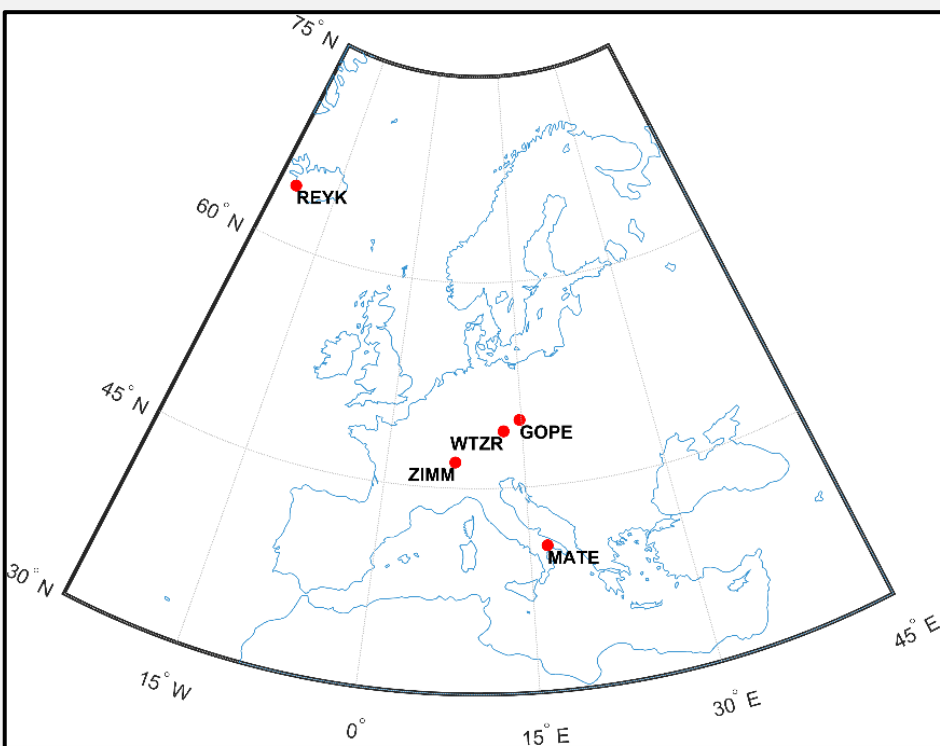
- **Networks:**

- TECT: global + supersites
- VOLC: regional (Stromboli, Volcano, Etna, Vesuvio from INGV)

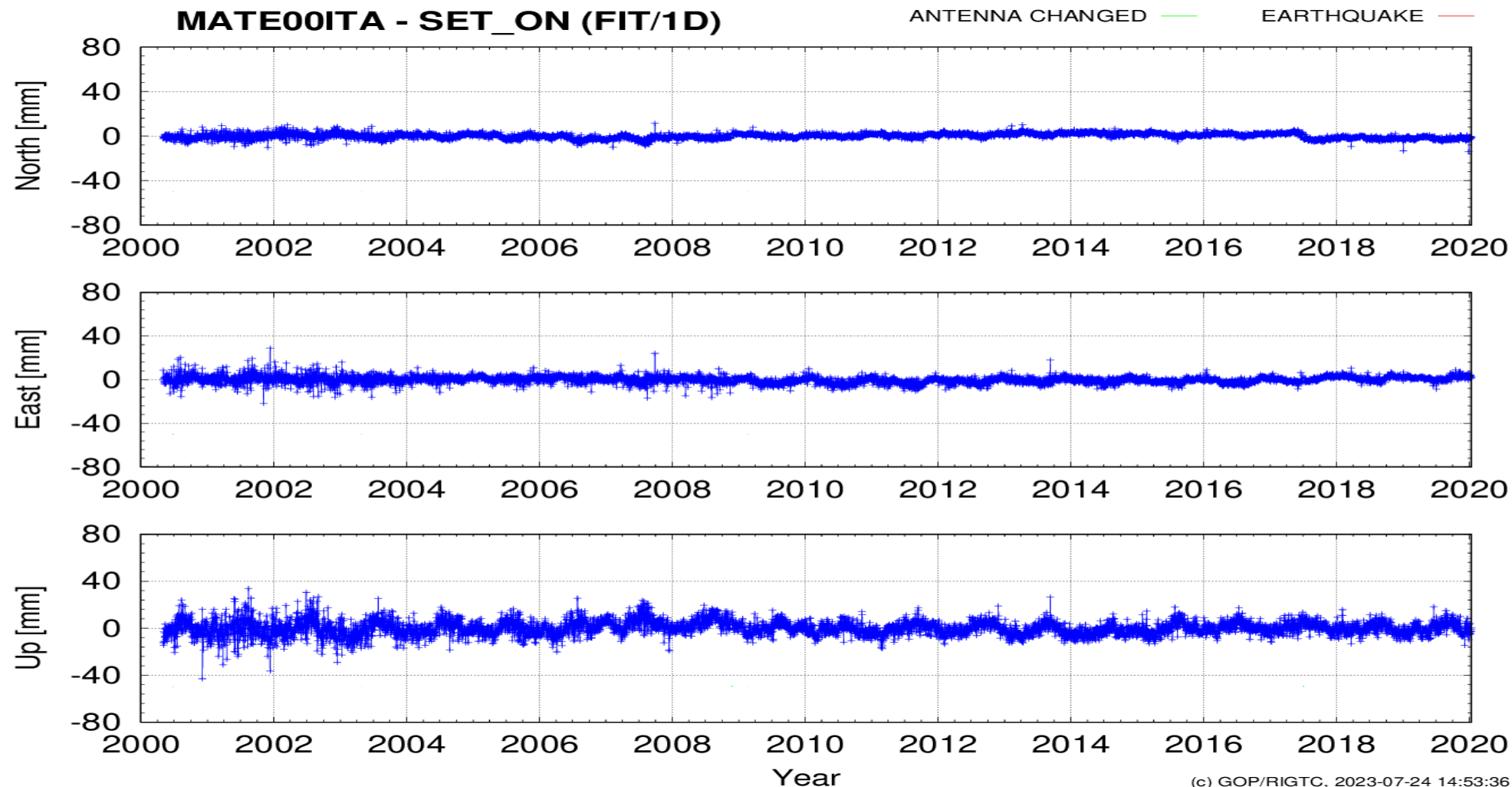
- **Strategies:**

- SET-ON – solid earth tides (full model)
- SET-DI – solid earth tides (full model without 2nd step long-period corrections ‘s2lo’)
- SET-OFF – no solid earth tides model (i.e. switched off)
- 1-day × 3-hour solutions
- *float × fixed ambiguities*

ID	Stations	Tides	CRD/data	Period	Comment
TECT_FL_1D_SET_ON	global + super	SET_ON	1 day / 300 s	2000-2020	Float ambiguities, ionosphere-free linear combination
TECT_FL_1D_SET_DI	global + super	SET_DIU	1 day / 300 s	2000-2020	Float ambiguities, ionosphere-free linear combination
TECT_AR_1D_SET_ON	global + super	SET_ON	1 day / 300 s	2000-2020	Fixed ambiguities, uncombined/undifferenced observations
TECT_AR_1D_SET_DI	global + super	SET_DIU	1 day / 300 s	2000-2020	Fixed ambiguities, uncombined/undifferenced observations

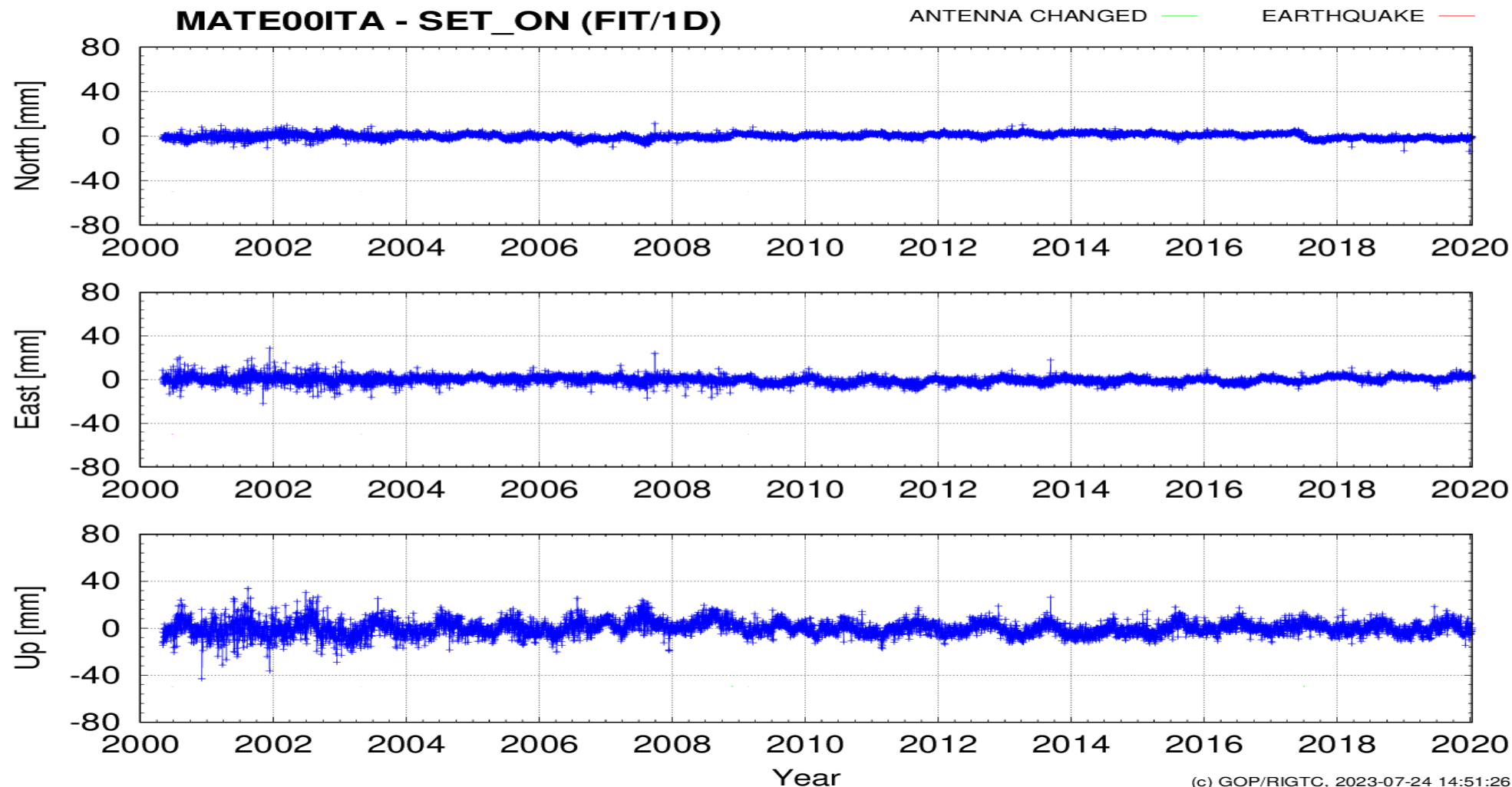


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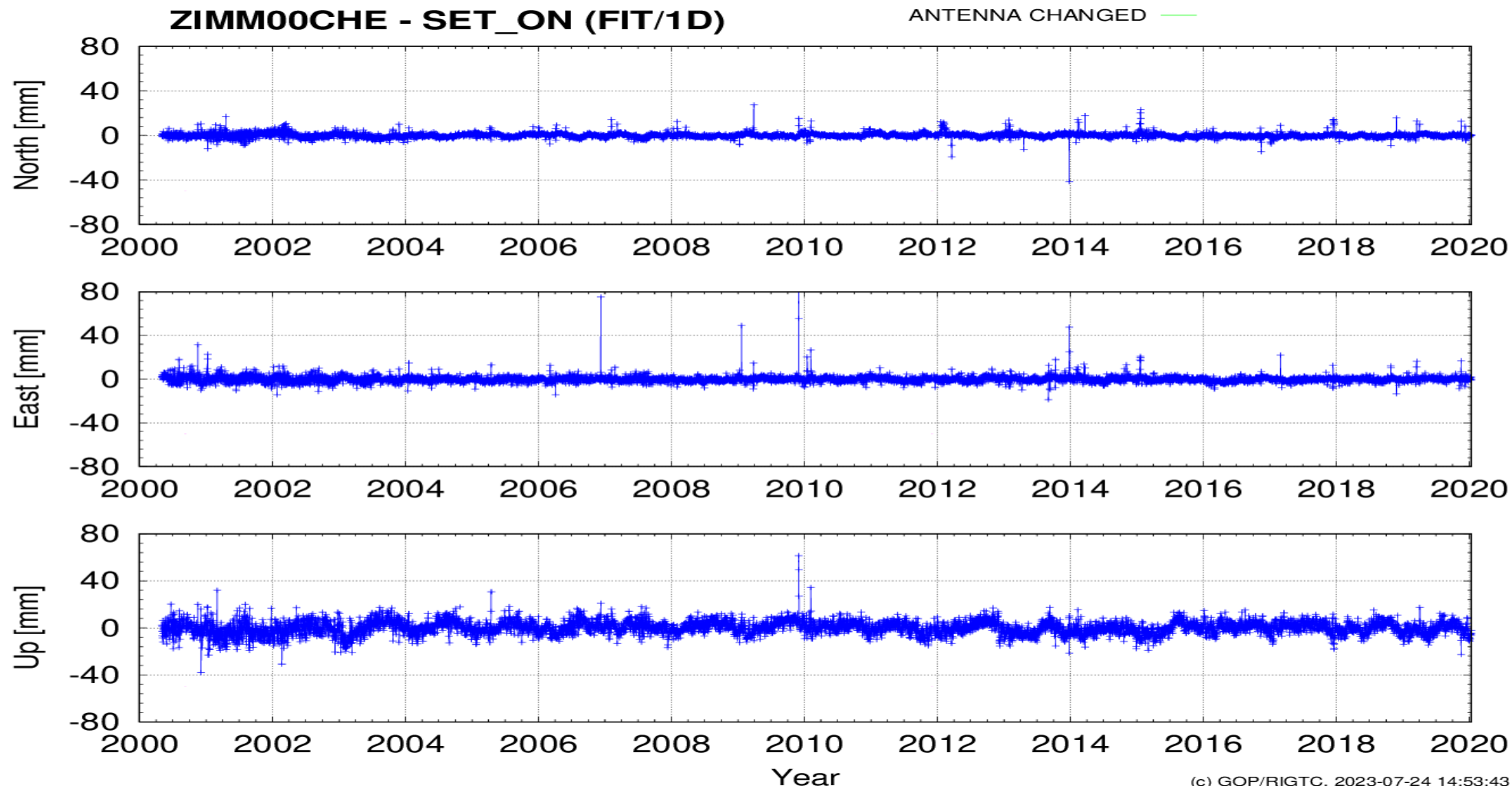


(c) GOP/RIGTC, 2023-07-24 14:53:36

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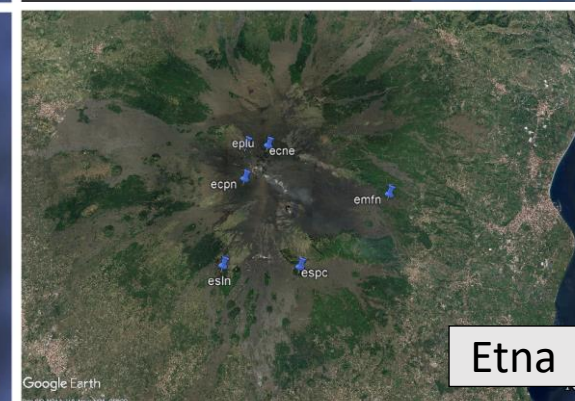
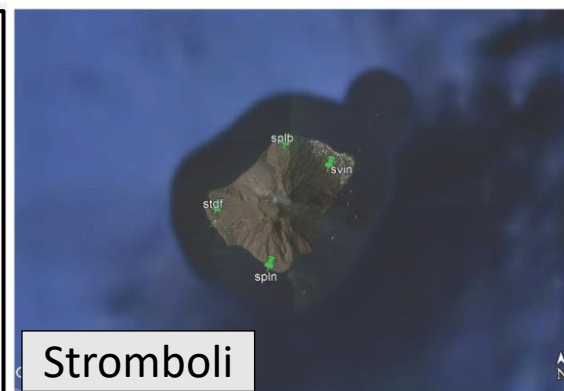
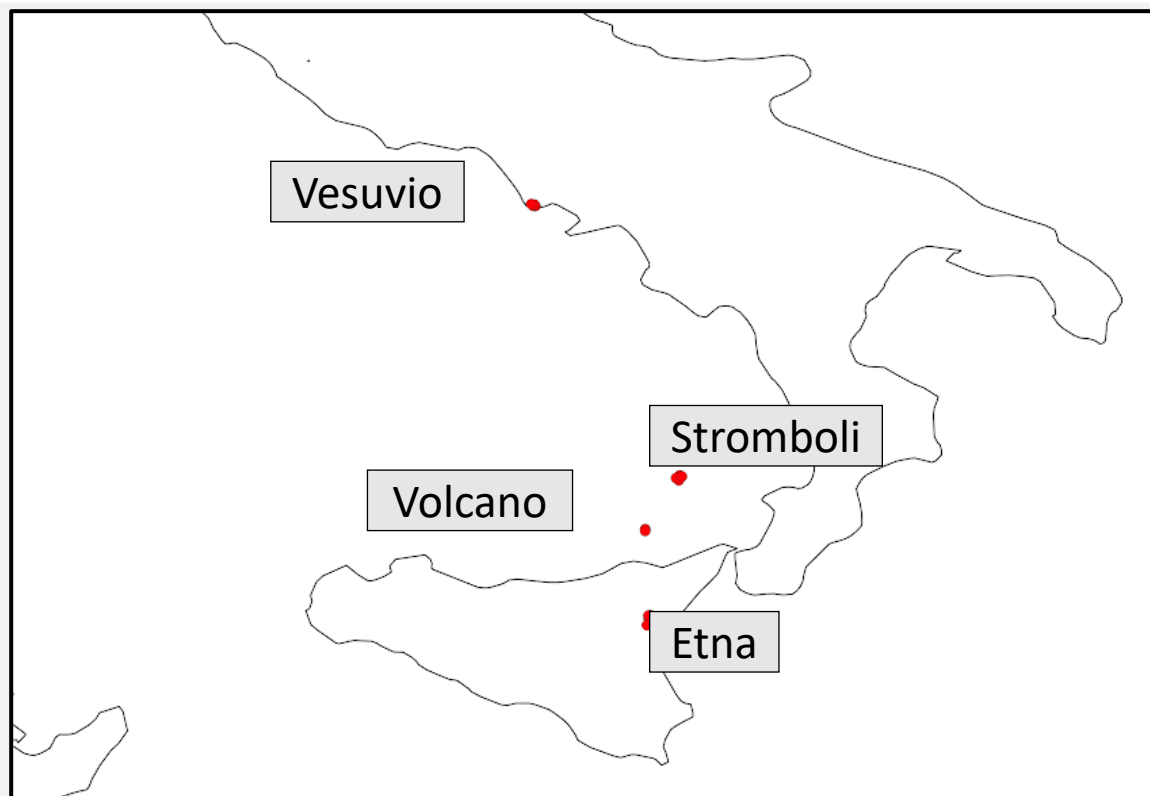


ZIMM

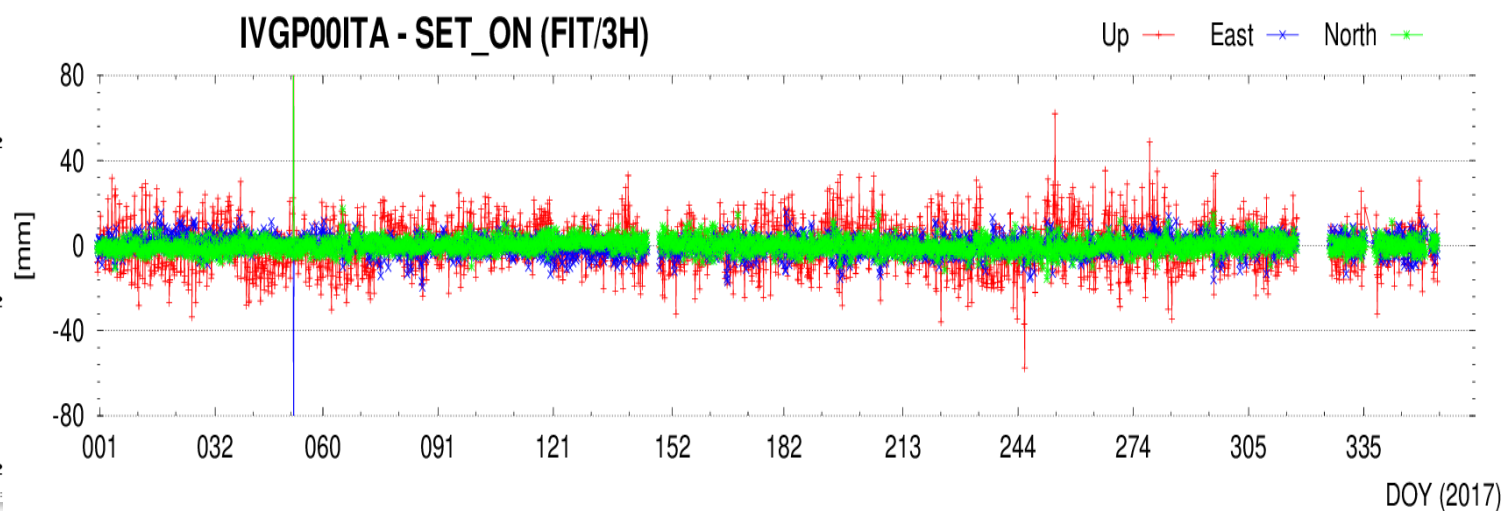
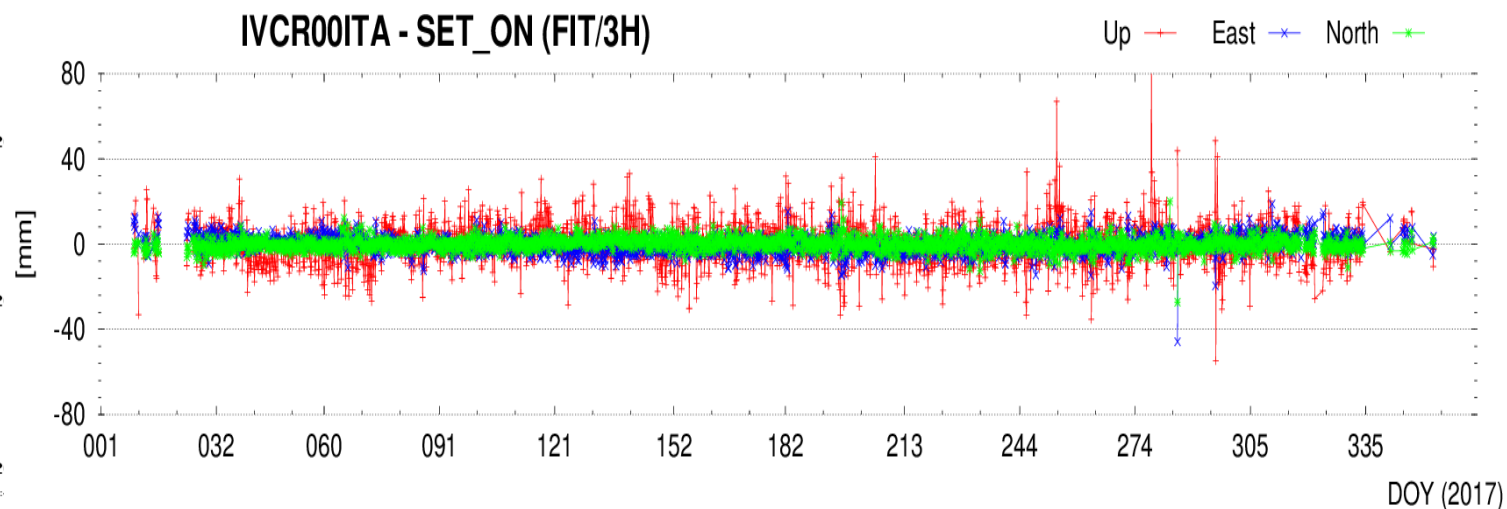
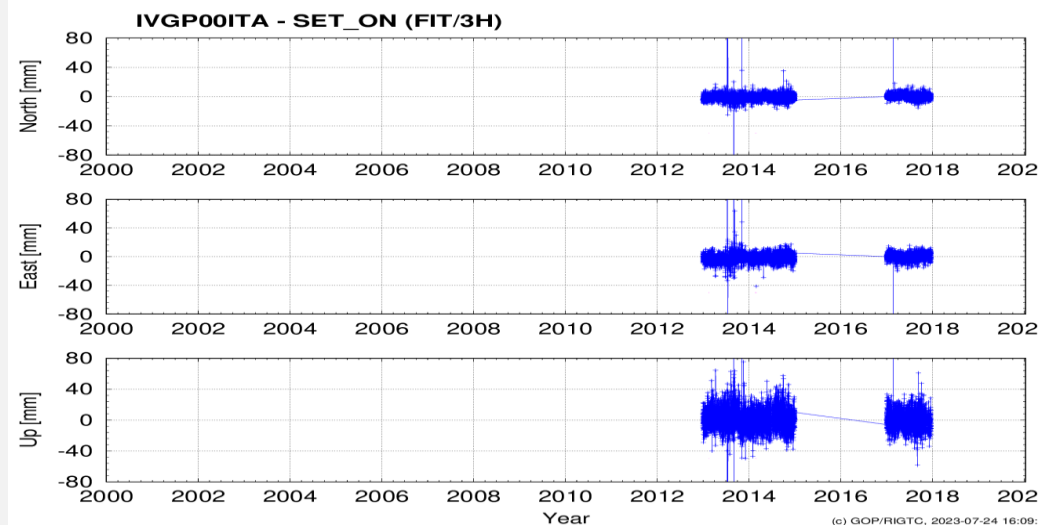
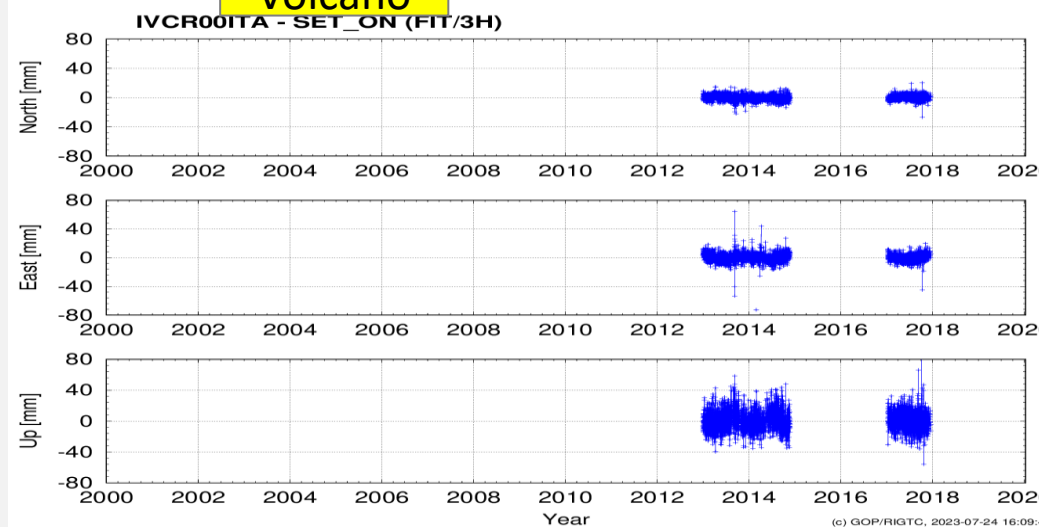


(c) GOP/RIGTC, 2023-07-24 14:53:43

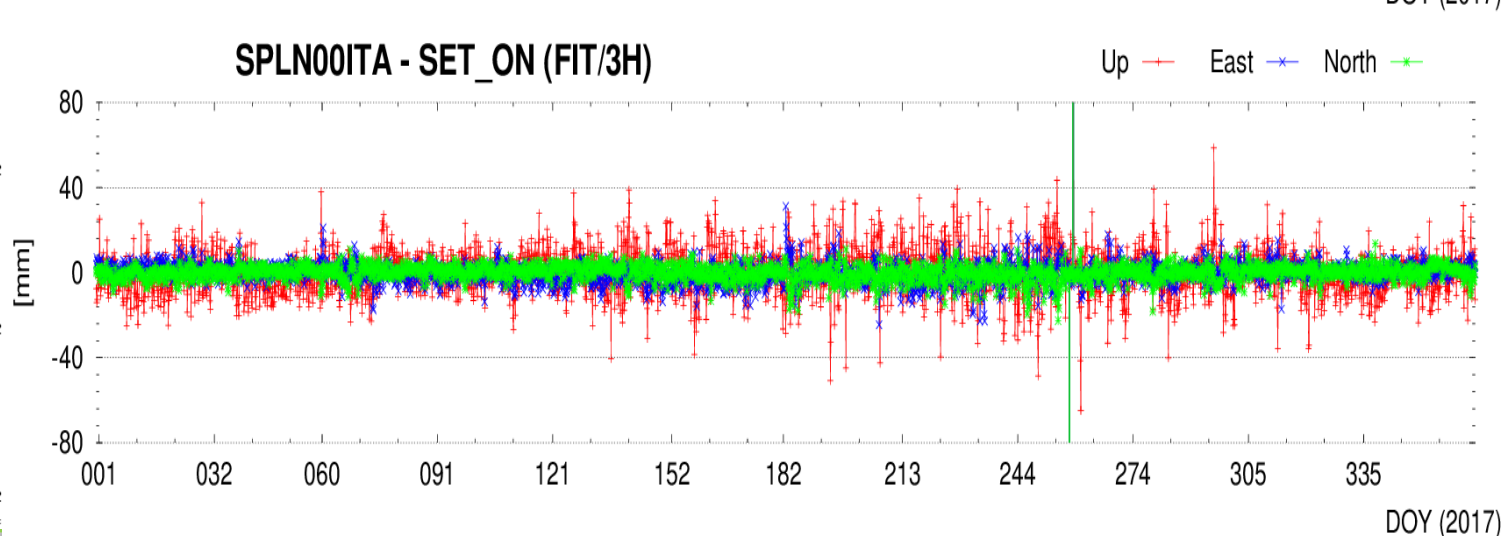
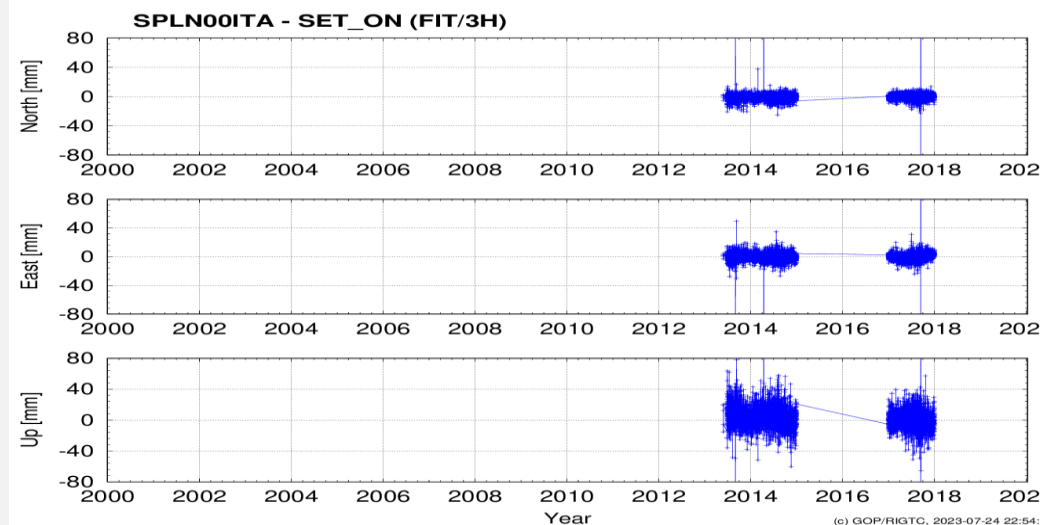
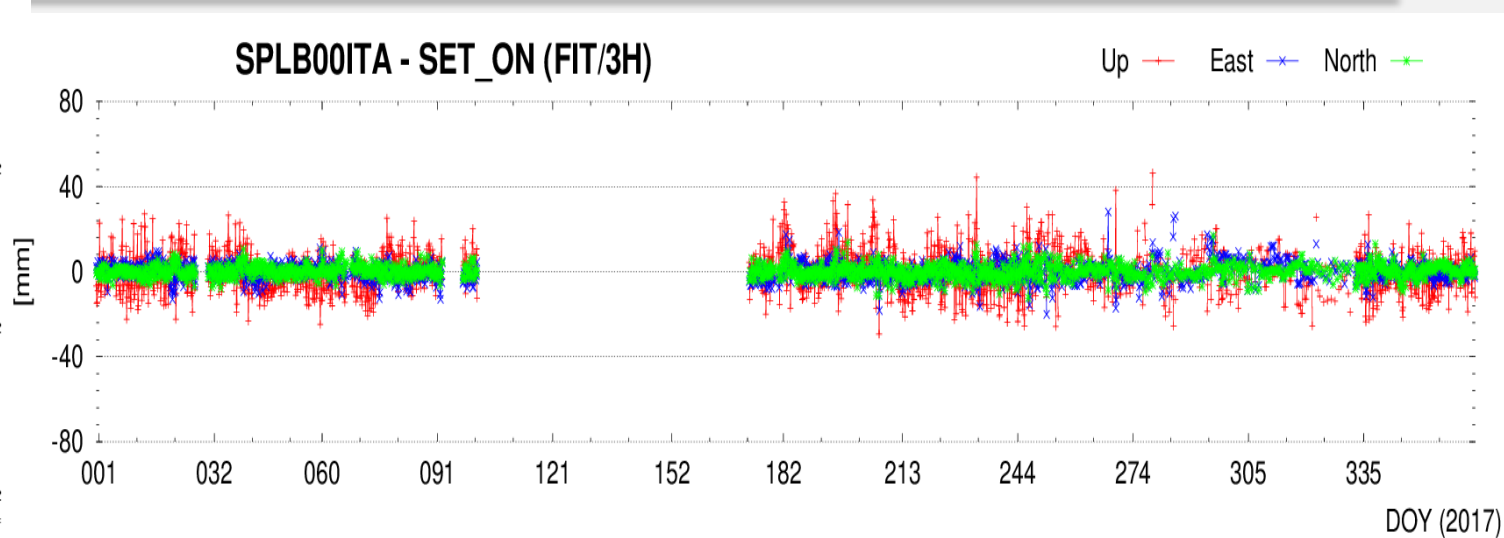
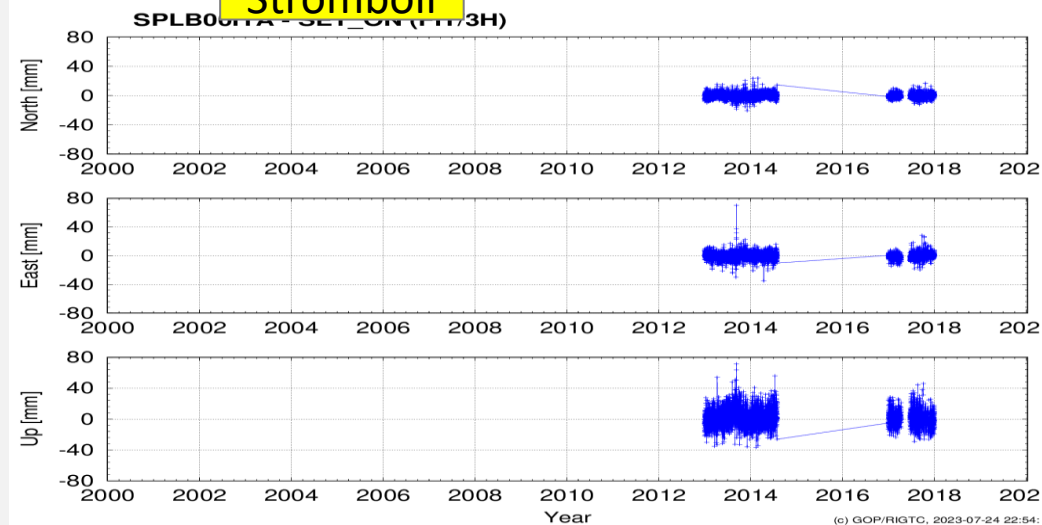
ID	Stations	Tides	CRD/data	Period	Comment
VOLC_FL_3H_SET_ON	RING+INGV	SET_ON	3-hour/30 s	2013, 2014, 2017	Float ambiguities, ionosphere-free linear combination
VOLC_FL_3H_SET_XX	RING+INGV	SET_OFF	3-hour/30 s	2013, 2014, 2017	Float ambiguities, ionosphere-free linear combination
VOLC_AR_3H_SET_ON	RING+INGV	SET_ON	3-hour/30 s	2013, 2014, 2017	Fixed ambiguities, uncombined/undifferenced observations
VOLC_AR_3H_SET_XX	RING+INGV	SET_OFF	3-hour/30 s	2013, 2014, 2017	Fixed ambiguities, uncombined/undifferenced observations



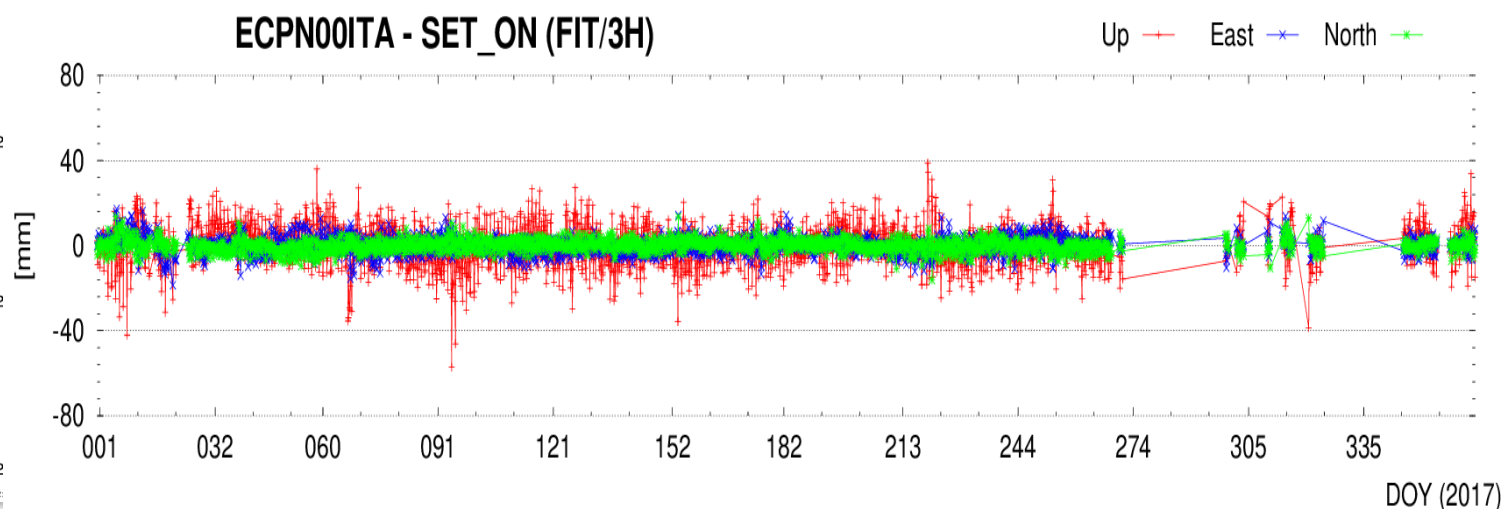
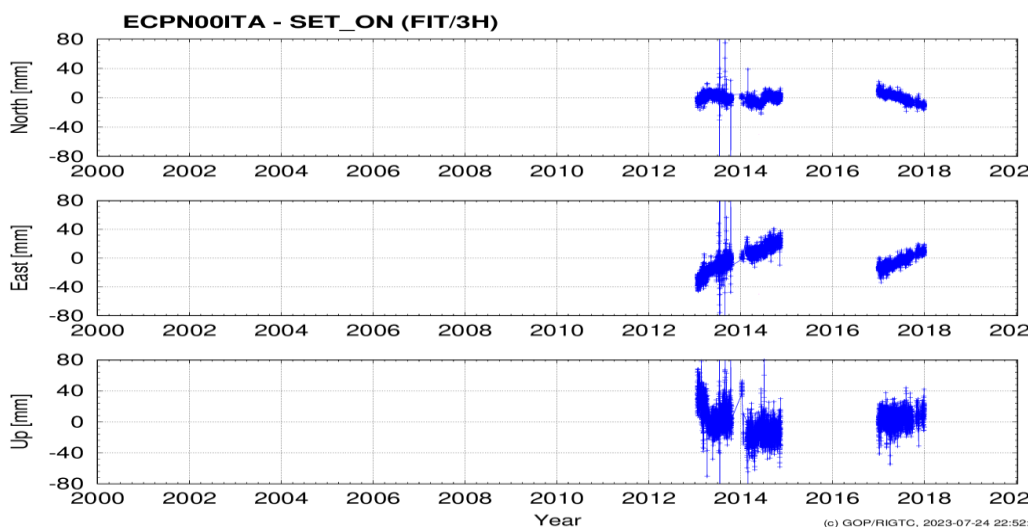
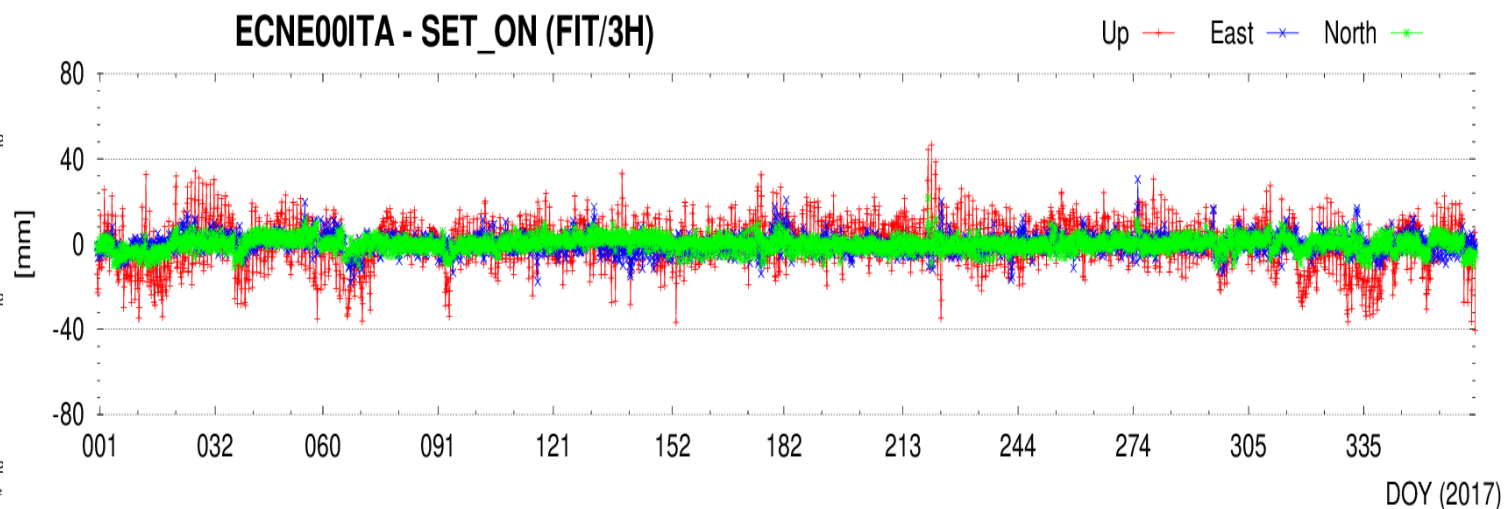
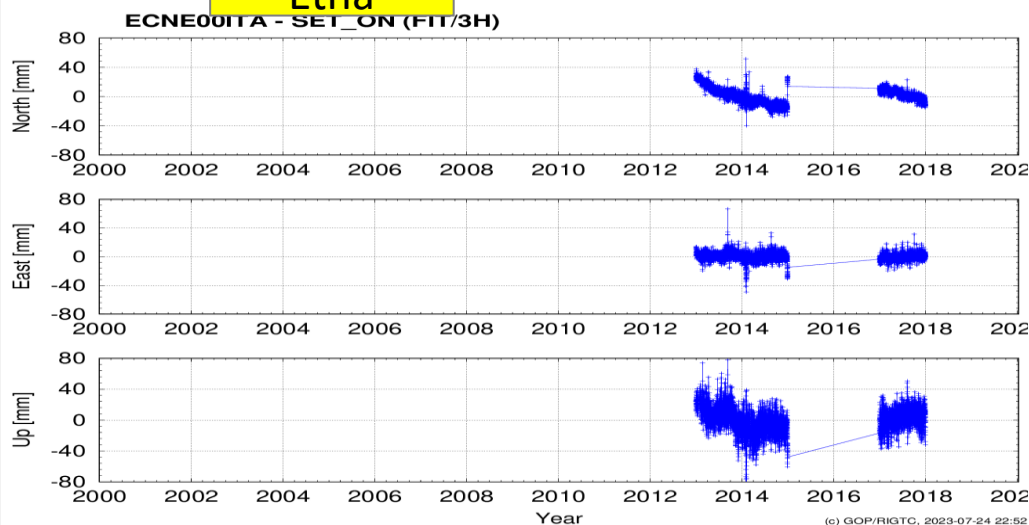
Volcano



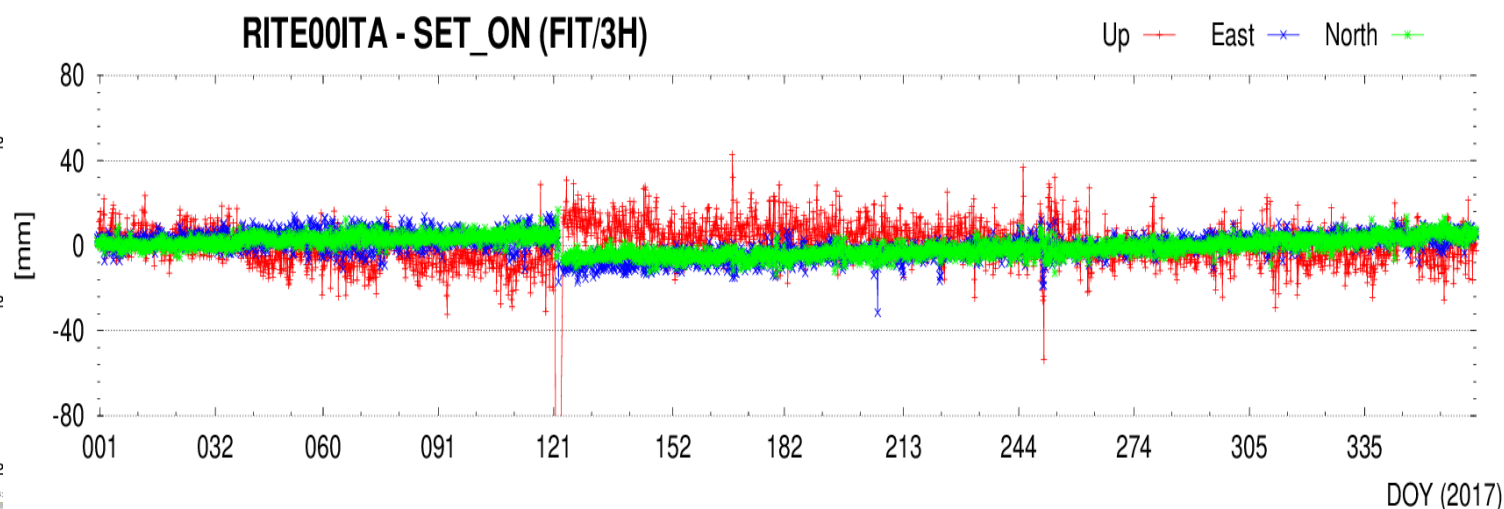
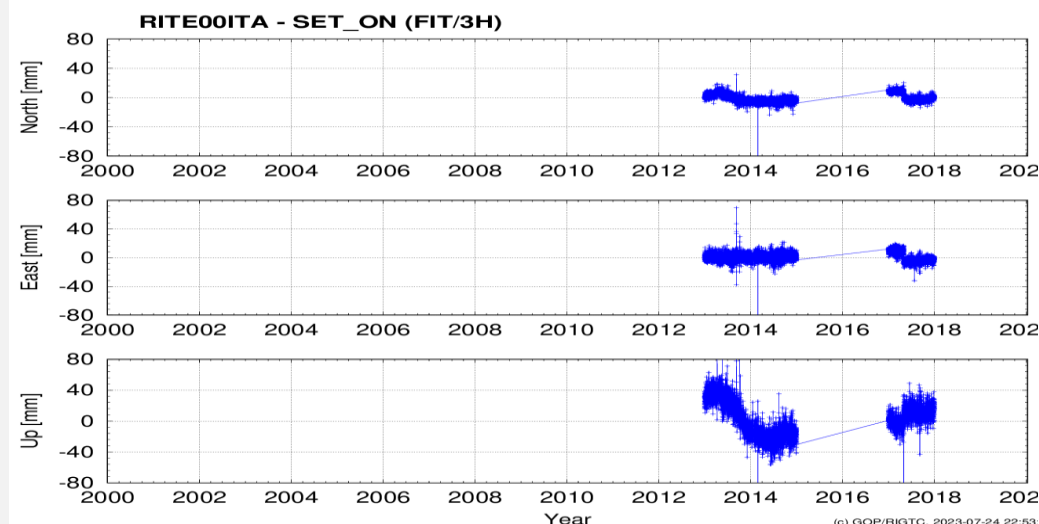
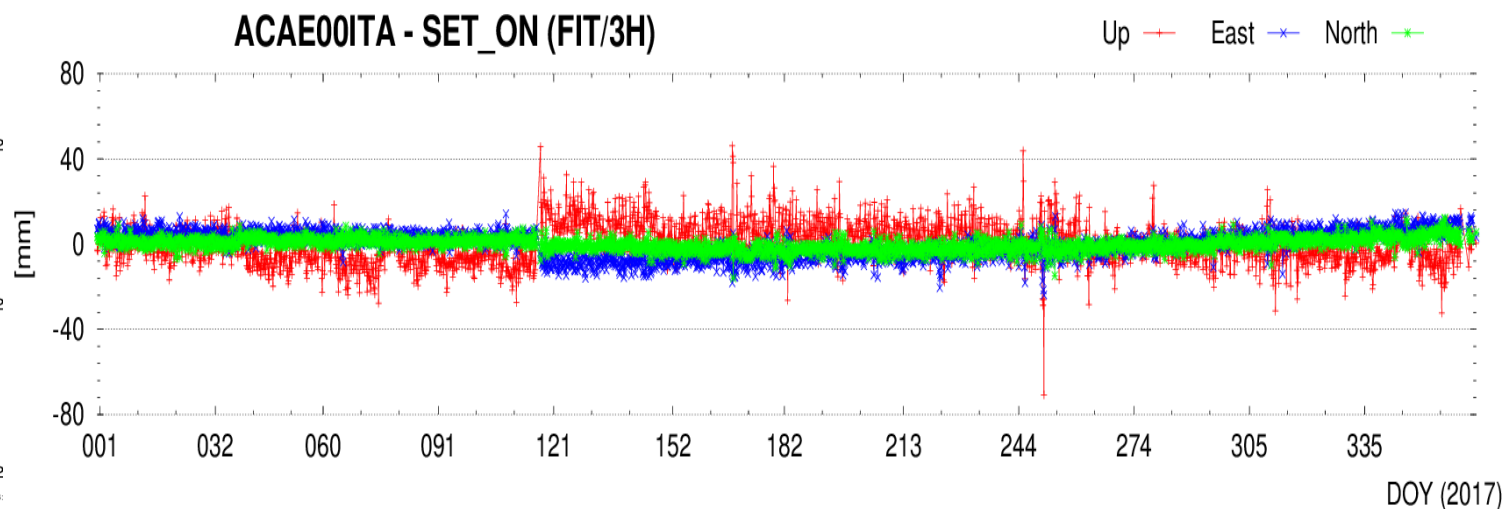
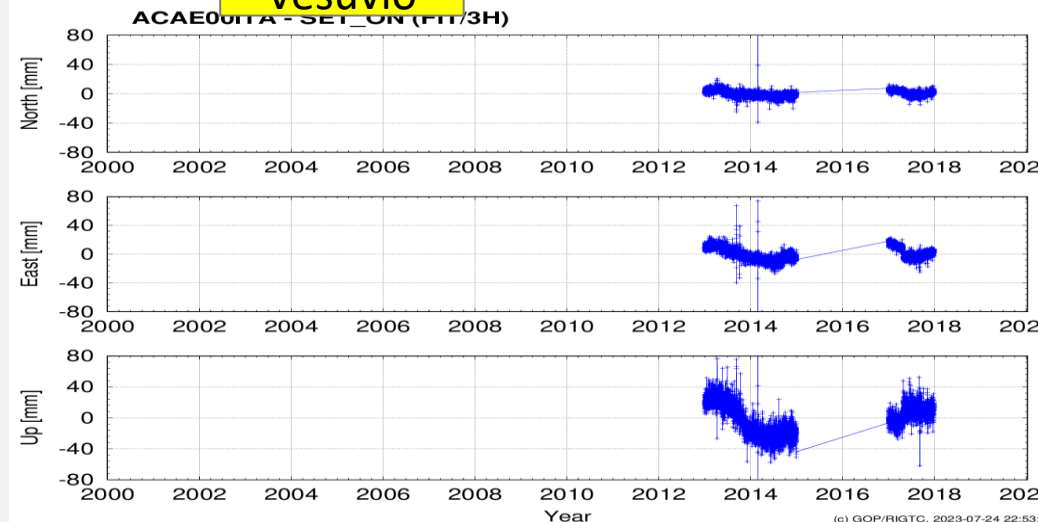
Stromboli



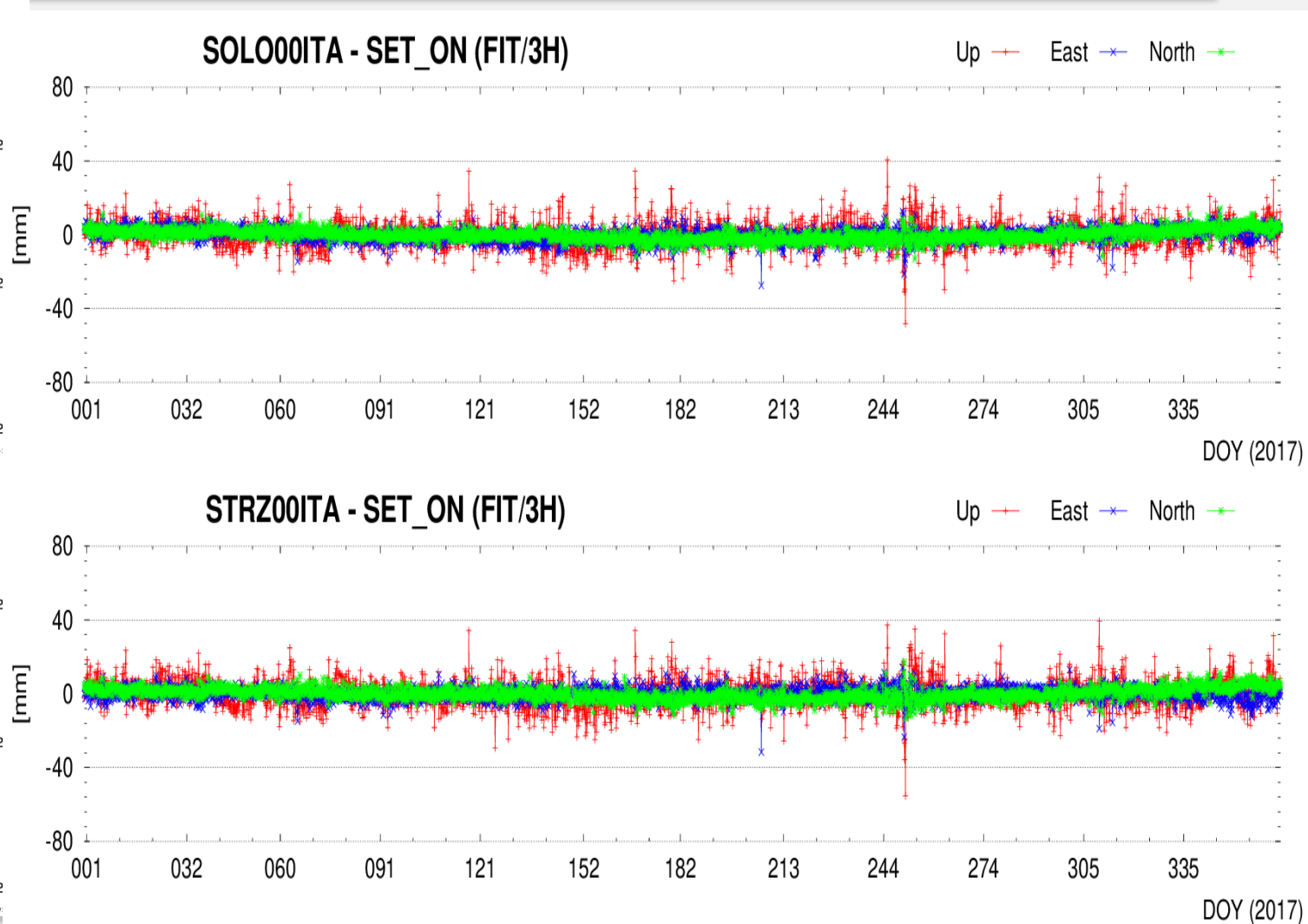
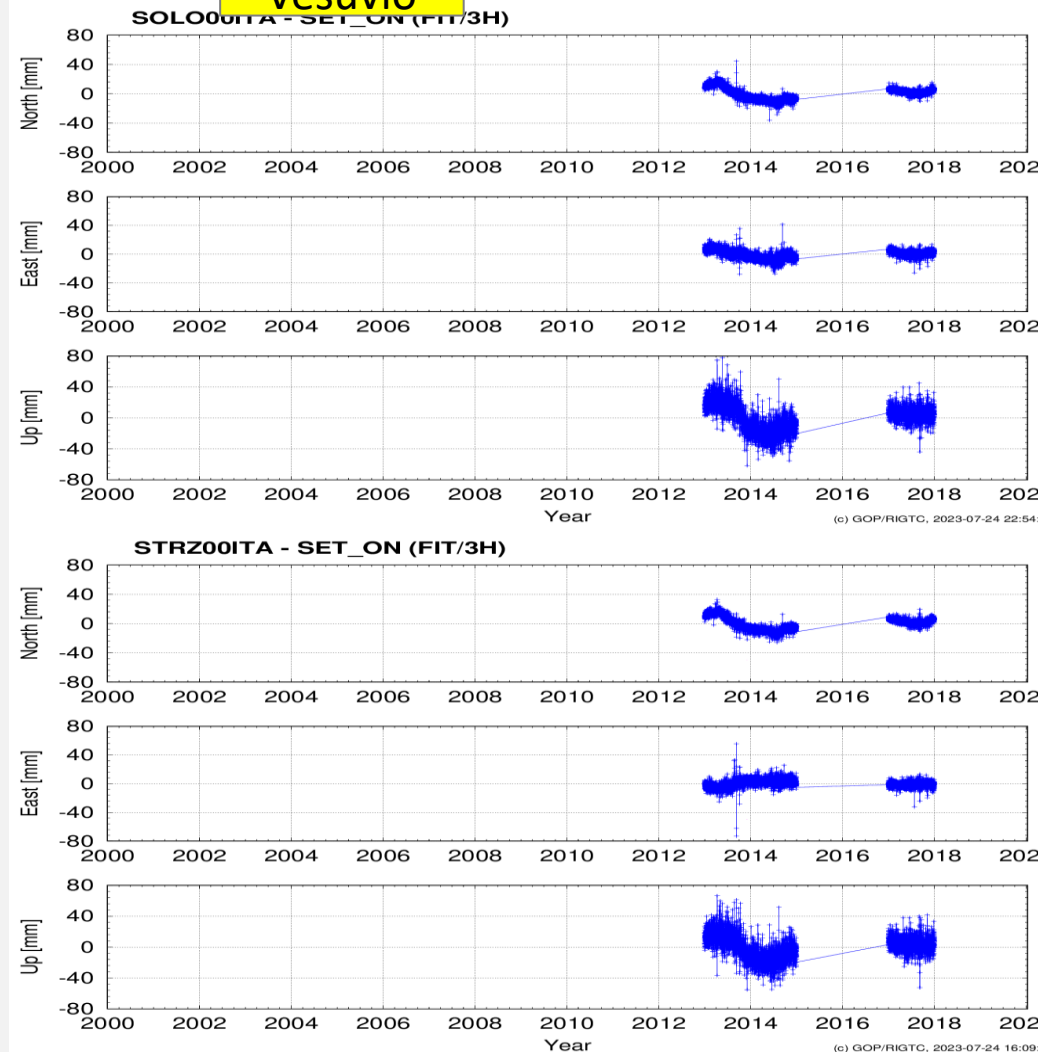
Etna



Vesuvio



Vesuvio



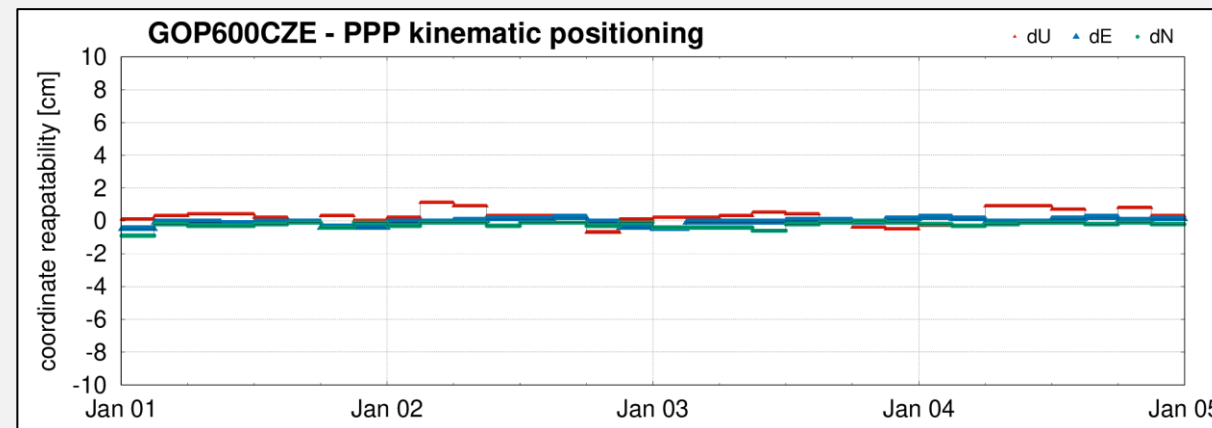
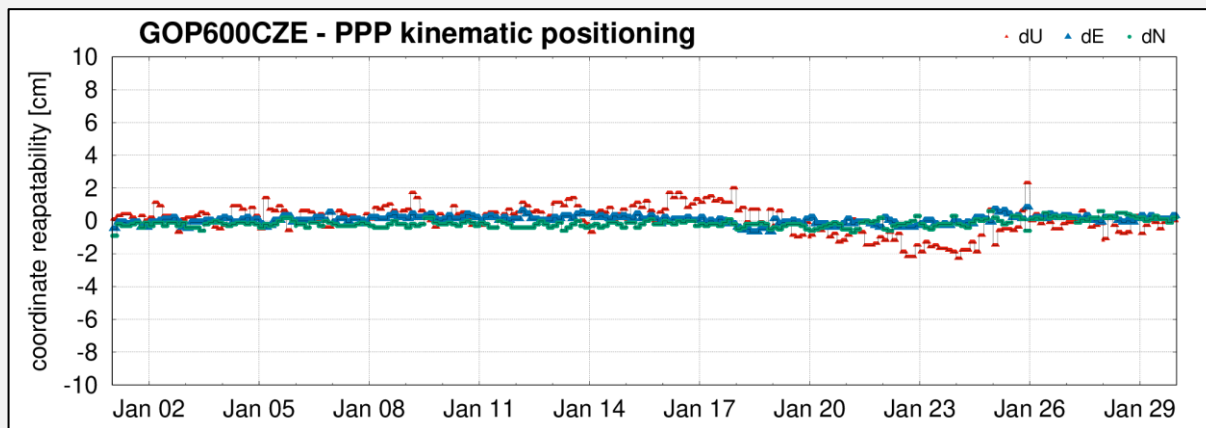
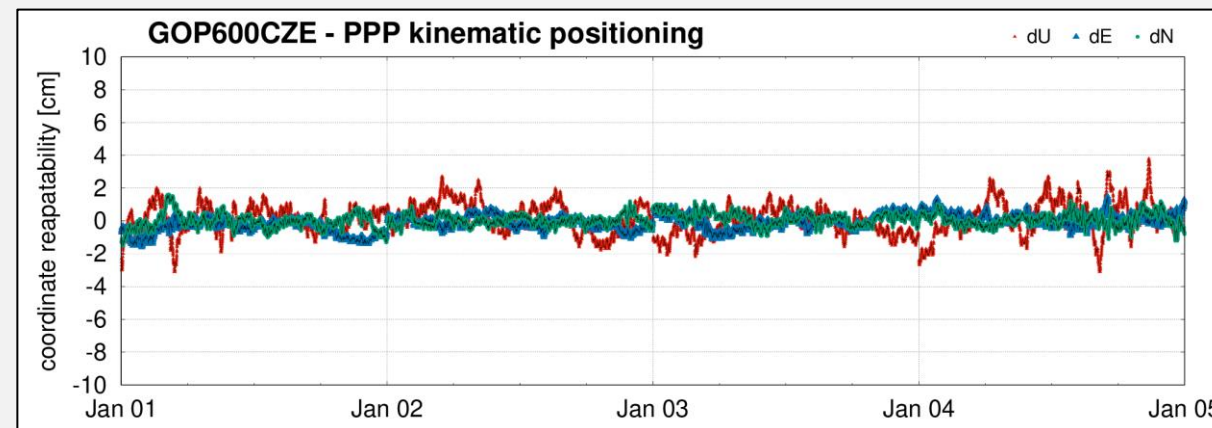
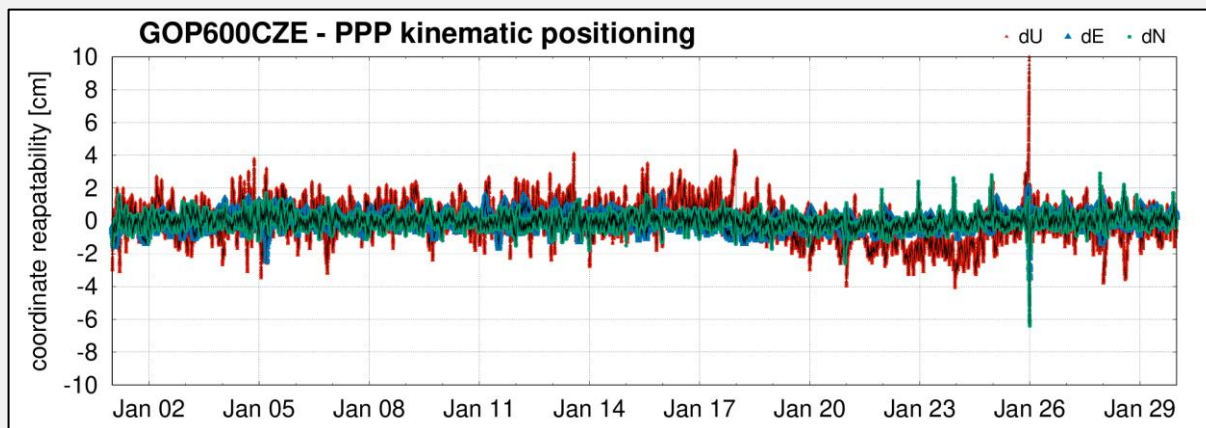
- **True kinematic solution**

- High-resolution coordinate time series (30s sampling)
- Accuracy not far from the static solution
- Optimal for PPP SET estimates

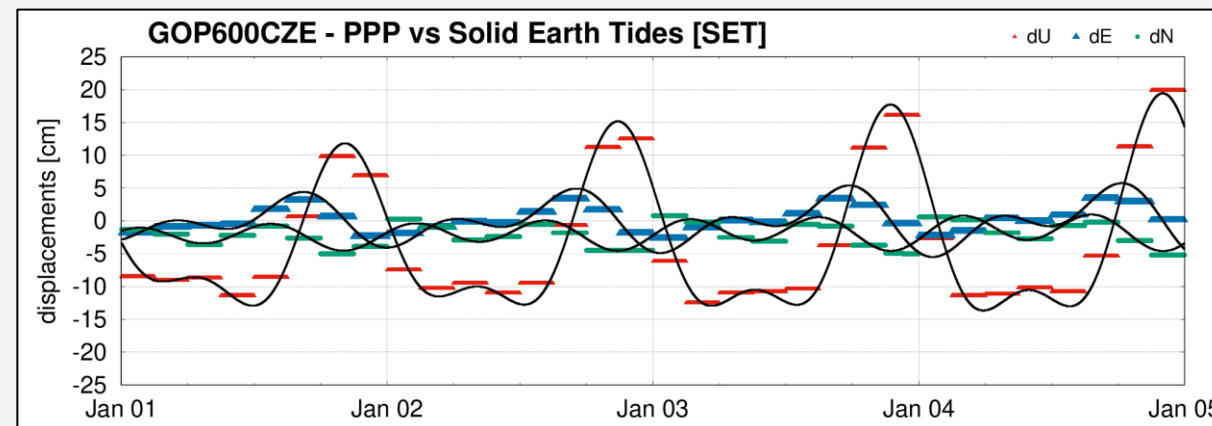
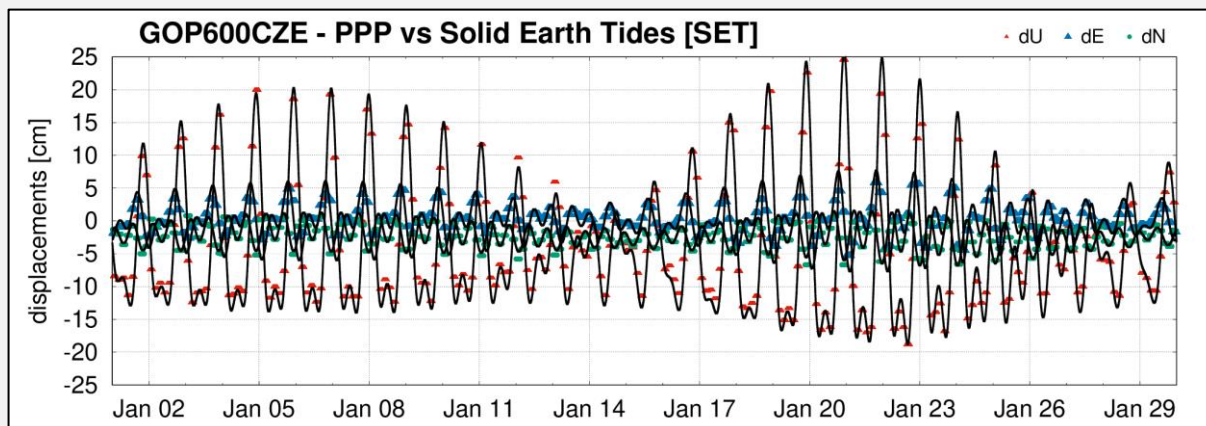
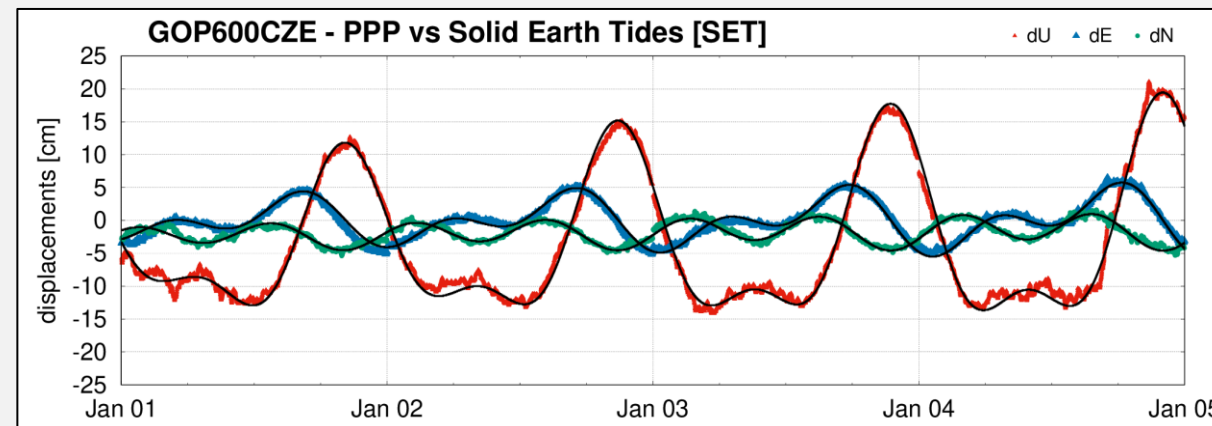
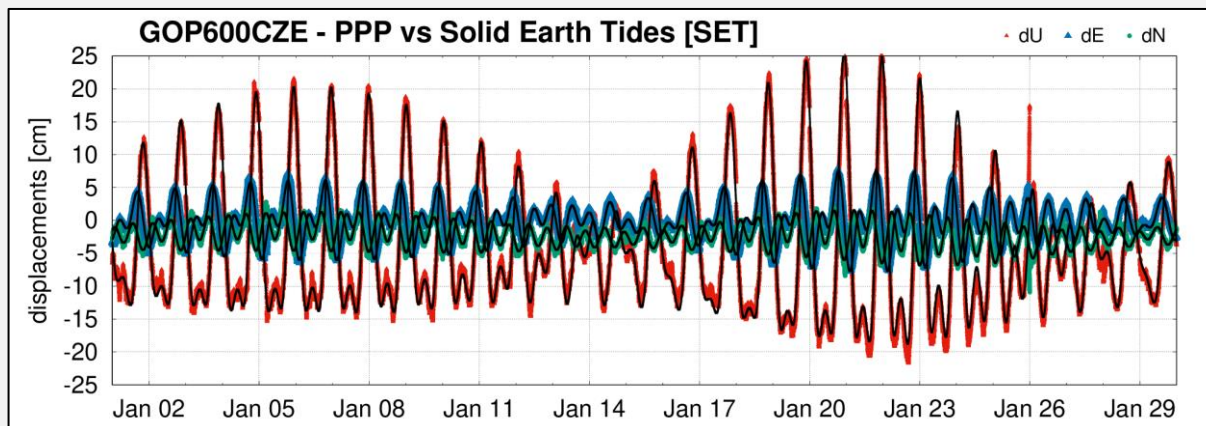
- **Ambiguity resolution**

- Undifferenced/uncombined observations (+ STEC estimates)
- Forward filter solution (not ready yet for backward smoothing)
- To improve high-rate kinematic solutions (FIXED epoch filtering possible)

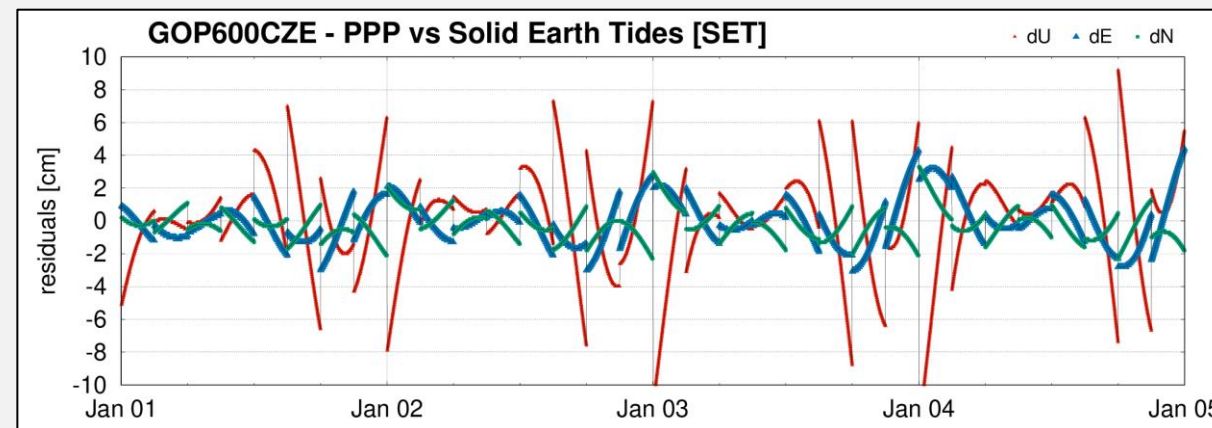
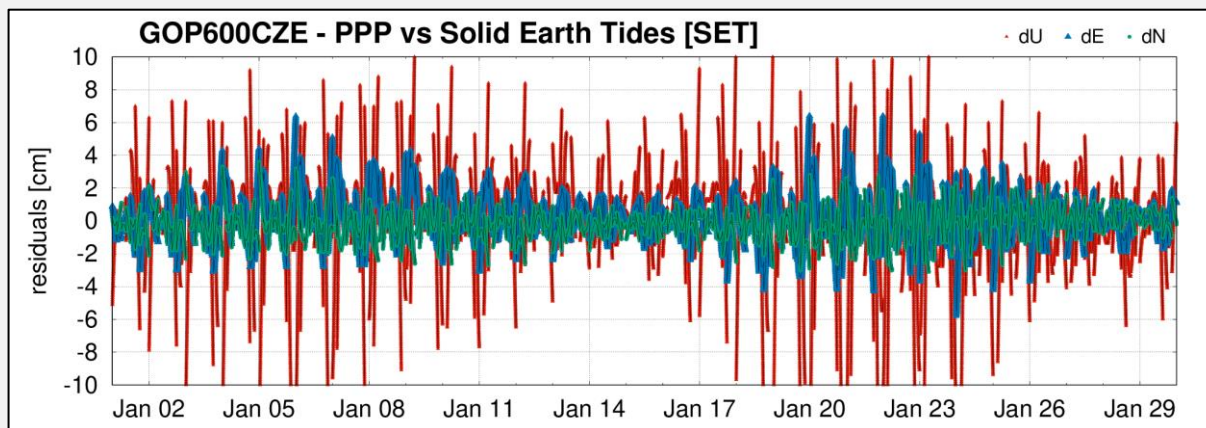
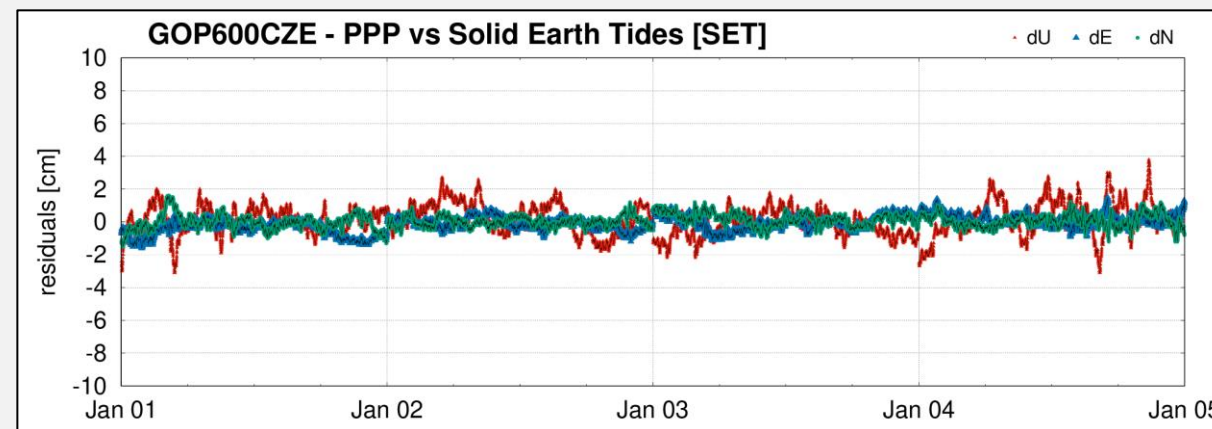
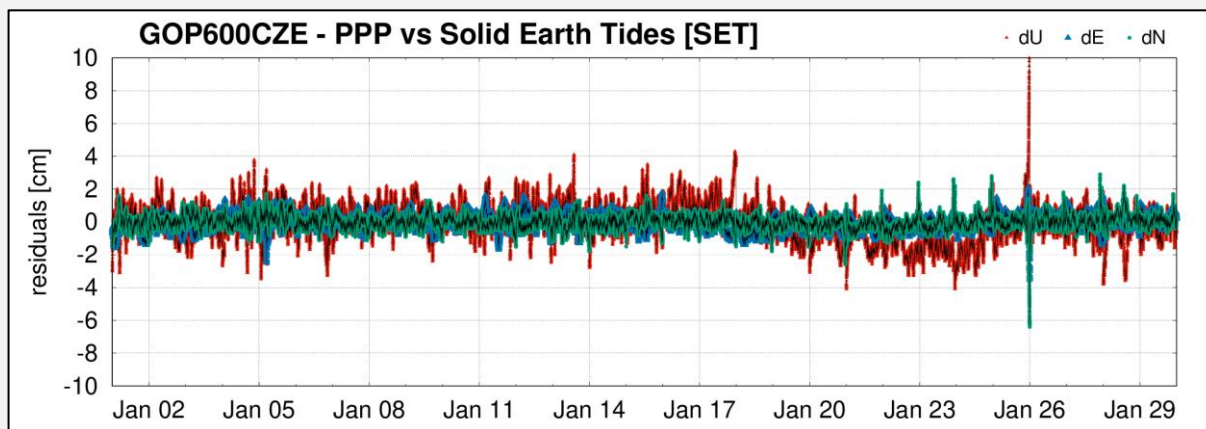
PPP 30s (top) vs 3h (bottom=LEGACY) – ionosphere-free LC / full IERS applied → coordinate repeatability



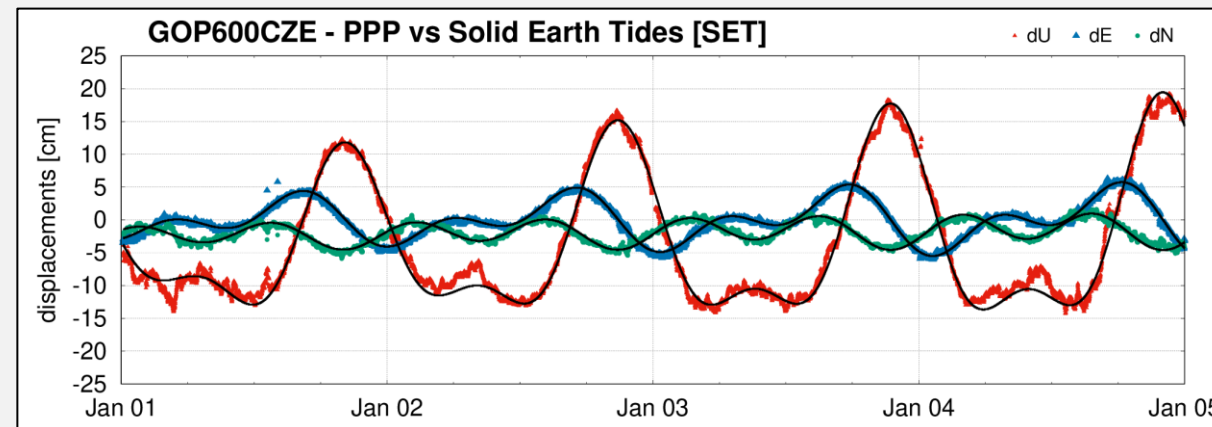
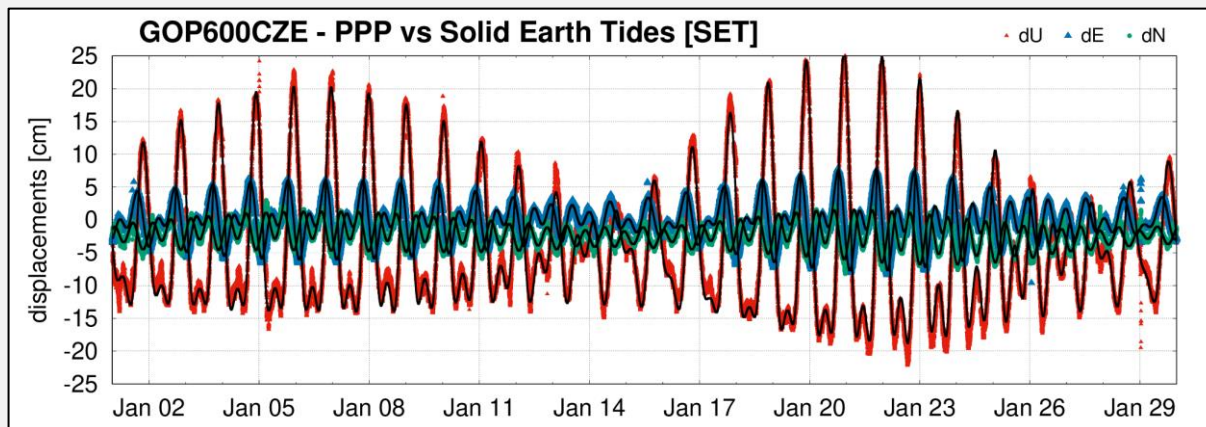
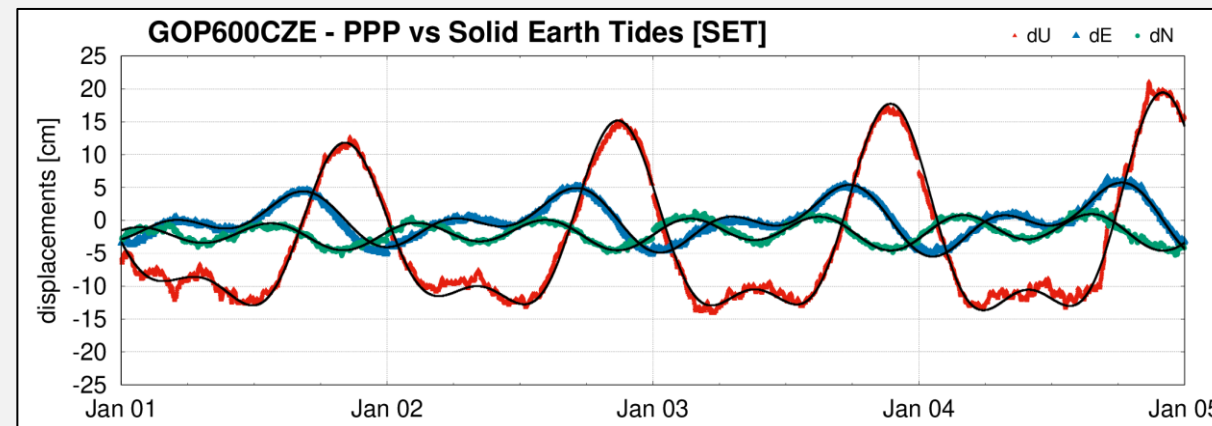
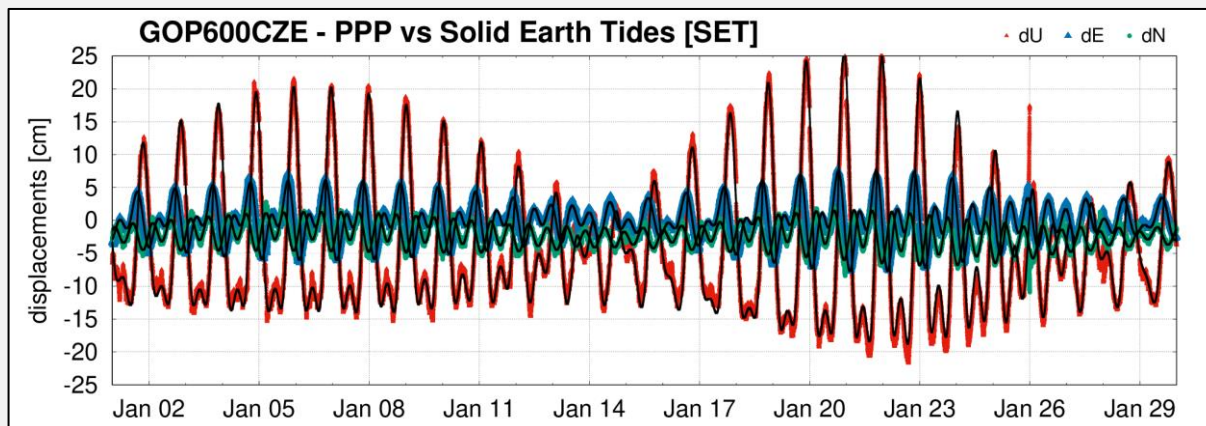
PPP 30s (top) vs 3h (bottom=LEGACY) – ionosphere-free LC / no IERS applied → comparison to the IERS2010 tides



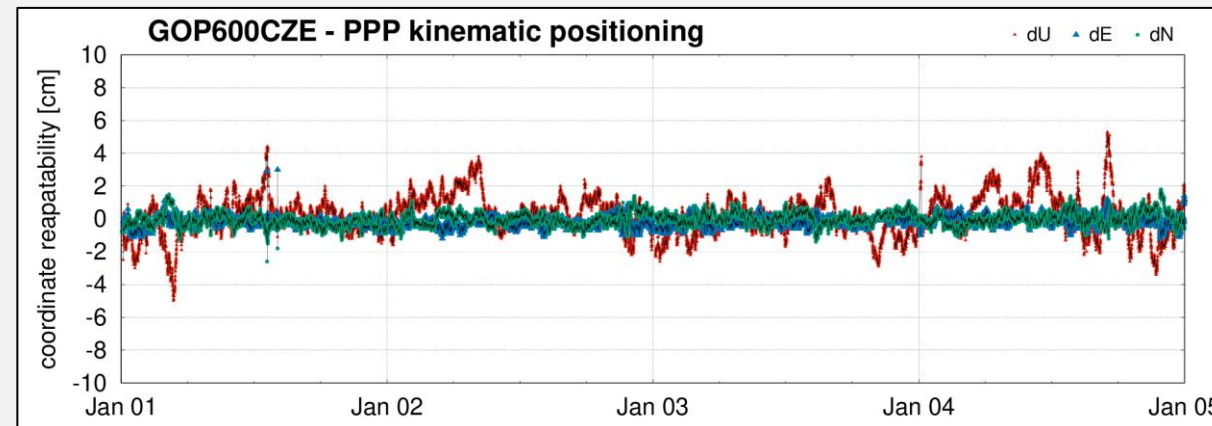
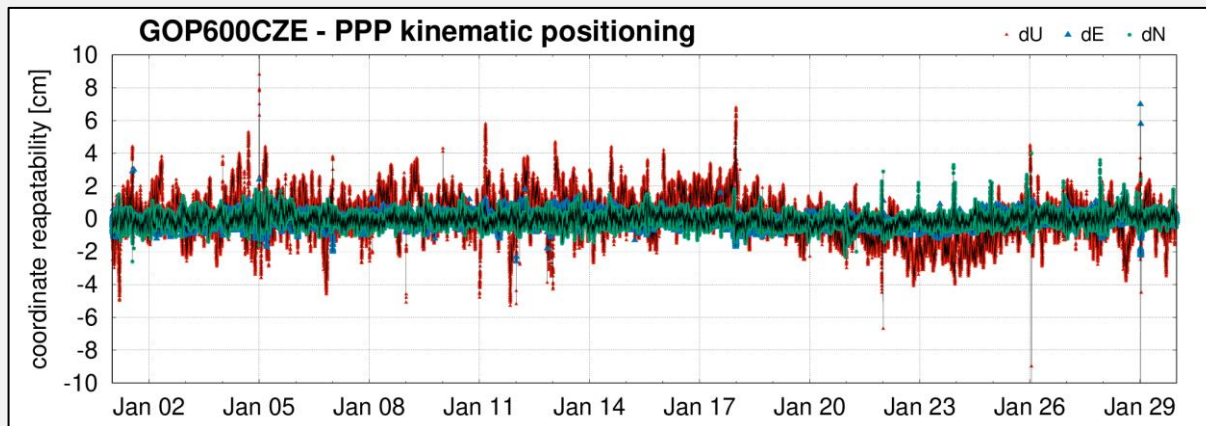
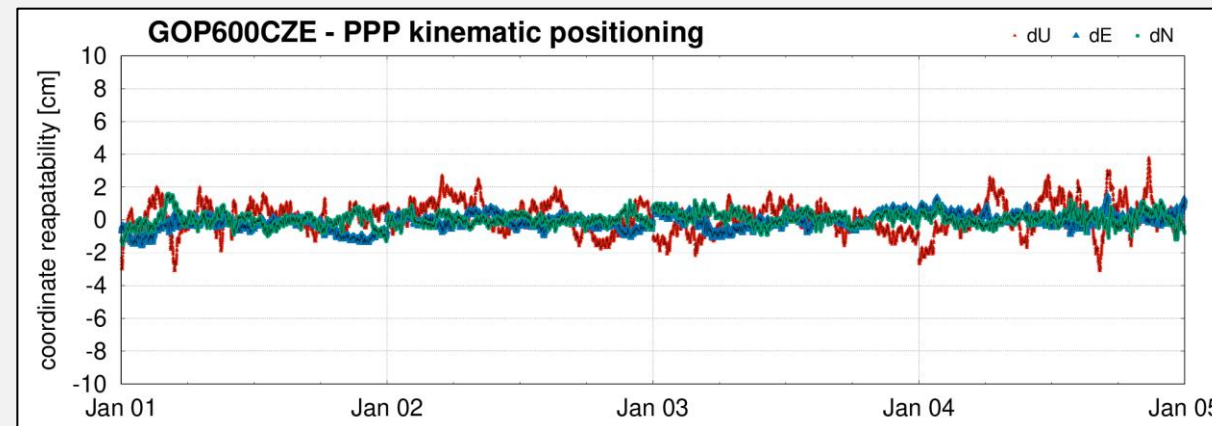
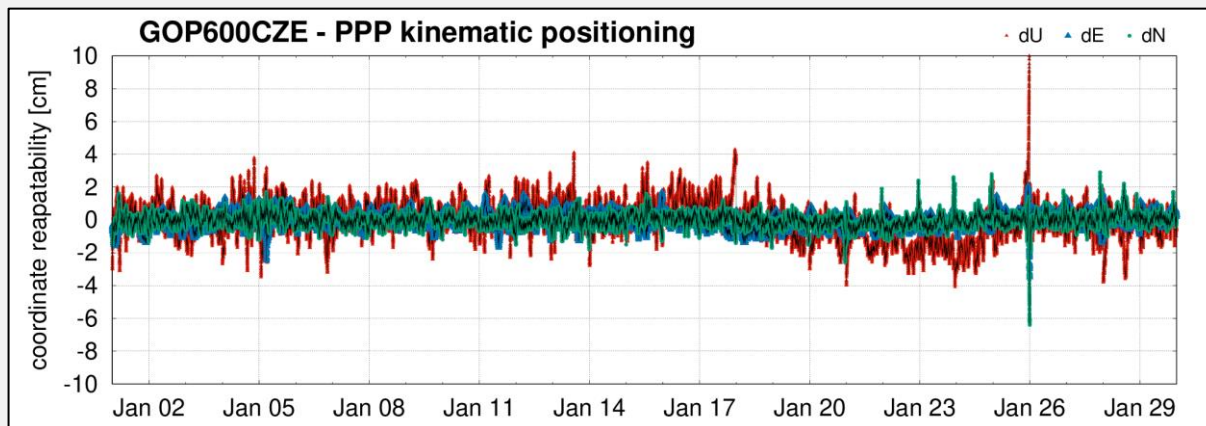
PPP 30s (top) vs 3h (bottom=LEGACY) – ionosphere-free LC / no IERS applied → residuals from the IERS2010 tides



PPP (top) vs PPP-AR (bottom) – uncombined-undifferenced / no IERS applied → comparison to the IERS2010 tides



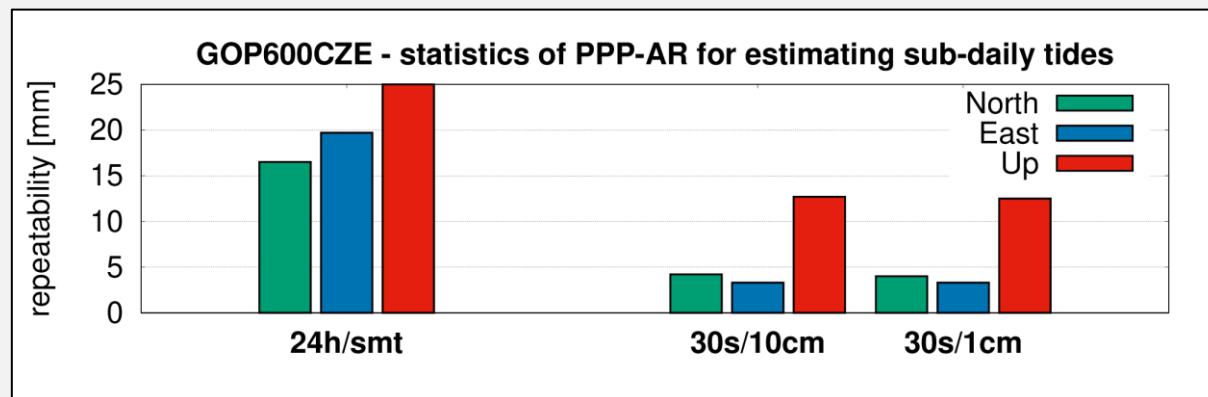
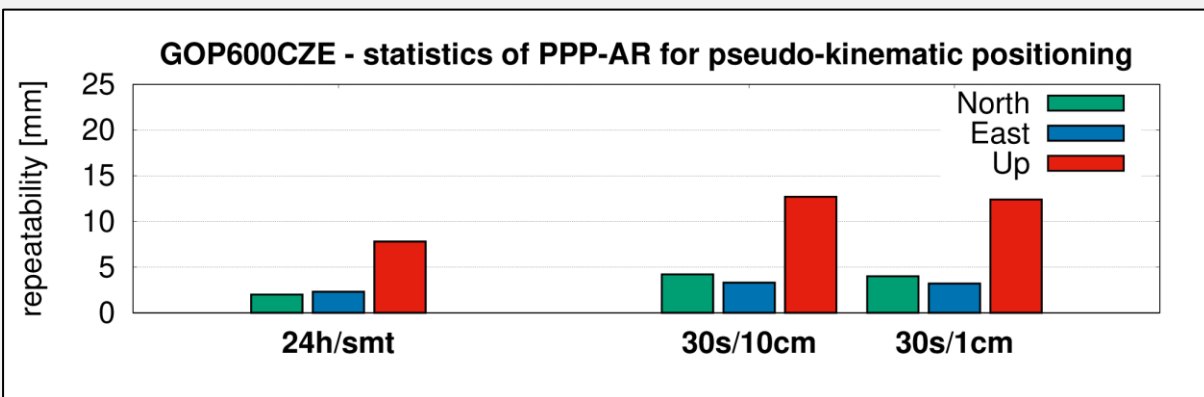
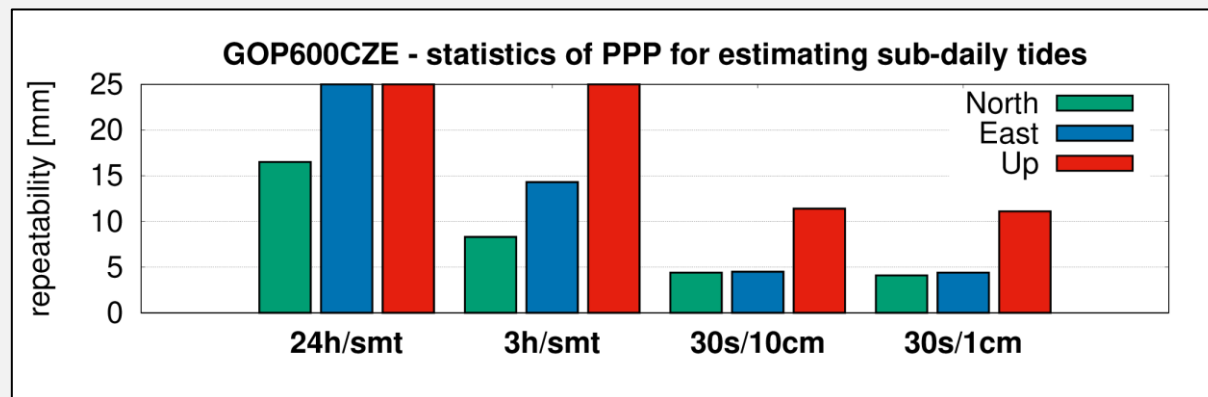
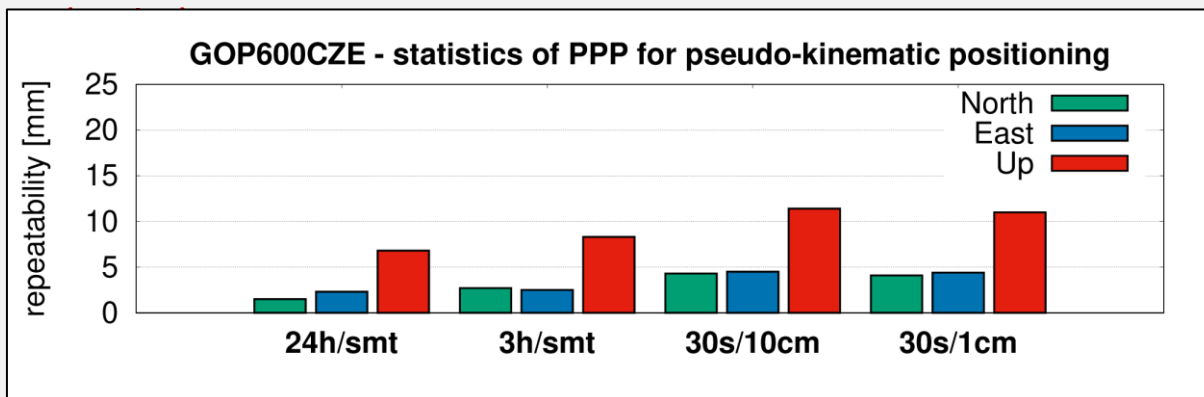
PPP (top) vs PPP-AR (bottom) – uncombined-undifferenced / full IERS applied → coordinate repeatability



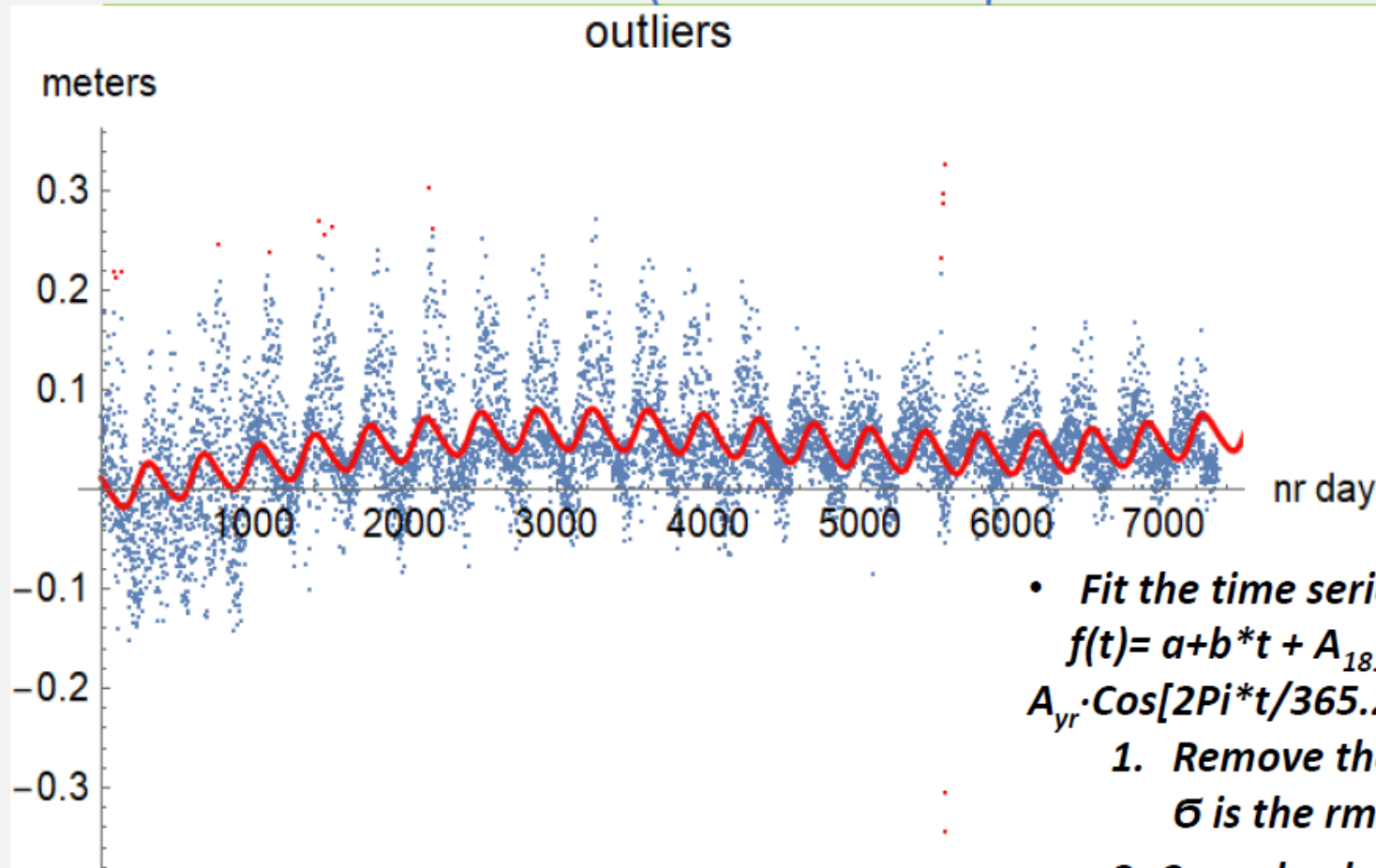
Different time resolution variants: daily/3h (static) and 30s (kinematic, 10cm/1cm white noise)

PPP (full IERS) – coordinate repeatability (sdev)

PPP (no model) residuals to the IERS2010 model (sdev)



- GNSS processing
 - for Solid Earth Tide modelling (TECT)
 - for tectonic hazards (TECT)
 - for volcanic hazards (VOLC)
- Stations:
 - TECT: global + supersites
 - VOLC: regional (Stromboli, Volcano, Etna, Vesuvio from INGV)
- Strategies:
 - SET-ON –solid earth tides (full model)
 - SET-DI – solid earth tides (full model without 2nd step long-period corrections ‘s2lo’)
 - SET-OFF – no solid earth tides model (switched off)
 - 1-day × 3-hour solutions
 - float × fixed ambiguities



- *Fit the time series with:*

$$f(t) = a + b \cdot t + A_{18.6} \cdot \cos[2\pi \cdot t / 18.6_{yr} + \phi_{18.6}] + A_{yr} \cdot \cos[2\pi \cdot t / 365.25_{days} + \phi_{yr}]$$
 1. *Remove the data: $y_{ti} - f(t_i) > 3 \cdot \sigma$ where σ is the rms of the fit*
 2. *Come back to 1 till no more rejections will occur*

The jumps and displacement

$$V_{tot} = V_t +$$

where

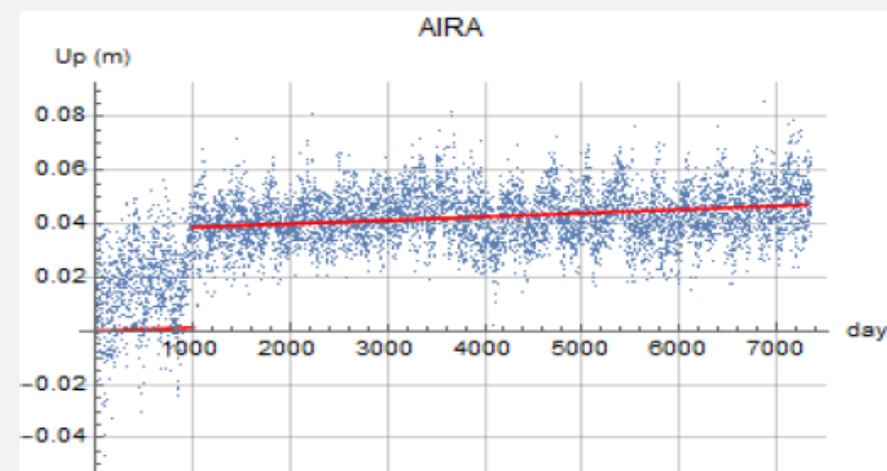
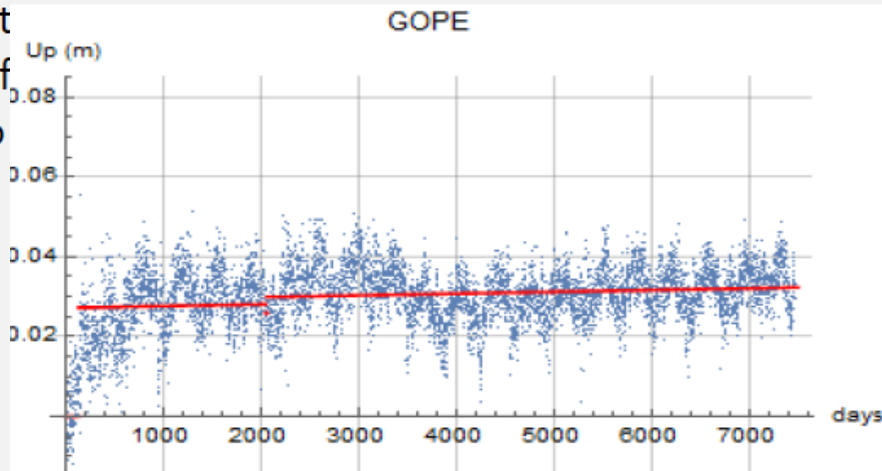
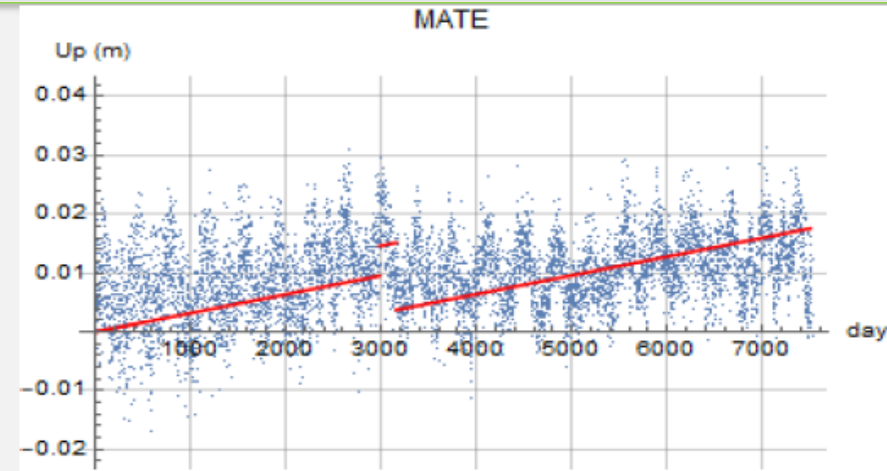
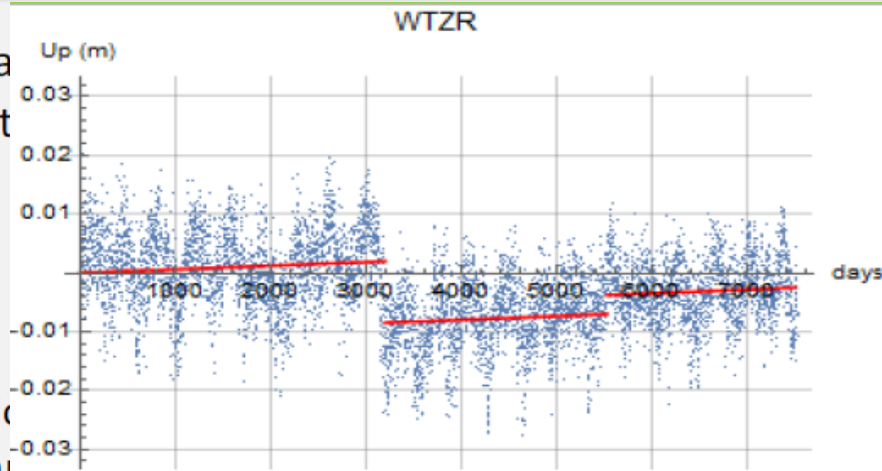
V_t = tectonic

V_{sl} and V_c are

V_{pgr} is due to

V_{hl} is the eff

V_a is due to



e.

oving Average
ws us to distinguish
e CDF is weighting

According IERS 2010 TN 36:

For Long Periodic Tides:

$$\Delta \mathbf{r}_f = \sqrt{\frac{5}{4\pi}} \cdot H_f \cdot \left\{ \begin{aligned} & \left[h(\phi) \cdot \left(\frac{3}{2} \sin^2 \phi - \frac{1}{2} \right) + \sqrt{\frac{4\pi}{5}} h' \right] \cdot \cos \theta_f \hat{\mathbf{r}} + \\ & + 3l(\phi) \cdot \sin \phi \cdot \cos \phi \cdot \sin \theta_f \hat{\mathbf{n}} + \\ & + \cos \phi \cdot \left(3l^{(1)} \cdot \sin^2 \phi - \sqrt{\frac{4\pi}{5}} l' \right) \cdot \sin \theta_f \hat{\mathbf{e}} \end{aligned} \right\}$$

For Diurnal Tides:

$$\Delta \mathbf{r}_f = \sqrt{\frac{5}{24\pi}} \cdot H_f \cdot \left\{ \begin{aligned} & 3h(\phi) \cdot \sin \phi \cdot \cos \phi \cdot \sin(\theta_f + \lambda) \hat{\mathbf{r}} + \\ & \left[3l(\phi) \cdot \cos 2\phi - 2l^{(1)} \cdot \sin^2 \phi + \sqrt{\frac{24\pi}{5}} l' \right] \cdot \sin(\theta_f + \lambda) \hat{\mathbf{n}} + \\ & \left[\left(3l(\phi) - \sqrt{\frac{24\pi}{5}} l' \right) \cdot \sin \phi - 3l^{(1)} \cdot \sin \phi \cdot \cos \phi \right] \cdot \cos(\theta_f + \lambda) \hat{\mathbf{e}} \end{aligned} \right\}$$

For Semidiurnal Tides:

$$\Delta \mathbf{r}_f = \sqrt{\frac{5}{96\pi}} \cdot H_f \cdot \left\{ \begin{aligned} & 3h(\phi) \cos^2 \phi \cdot \cos(\theta_f + 2\lambda) \hat{\mathbf{r}} + \\ & -6 [l(\phi) + l^{(1)}] \cdot \sin \phi \cdot \cos \phi \cdot \cos(\theta_f + 2\lambda) \hat{\mathbf{n}} + \\ & -6 [l(\phi) + l^{(1)} \cdot \sin^2 \phi] \cdot \cos \phi \cdot \sin(\theta_f + 2\lambda) \hat{\mathbf{e}} \end{aligned} \right\}$$

where

$$h(\phi) = h^{(0)} + h^{(2)} \cdot \left[\frac{3}{2} \cdot \sin^2 \phi - \frac{1}{2} \right]$$

$$l(\phi) = l^{(0)} + l^{(2)} \cdot \left[\frac{3}{2} \cdot \sin^2 \phi - \frac{1}{2} \right]$$

Where $h^{(0)}$ and $l^{(0)}$ are the Love and Shida Numbers. They define the tidal (vertical and planar) response of a rigid planet. It is =0 if totally rigid; =1 if totally fluid>!

For Long Periodic Tidal Constituents we have applied:

$$\Delta \mathbf{r}_f = \sqrt{\frac{5}{4\pi}} \cdot H_f \cdot \left\{ \left[h(\phi) \cdot \left(\frac{3}{2} \sin^2 \phi - \frac{1}{2} \right) + \sqrt{\frac{4\pi}{5}} h' \right] \cdot \cos \theta_f \hat{\mathbf{r}} \right. \\ \left. + 3l(\phi) \cdot \sin \phi \cdot \cos \phi \cdot \sin \theta_f \hat{\mathbf{n}} \right. \\ \left. + \cos \phi \cdot \left(3l^{(1)} \cdot \sin^2 \phi - \sqrt{\frac{4\pi}{5}} l' \right) \cdot \sin \theta_f \hat{\mathbf{e}} \right\}$$

where

$$h(\phi) = h^{(0)} + h^{(2)} \cdot \left[\frac{3}{2} \cdot \sin^2 \phi - \frac{1}{2} \right]$$

$$l(\phi) = l^{(0)} + l^{(2)} \cdot \left[\frac{3}{2} \cdot \sin^2 \phi - \frac{1}{2} \right]$$

H_f = amplitude (m) of the tidal term of frequency f ,

Φ = geocentric latitude of station,

λ = east longitude of station,

Θ_f = tide argument for tidal constituent with frequency f .

$\hat{\mathbf{r}}$ = unit vector in radial direction,

$\hat{\mathbf{e}}$ = unit vector in east direction,

$\hat{\mathbf{n}}$ = unit vector perpendicular to $\hat{\mathbf{r}}$ in the northward direction.

Period (days)	Amp. of SET Hf (m)	Freq. (cpsd)	Phase	$h^{(0)R}$	$h^{(0)I}$	$h^{(2)}$	h'	$l^{(0)R}$	$l^{(0)I}$	$l^{(1)}$	$l^{(2)}$
6798.38	0.02793	0.000147	NA	0.6344	-0.0093	-0.0006	0.0001	0.0936	-0.0028	0	-0.0002
182.62	0.0310	0.005476	NA	0.6182	-0.0054	-0.0006	0.0001	0.0886	-0.0016	0	-0.0002
27.55	-0.0352	0.036297	NA	0.6126	-0.0041	-0.0006	0.0001	0.087	-0.0012	0	0.0002
13.66	-0.06663	0.073206	NA	0.6109	-0.0037	-0.0006	0.0001	0.0864	-0.0011	0	0.0002
13.63	-0.02762	0.073149	NA	0.6109	-0.0037	-0.0006	0.0001	0.0864	-0.0011	0	0.0002

H_f = amplitude (m) of the tidal term of frequency f ,

Φ = geocentric latitude of station,

λ = east longitude of station,

Θ_f = tide argument for tidal constituent with frequency f

$\hat{r}$ = unit vector in radial direction,

$\hat{e}$ = unit vector in east direction,

$\hat{n}$ = unit vector perpendicular to $\hat{r}$ in the northward direction.

0 NLLS applied in one by one mode for Long Periodic Tidal Constituents

We have applied a Levenberg Marquardt non linear least square fit.

We have fixed a constraint in the values of LOVE & SHIDA nrs:

$$L_{GSET}-0.3 < L < L_{GSET}+0.3;$$

$$S_{GSET}-0.05 < S < S_{GSET}+0.05$$

Values close to the edges mean that the regression doesn't converge.

We have estimated L-S of each 5 tidal constituents one by one, together with the slope $a+b \cdot t$, the (very strong) annual harmonic and the phase of the tidal constituents:

Added Parameter: phase of tidal constituent for each stations

$$\sin[\theta_f + m\lambda] \rightarrow \sin[\omega_f \cdot t + \varphi_f + m\lambda]$$

φ_f to be computed with the tide model

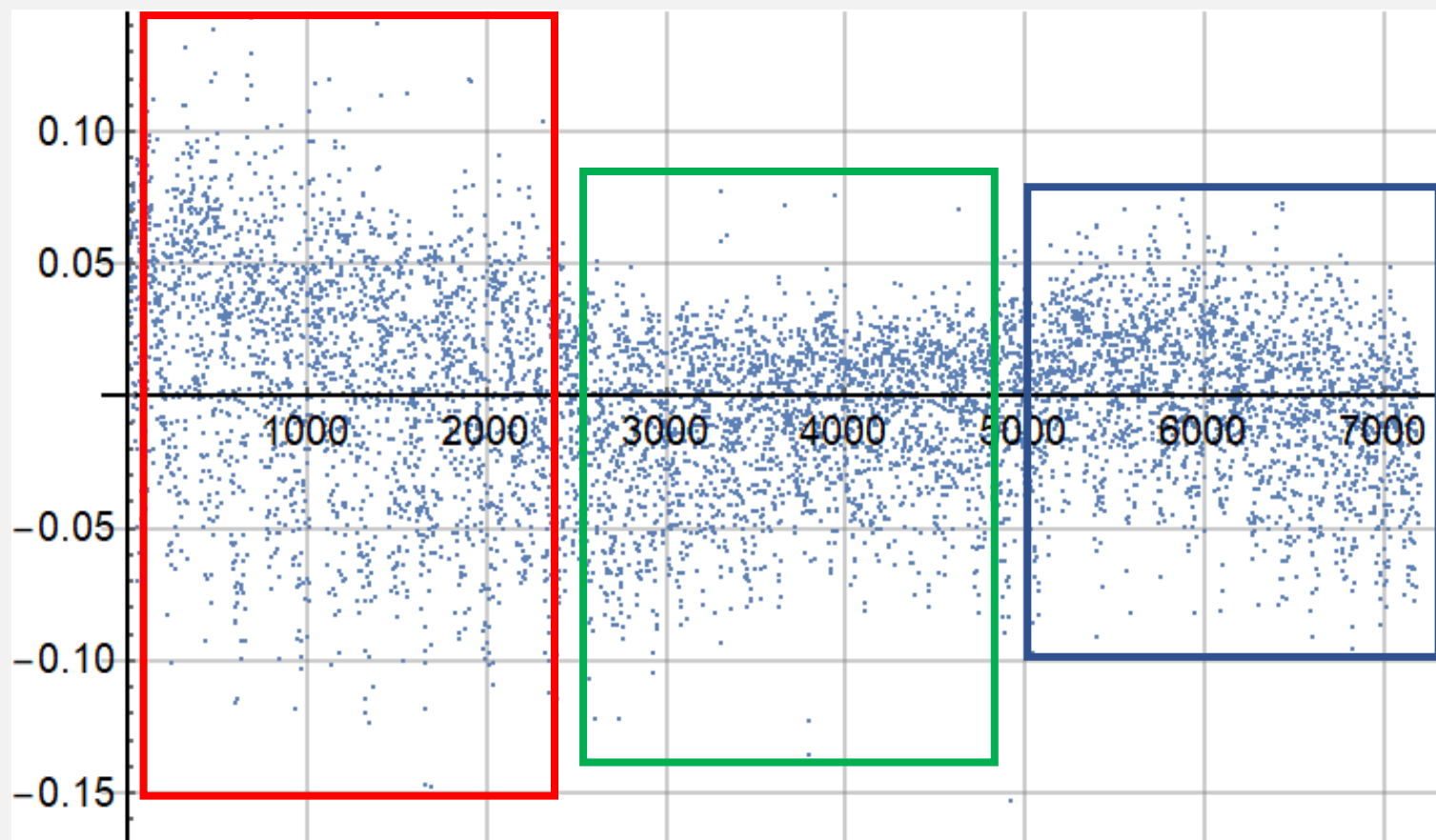
We have put the constraint as 0 the first value of NEU time series

Table 5: Table of estimated Love/Shida numbers for site-specific LSET v2 results; red color indicates values stemming from GSET, values deviating to the IERS2010 (GSET) model are indicated with underline

STATION	LAT	LON	LOVE 18,6Y	LOVE 0,5Y	LOVE 27,55D	LOVE 13,66D	LOVE 13,63D	SHIDA 18,6Y	SHIDA 0,5Y	SHIDA 27,55D	SHIDA 13,66D	SHIDA 13,63D
GOPE	49,9137	14,7856	0,5744	0,5712	0,6126	0,6109	0,6109	0,093656	0,088604	0,087256	0,086086	0,086254
GOP7	49,9137	14,7856	0,5493	0,5398	0,5221	0,5326	0,6109	0,081148	0,088600	0,086916	0,086843	0,086300
MATE	40,6491	16,7045	0,5509	0,5712	0,5685	0,5707	0,5697	0,093509	0,088602	0,086902	0,086637	0,086503
MAT1	40,6491	16,7045	0,5974	0,5883	0,5667	0,5547	0,5543	0,093450	0,088605	0,086867	0,086658	0,086573
WTZR	49,1442	12,8789	0,5568	0,5711	0,6126	0,5740	0,5709	0,093698	0,088608	0,087075	0,086402	0,086392
WTZZ	49,1442	12,8789	0,5946	0,6182	0,5665	0,5245	0,6109	0,092586	0,088600	0,086868	0,087419	0,086509
ZIMM	46,8771	7,4653	0,5592	0,5711	0,5675	0,5728	0,5705	0,093497	0,088607	0,086938	0,086422	0,086400
AIRA	31,8241	130,5996	0,5944	0,5712	0,5700	0,5678	0,5685	0,093603	0,088597	0,087004	0,086389	0,086396
ALBH	48,3898	236,5125	0,5573	0,5711	0,5666	0,5738	0,5708	0,093634	0,088605	0,087009	0,086524	0,086406
ALIC	-23,6701	133,8855	0,5939	0,5713	0,5711	0,6109	0,5677	0,093583	0,088605	0,086841	0,086715	0,086480
ANKR	39,8874	32,7585	0,5576	0,5706	0,5694	0,5675	0,5683	0,093407	0,088601	0,086997	0,086395	0,086400
AQUI	42,3682	13,3502	0,5573	0,5712	0,5677	0,5700	0,5683	0,093598	0,088603	0,086894	0,086646	0,086487
ARTU	56,4298	58,5605	0,5733	0,5711	0,7295	0,6109	0,6109	0,093636	0,088610	0,087342	0,086400	0,085878
AV27	54,4924	195,2768	0,6035	0,5350	0,5753	0,6352	0,6516	0,093600	0,088600	0,087000	0,086400	0,086400
BAKO	-6,4911	106,8489	0,5954	0,5713	0,5728	0,6109	0,5670	0,093772	0,088598	0,087002	0,086651	0,086503
BEPK	35,8784	241,9259	0,5705	0,5855	0,5554	0,5552	0,5552	0,093597	0,088601	0,087000	0,086401	0,086400
BHST	-39,4892	176,0632	0,6272	0,6109	0,6126	0,6109	0,6109	0,093625	0,085109	0,087000	0,086400	0,086400
CAS1	-66,2834	110,5197	0,6372	0,5711	0,6126	0,5780	0,5729	0,093600	0,088440	0,087442	0,088716	0,085896
CCCC	35,5653	242,3288	0,5705	0,5855	0,5554	0,5552	0,5552	0,093606	0,088604	0,086997	0,086403	0,086402
DARW	-12,8437	131,1327	0,6344	0,6182	0,6126	0,6109	0,6109	0,093600	0,088600	0,086641	0,086301	0,086389
DRAG	31,5932	35,3921	0,5573	0,5714	0,5701	0,5678	0,5685	0,093602	0,088601	0,087003	0,086394	0,086397
FAIR	64,9780	212,5008	0,5546	0,5711	0,6126	0,5734	0,5685	0,093600	0,088661	0,087000	0,086400	0,086400
FIOC	64,8749	341,9940	0,6344	0,5248	0,5896	0,6791	0,6720	0,093600	0,088600	0,087216	0,086400	0,086400
HOB2	-42,8047	147,4387	0,5924	0,5712	0,5681	0,5713	0,5699	0,093620	0,088589	0,087206	0,085953	0,086227
HOFN	64,2673	344,8021	0,6344	0,5710	0,6126	0,6371	0,5733	0,093646	0,088684	0,087309	0,086319	0,086197
HOLB	50,6404	231,8650	0,5745	0,5711	0,5663	0,5745	0,5711	0,093561	0,088606	0,086992	0,086600	0,086407
HYDE	17,4173	78,5509	0,6344	0,5895	0,6126	0,6109	0,6109	0,056625	0,088600	0,087000	0,086400	0,086400
CHUR	58,7591	265,9113	0,5452	0,5712	0,6126	0,5769	0,5721	0,093447	0,088888	0,086921	0,086400	0,086528
IISC	13,0212	77,5704	0,5569	0,5733	0,6126	0,6109	0,6109	0,093382	0,088756	0,087014	0,086618	0,086404
ISTA	41,1044	29,0193	0,5645	0,6182	0,6126	0,5542	0,5543	0,093881	0,088758	0,087000	0,086509	0,086529
KAON	19,2779	204,7176	0,6344	0,6182	0,5518	0,6109	0,6109	0,093600	0,088600	0,088353	0,086400	0,086400
KOUC	-20,5587	164,2873	0,5959	0,5712	0,5715	0,5650	0,5673	0,093429	0,088605	0,086751	0,086572	0,086410
KOUR	5,2522	307,1940	0,5955	0,5713	0,5724	0,5632	0,6109	0,093598	0,088603	0,087233	0,086030	0,086139
LHAS	29,6573	91,1040	0,5739	0,5655	0,5651	0,5631	0,5631	0,093609	0,088603	0,087084	0,086298	0,086530
LPGS	-34,9067	302,0677	0,5923	0,5712	0,5695	0,5688	0,5689	0,093593	0,088600	0,086998	0,086401	0,086401
MAUI	20,7067	203,7430	0,5567	0,5713	0,5715	0,5649	0,5673	0,093488	0,088599	0,087076	0,086376	0,086324
MENL	-39,4442	176,6965	0,5506	0,6182	0,6126	0,5501	0,6109	0,093600	0,088600	0,087000	0,086400	0,086400
METS	60,2175	24,3953	0,5732	0,5711	0,6126	0,6237	0,5728	0,093809	0,088614	0,087357	0,086134	0,086236
MKEA	19,8014	204,5437	0,5562	0,5712	0,5716	0,5647	0,5672	0,093569	0,088597	0,087104	0,086377	0,086316
NICO	35,1410	33,3964	0,5762	0,5712	0,5695	0,5689	0,5689	0,093600	0,088600	0,087000	0,086400	0,086400

STATION	LAT	LON	LOVE 18,6Y	LOVE 0,5Y	LOVE 27,55D	LOVE 13,66D	LOVE 13,63D	SHIDA 18,6Y	SHIDA 0,5Y	SHIDA 27,55D	SHIDA 13,66D	SHIDA 13,63D
NOT1	36,8758	14,9898	0,5508	0,5559	0,5554	0,5574	0,5574	0,093531	0,088599	0,086992	0,086482	0,086409
NRIL	69,3618	88,3598	0,6344	0,5564	0,6126	0,5650	0,5209	0,099802	0,088600	0,087000	0,087641	0,086400
ONSA	57,3953	11,9255	0,5552	0,5711	0,6126	0,6109	0,5723	0,093469	0,088614	0,087227	0,086272	0,086252
ORVB	39,5546	238,4997	0,5757	0,5712	0,5686	0,5708	0,5696	0,093606	0,088601	0,087003	0,086402	0,086399
P104	39,9421	139,7035	0,6309	0,5487	0,5892	0,6100	0,5772	0,093599	0,088600	0,087000	0,086400	0,102736
P201	45,4078	141,6853	0,6344	0,6182	0,6126	0,5879	0,5884	0,093600	0,088600	0,084944	0,085391	0,086400
PETP	53,0667	158,6071	0,5912	0,5854	0,5778	0,6109	0,6109	0,093597	0,088614	0,086895	0,086968	0,086631
PIMO	14,6357	121,0777	0,6344	0,6182	0,6126	0,6109	0,6109	0,093600	0,088663	0,087000	0,086400	0,085966
POL2	42,6798	74,6943	0,5565	0,5712	0,5677	0,5719	0,5700	0,093517	0,088603	0,086997	0,086536	0,086416
RAMT	35,3387	242,3167	0,5509	0,5855	0,5554	0,5552	0,5552	0,093601	0,088600	0,087000	0,086400	0,086400
REYK	64,1388	338,0445	0,5555	0,5710	0,6126	0,5786	0,5727	0,093965	0,088660	0,087305	0,086320	0,086215
SANT	-33,1503	289,3314	0,5942	0,5712	0,5698	0,5683	0,5687	0,093660	0,088601	0,087003	0,086393	0,086398
STJO	47,5952	307,3223	0,5911	0,5710	0,5669	0,5730	0,5707	0,093608	0,088613	0,086931	0,086766	0,086499
SUMK	44,2081	73,9971	0,5746	0,5712	0,6126	0,6109	0,5708	0,093607	0,088601	0,087057	0,086416	0,086392
SUWN	37,2755	127,0542	0,5571	0,5712	0,5692	0,5695	0,5692	0,093610	0,088602	0,086998	0,086459	0,086405
TEHN	35,6973	51,3341	0,5547	0,5548	0,5997	0,5542	0,5534	0,093601	0,088606	0,086991	0,086390	0,086398
TPW2	46,2074	236,2316	0,5749	0,5711	0,6126	0,6109	0,5705	0,093552	0,088603	0,086996	0,086538	0,086414
TSEA	61,1873	210,1050	0,6344	0,5711	0,6126	0,6109	0,5727	0,093431	0,088609	0,087289	0,084344	0,086044
UCLU	48,9256	234,4584	0,5579	0,5706	0,5671	0,6109	0,5707	0,093413	0,088604	0,086989	0,086634	0,086341
ULAB	47,8651	107,0523	0,6344	0,5544	0,5546	0,6109	0,5565	0,094021	0,088873	0,086707	0,086215	0,086474
USUD	36,1331	138,3620	0,5603	0,5712	0,5693	0,5692	0,5691	0,093619	0,088601	0,087010	0,086340	0,086394
VGMO	-39,4074	175,7543	0,6344	0,6182	0,6126	0,6109	0,5463	0,093600	0,087421	0,087000	0,086400	0,086400
VGMT	-39,3846	175,4705	0,5643	0,6182	0,5617	0,5621	0,5629	0,094117	0,088600	0,087000	0,086400	0,086400
VGOB	-39,1998	175,5422	0,6344	0,6182	0,6126	0,6109	0,5518	0,094669	0,087935	0,088468	0,086400	0,125084
VILL	40,4436	356,0480	0,6344	0,5711	0,5685	0,5706	0,5696	0,094120	0,088599	0,086878	0,086653	0,086475
VNDP	34,5563	239,3836	0,5763	0,5713	0,5694	0,5687	0,5688	0,093599	0,088600	0,087000	0,086398	0,086399
WGTN	-41,3235	174,8059	0,5509	0,5518	0,5500	0,5791	0,5806	0,095689	0,088674	0,086972	0,086589	0,086496
WHIT	60,7505	224,7779	0,5733	0,5712	0,6126	0,6109	0,6109	0,093600	0,088605	0,087126	0,086327	0,086243
WPUK	-40,0642	176,4406	0,6344	0,6182	0,6126	0,6126	0,6109	0,093460	0,087632	0,087013	0,057460	0,086400
WUHN	30,5317	114,3573	0,5579	0,5712	0,5702	0,5675	0,5683	0,093597	0,088598	0,087009	0,086244	0,086386
XMIS	-10,4500	105,6885	0,6344	0,6182	0,5732	0,6109	0,6109	0,093600	0,095682	0,087000	0,086400	0,086400
ZECK	43,7884	41,5651	0,5502	0,5711	0,6126	0,6109	0,5702	0,093485	0,088594	0,087067	0,086892	0,086414

Release V3: why not ?



Less noisy!

- **Software modification & strategy**

- Implementing Local SET in the G-Nut/Geb software
- Implementing SET decomposition in the G-Nut software (new module for validation)
- Testing the software & processing strategy

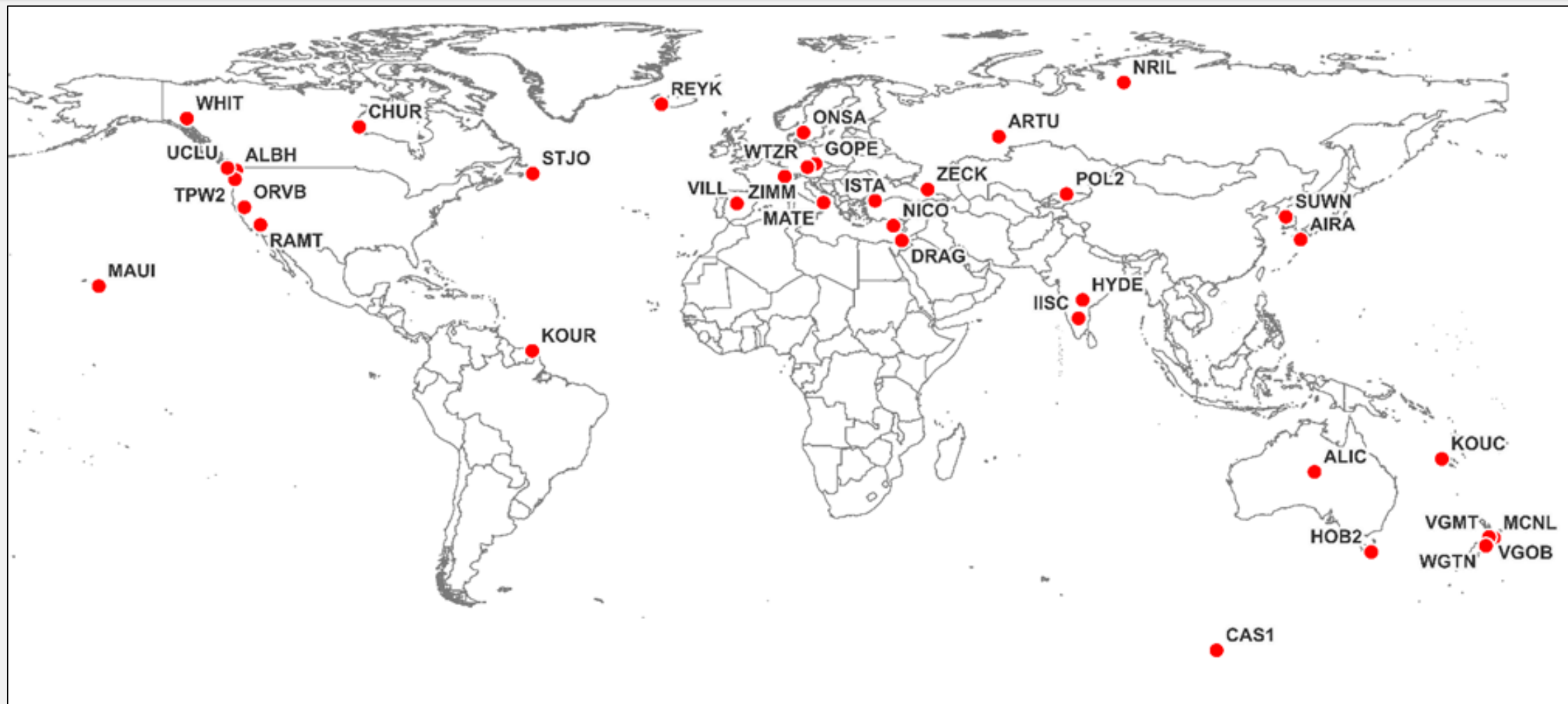
- **GNSS processing design (initial testing)**

- 39 station selected from GLOBAL network
- 2000-2020 data processing
- Configuration consistent with/without LSET model
- Daily coordinate output + repeatability

- **Three iterative updates of the LSET solution**

- Different modelling applied (see later slides)

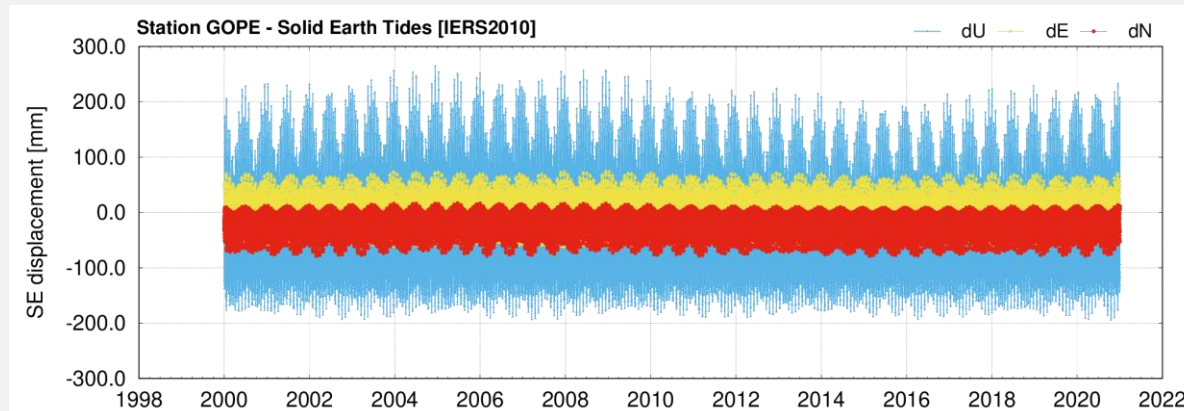
Stations (39) selected for LSET validation



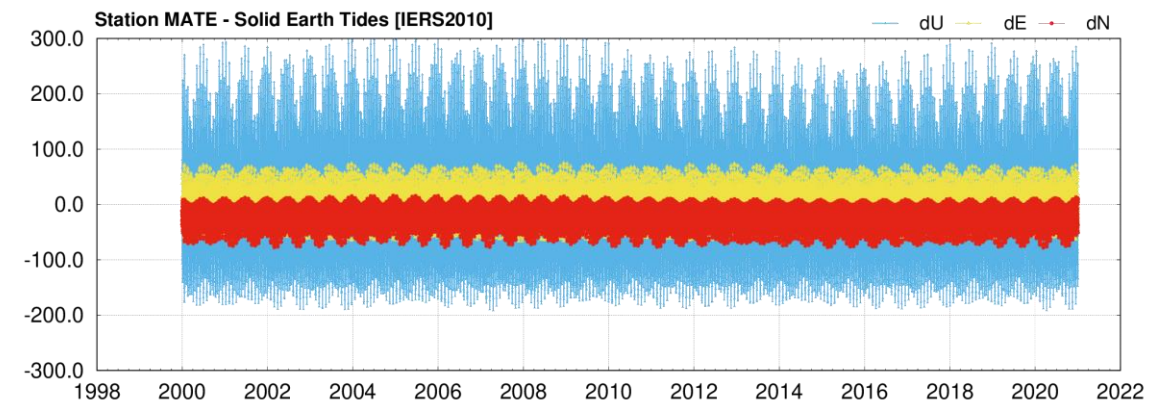
IERS2010 conventions, attractions from MOON & SUN

- **in2d** – in-phase degree 2 nominal tides (step1)
- **in3d** – in-phase degree 3 nominal tides (step1)
- **ou3d** – out-of-phase degree 2 nominal tides (step1)
- **s2di** – frequency-dependent short-term tides (step2, deviations from nominal)
- **s2lo** – frequency-dependent long-term tides (step2, deviations from nominal)

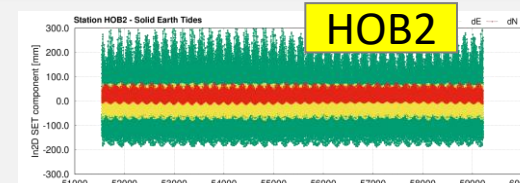
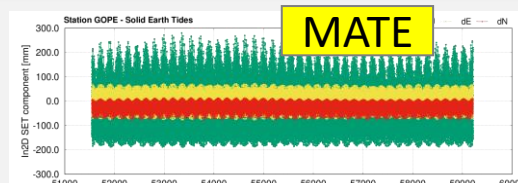
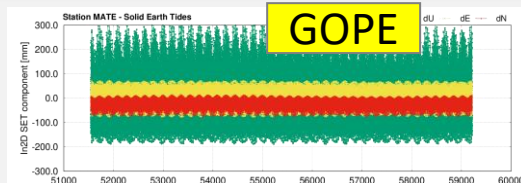
GOPE (full SET)



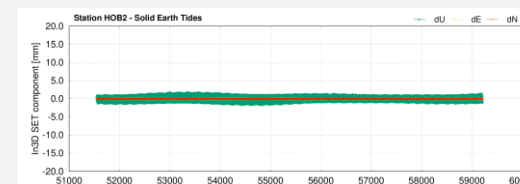
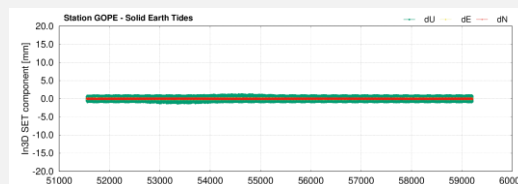
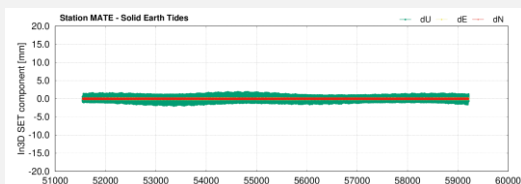
MATE (full SET)



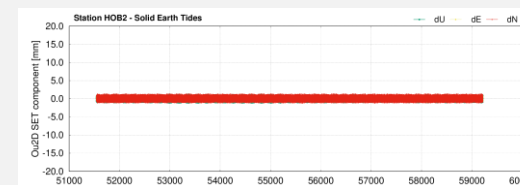
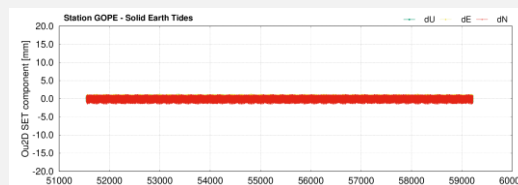
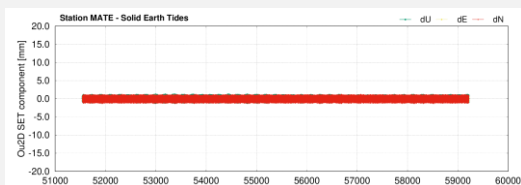
in2d



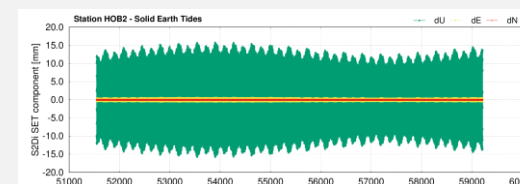
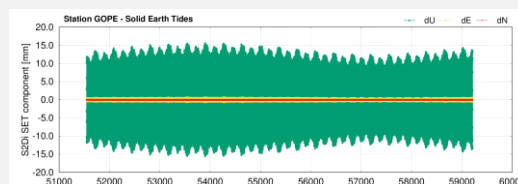
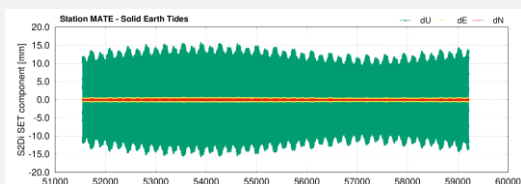
in3d



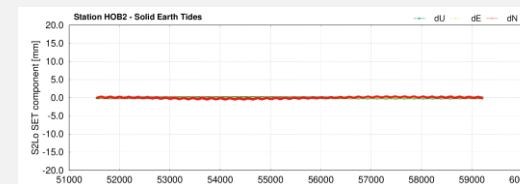
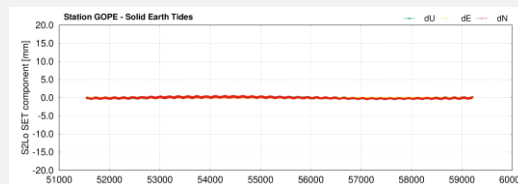
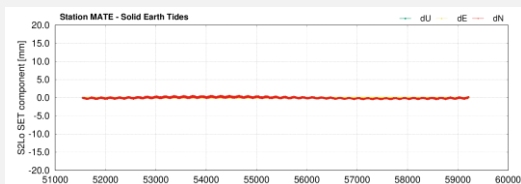
ou2d

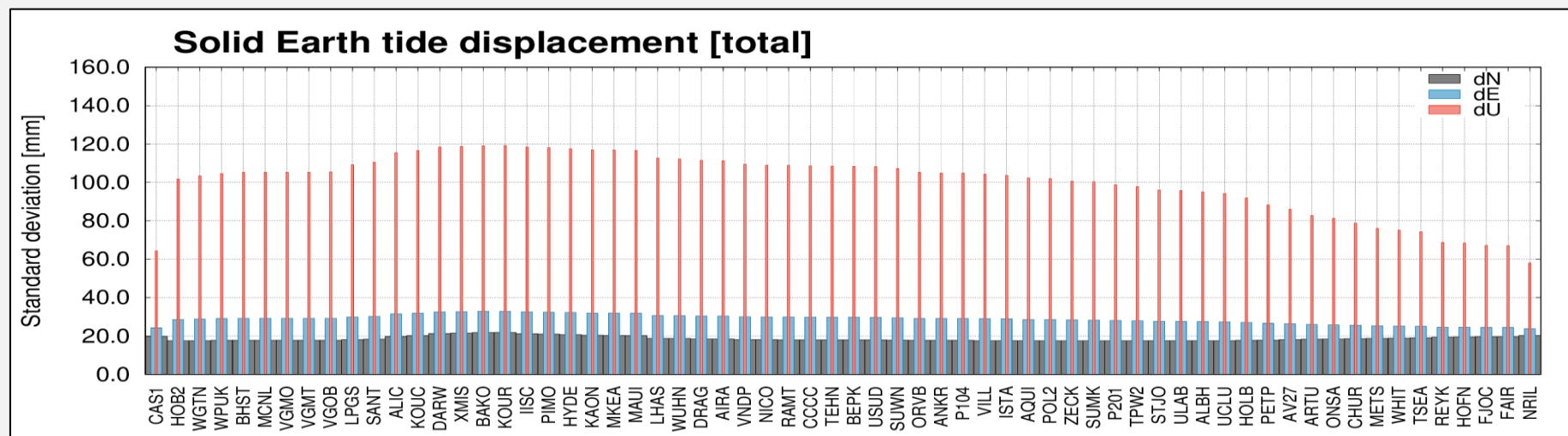
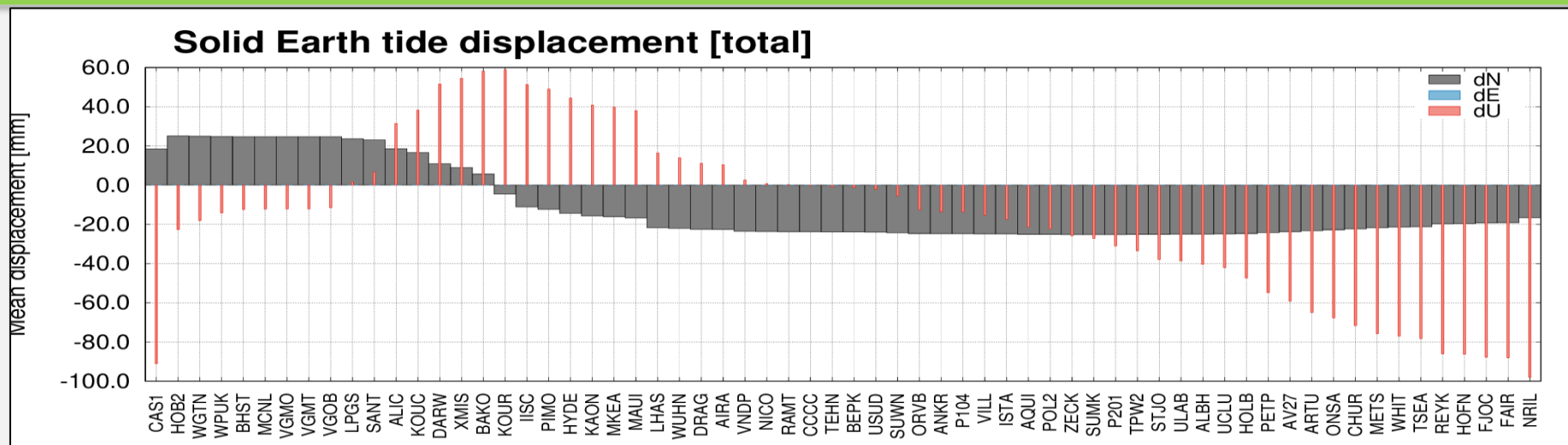


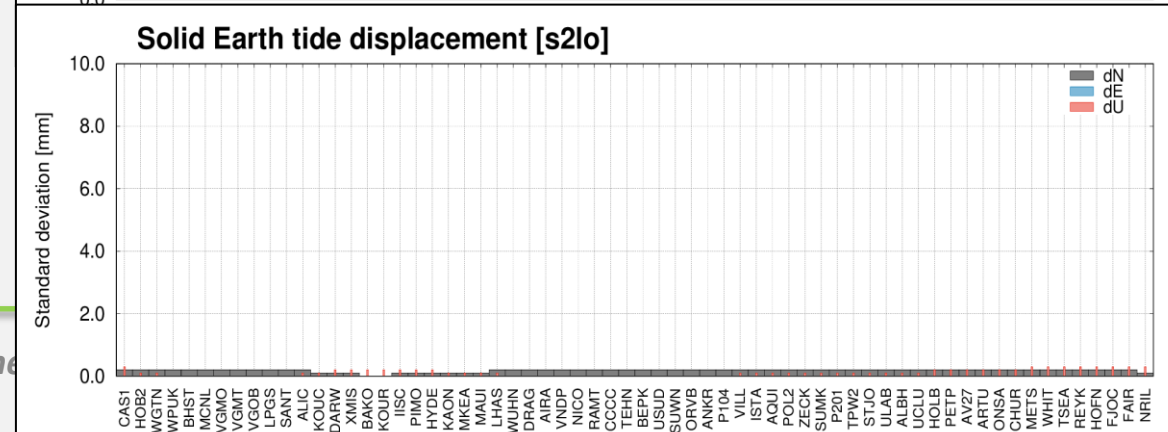
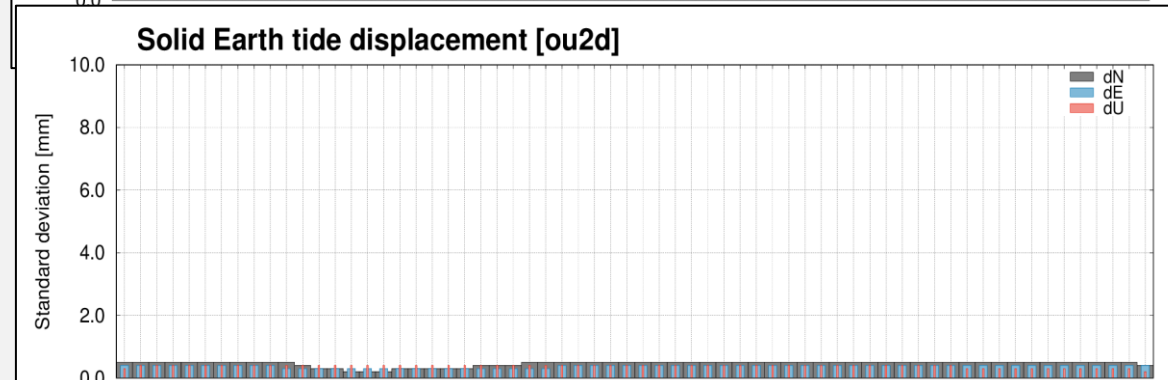
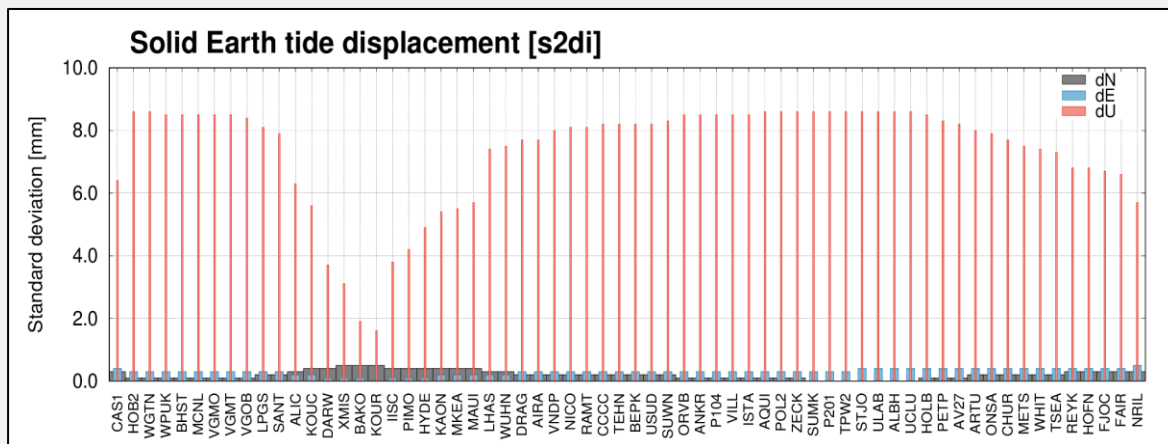
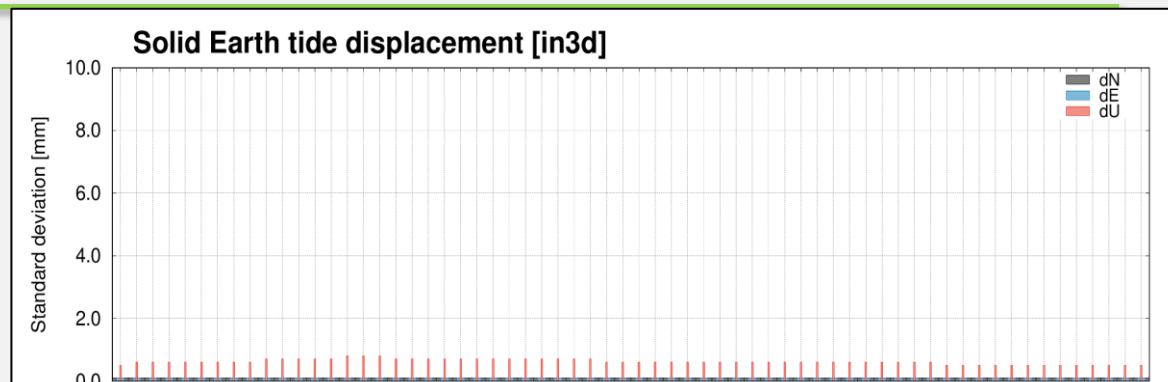
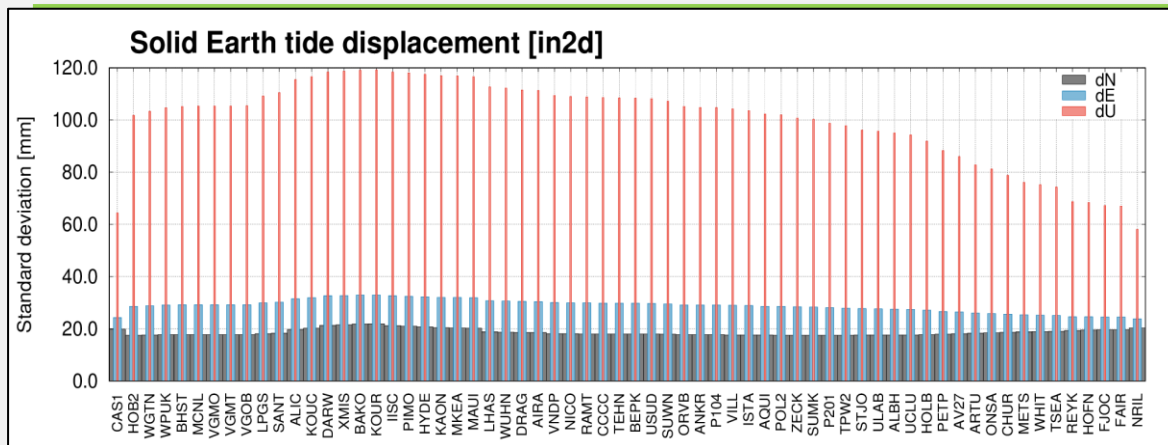
s2di



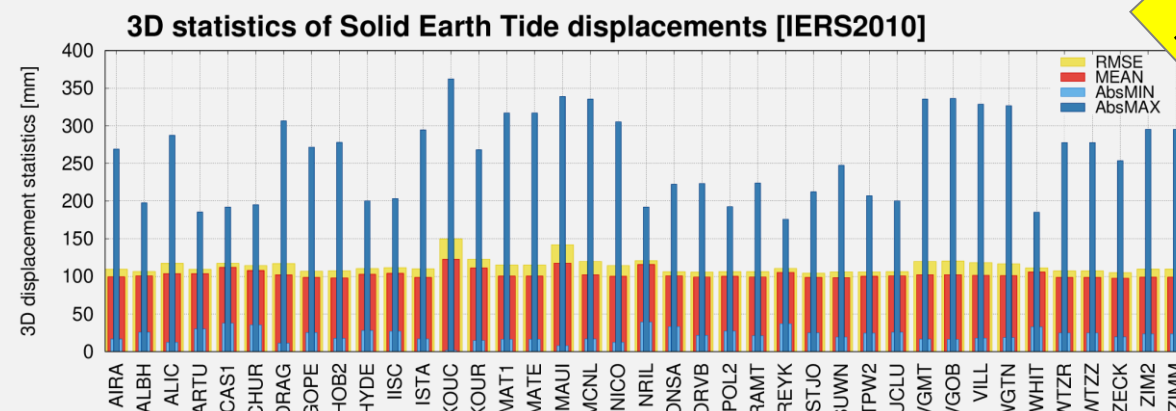
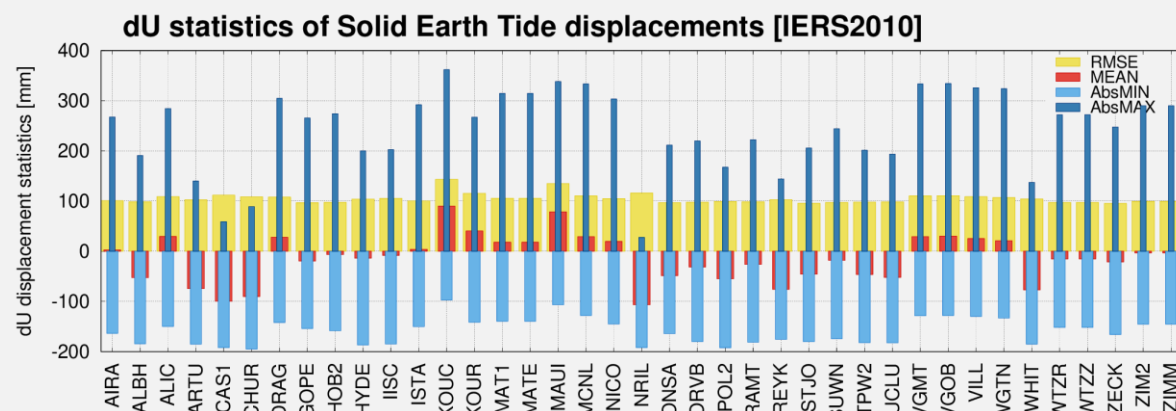
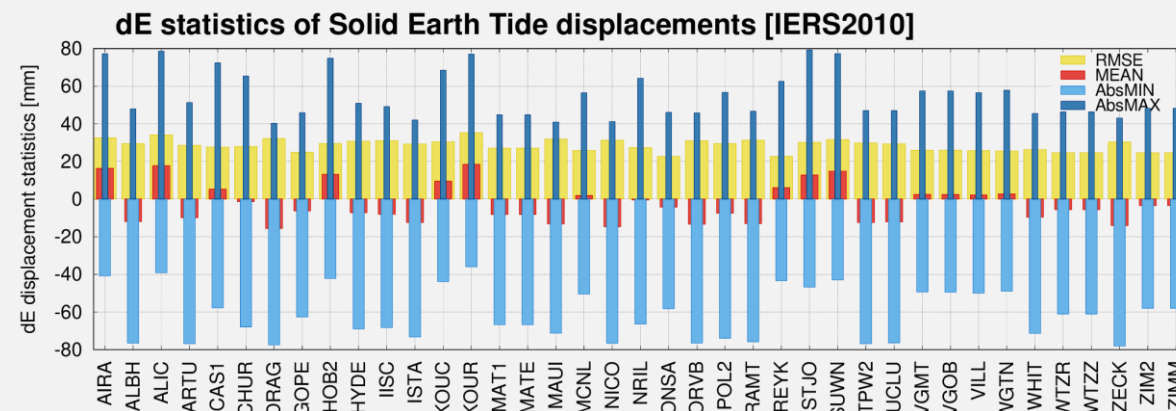
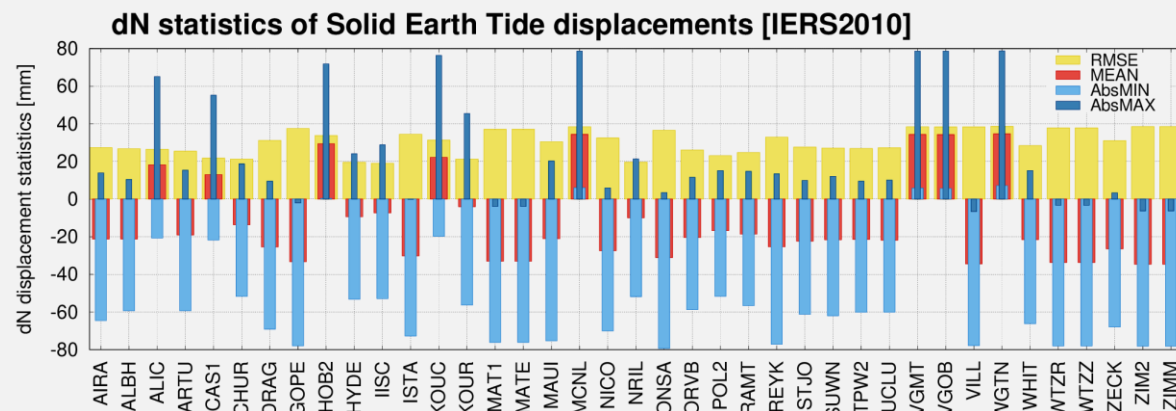
s2lo





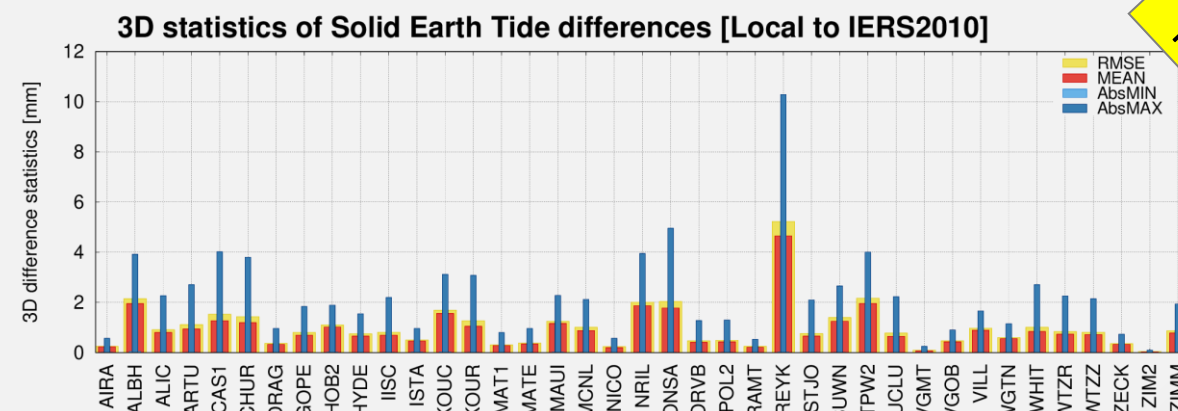
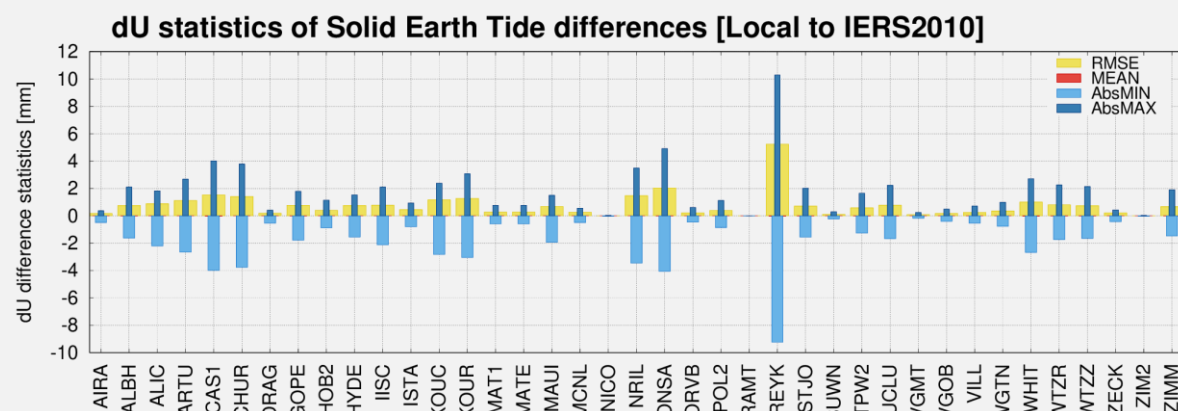
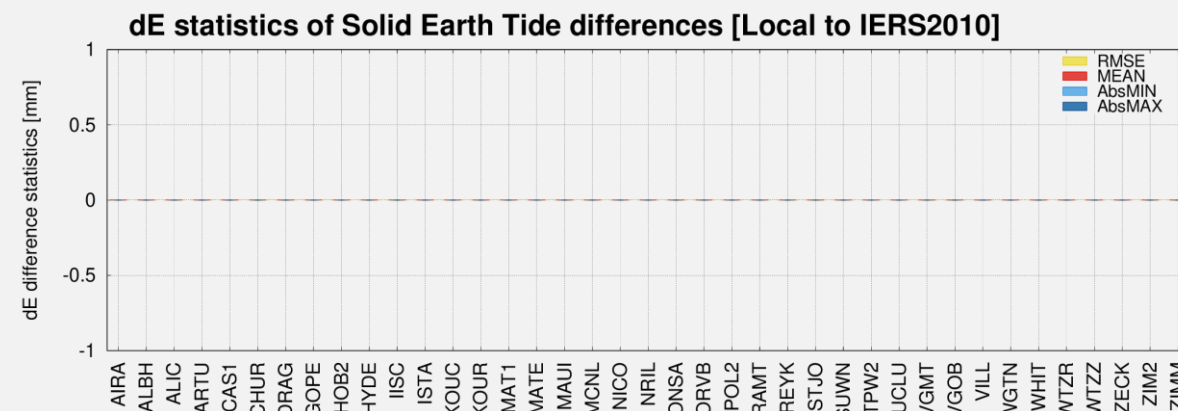
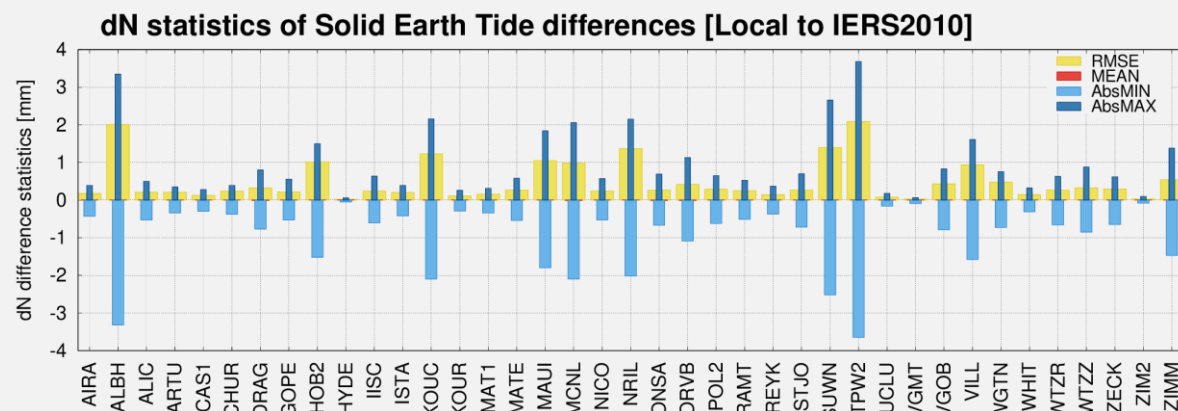


Components: dN + dU (left) and dE + 3D (right)



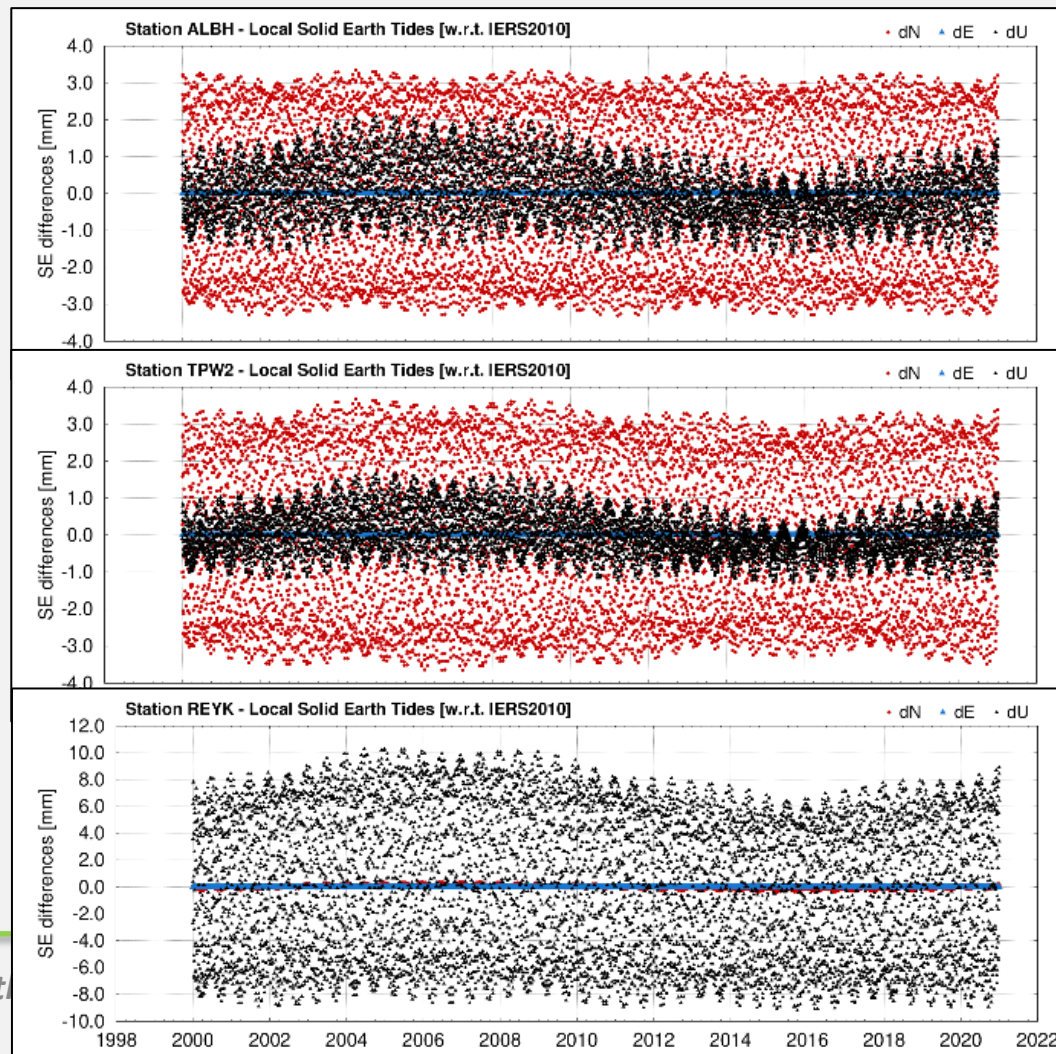
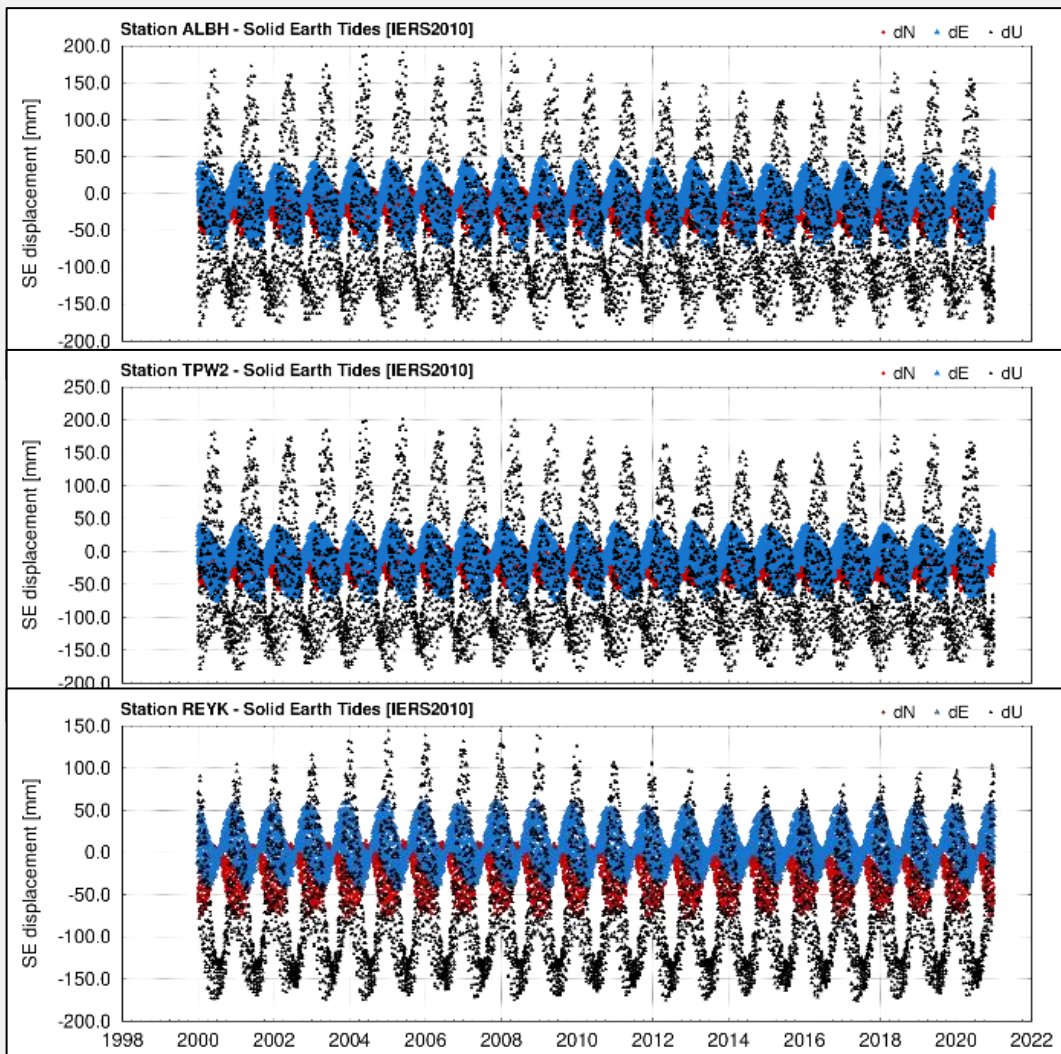
Total

The highest LSET – IERS2010 differences – REYK (dU $\approx$ 10mm), ALBH + TPW2 (dN $\approx$ 3-4mm)

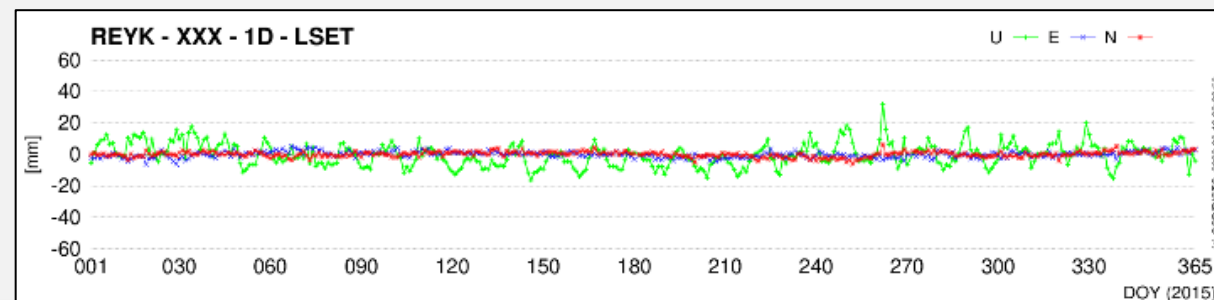
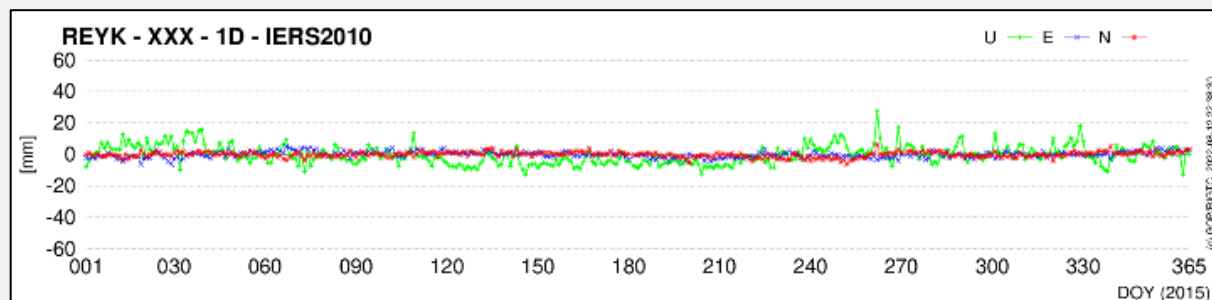
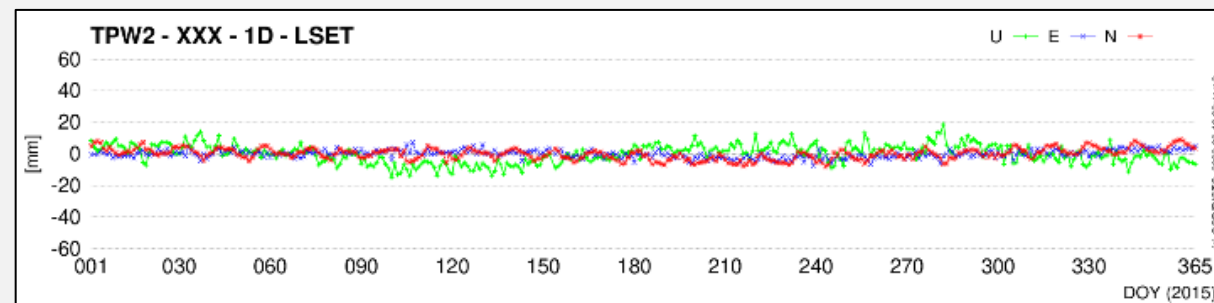
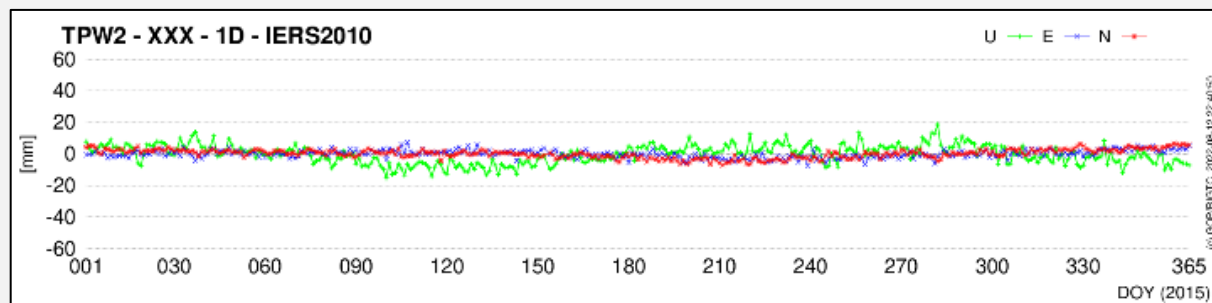
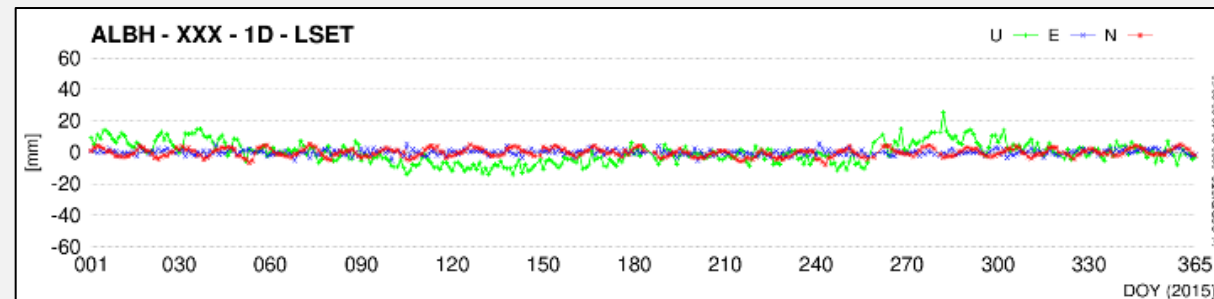
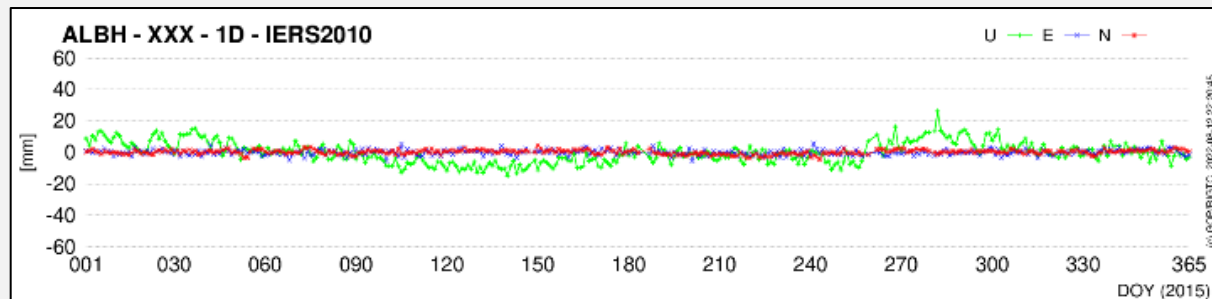


Total

- Full LSET (left) + LSET-IERS2010 (right) ... dominant frequency 13.66 days (max 4 mm, but REYK 10mm)



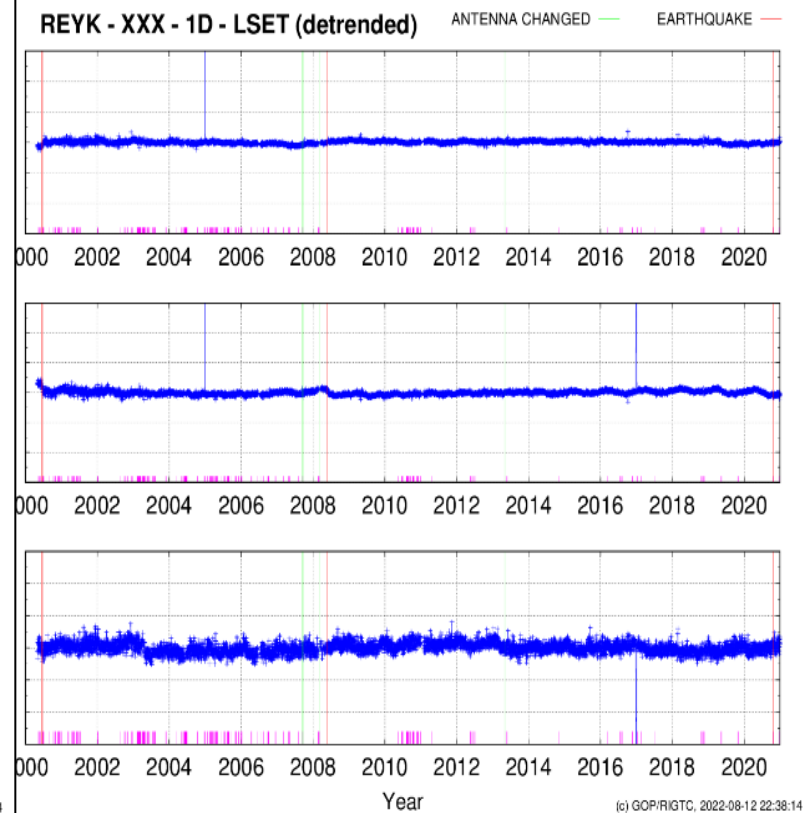
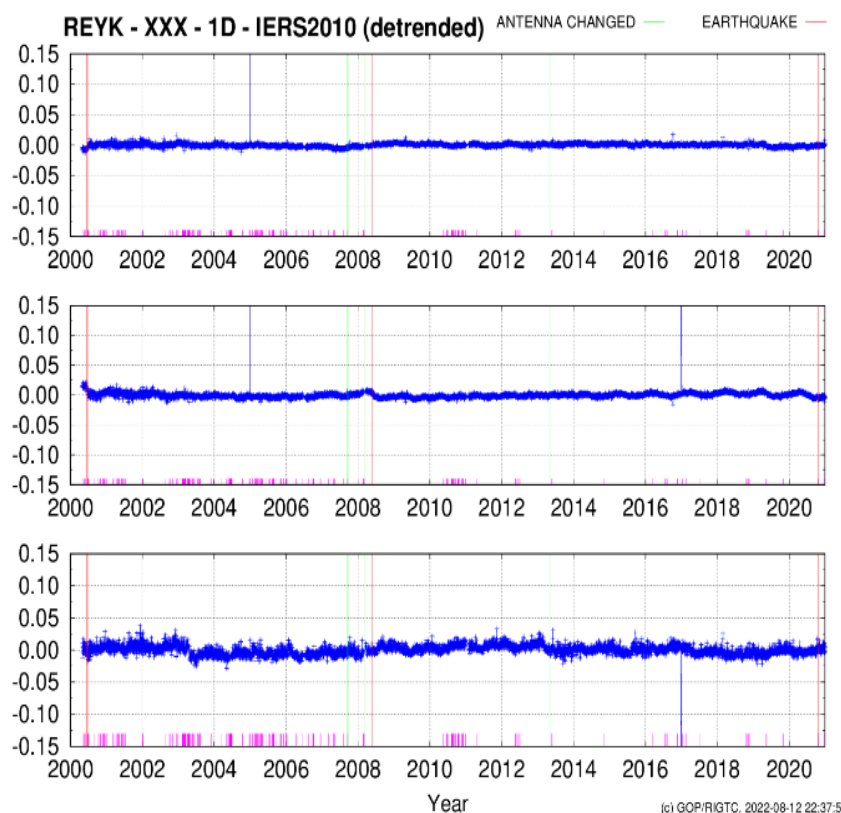
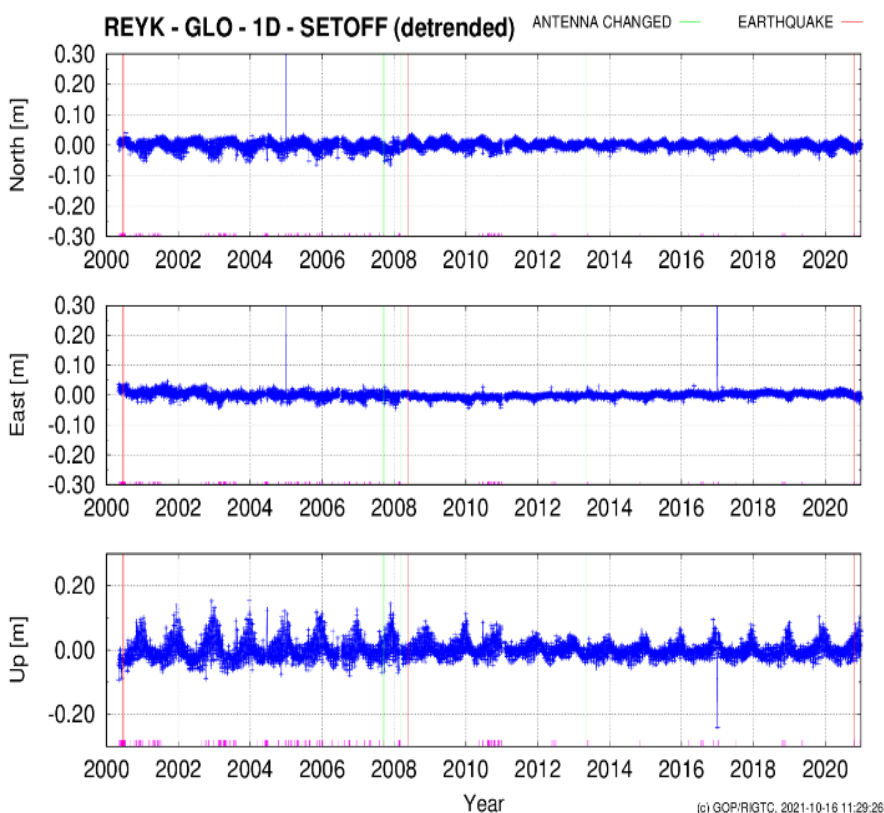
year 2015 – IERS2010 (left) + LSET (right) ... stations: ALBH, TPW2, REYK



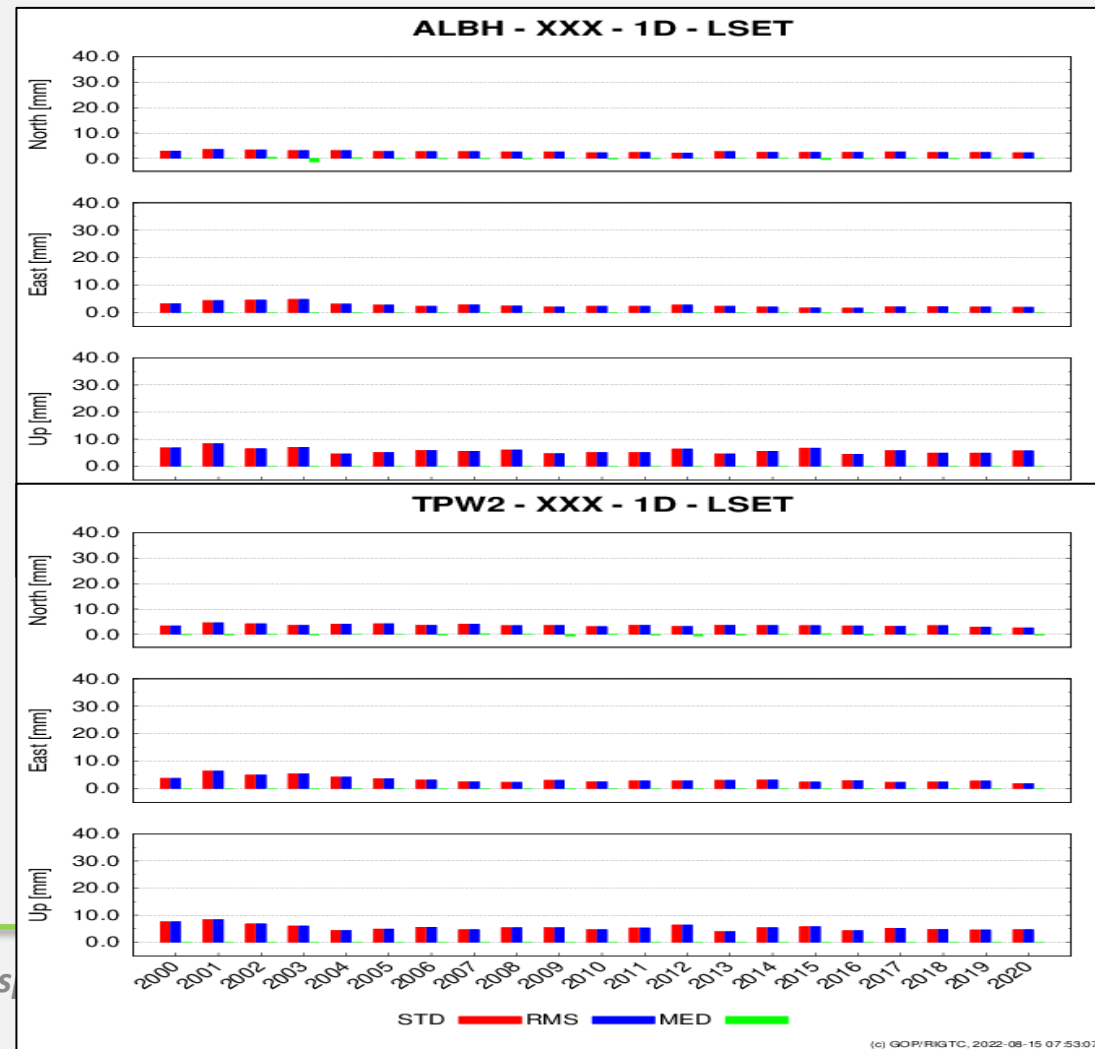
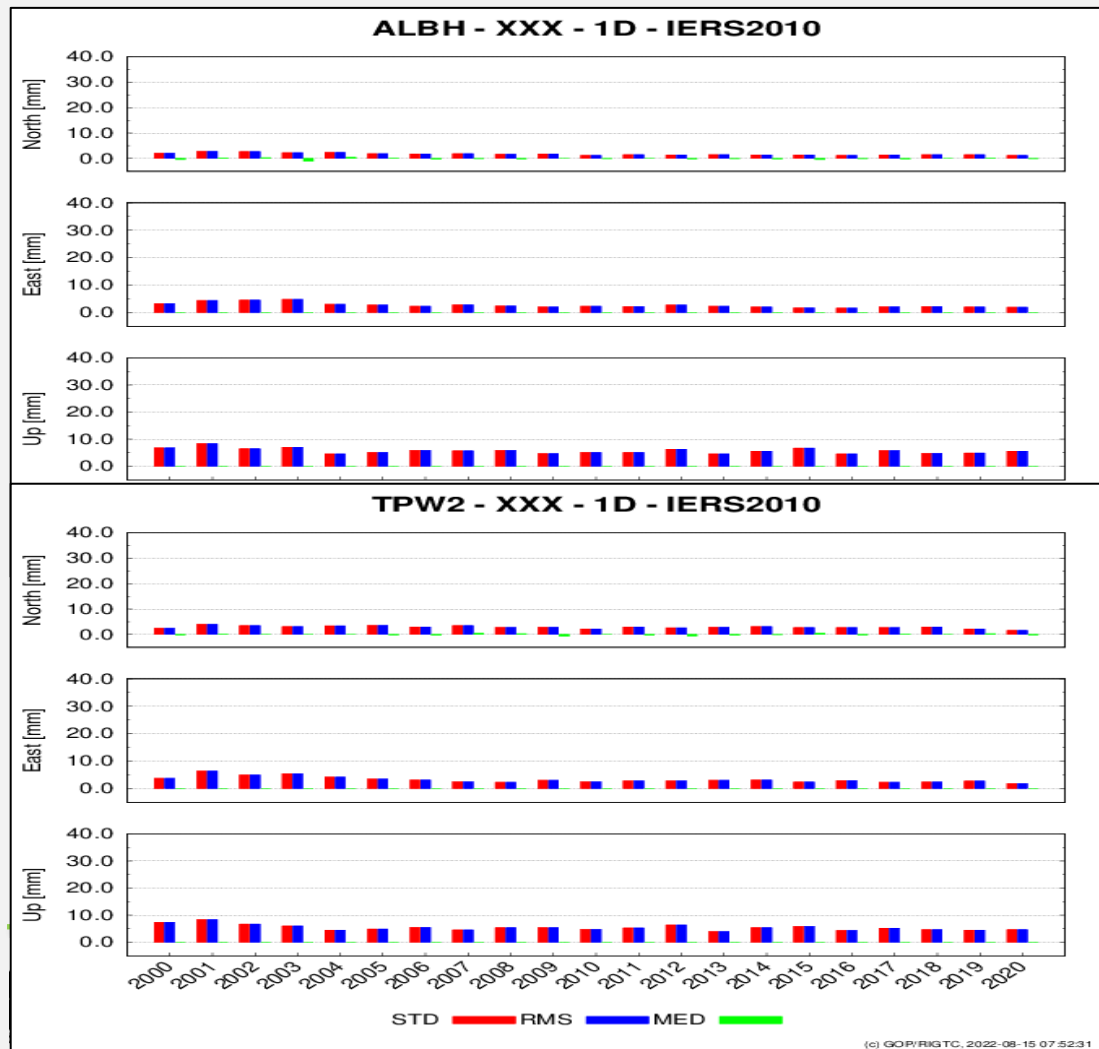
20-years N/E/U time series – station REYK
no model (left)

using IERS2010 (middle)

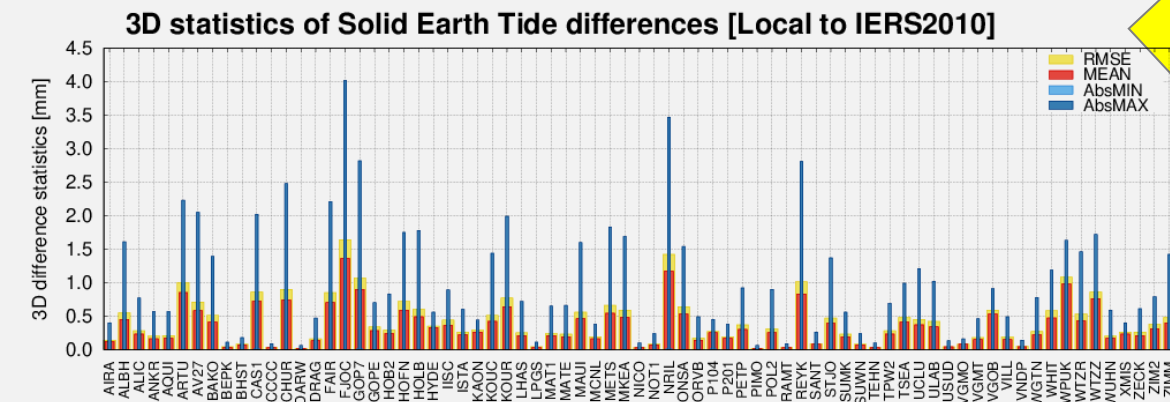
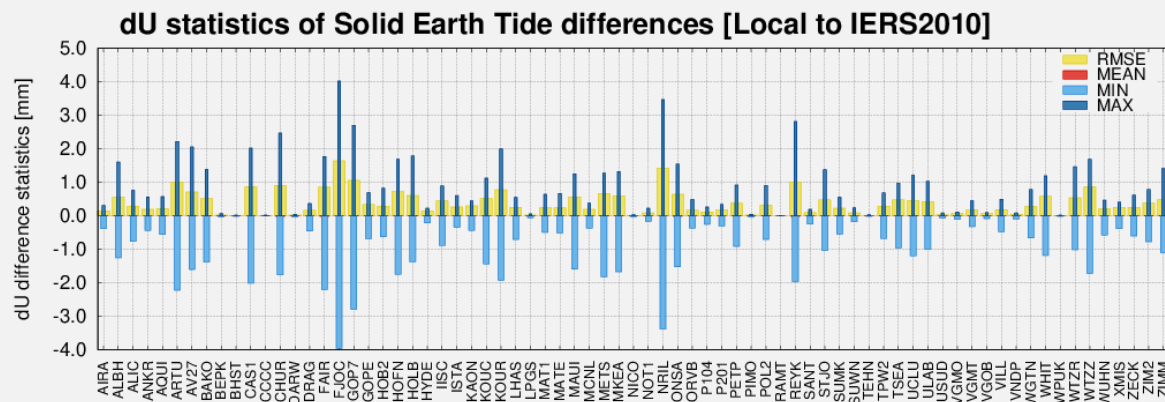
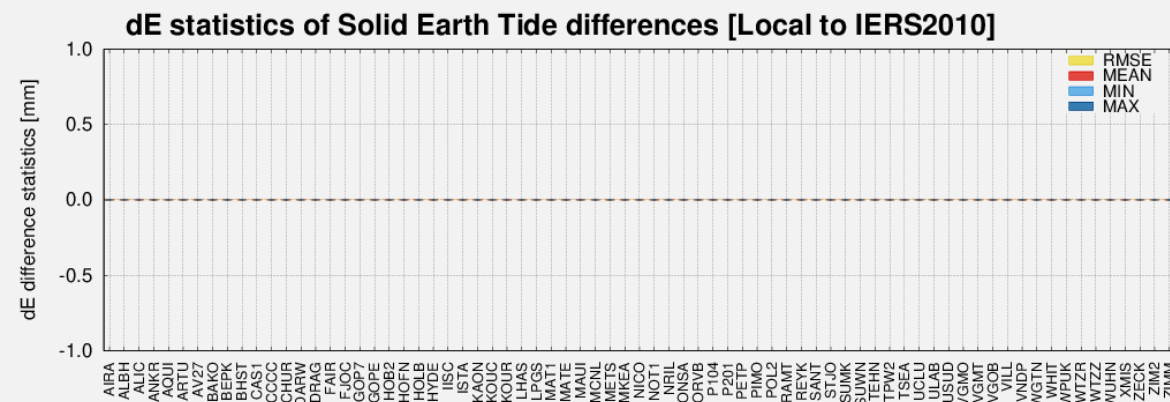
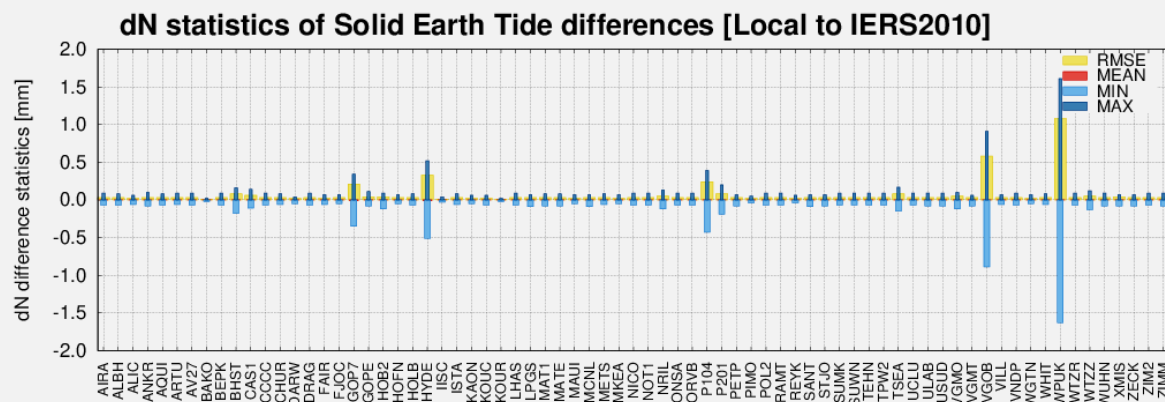
using LSET (right)



Yearly repeatability of N/E/U components when using IERS2010 (left) + LSET (right)

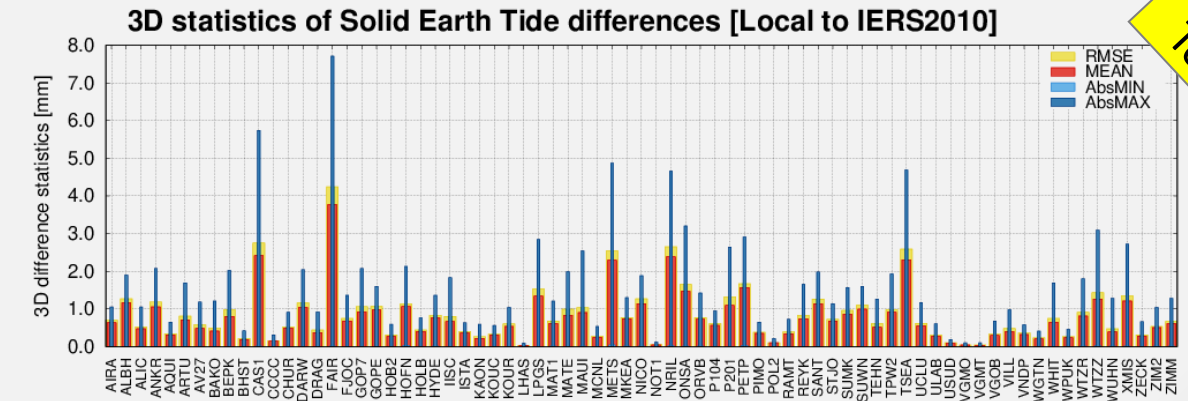
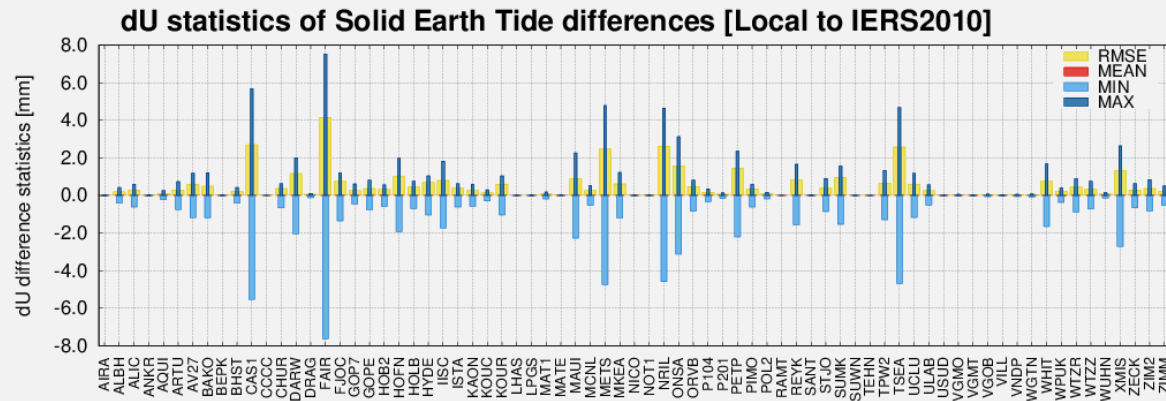
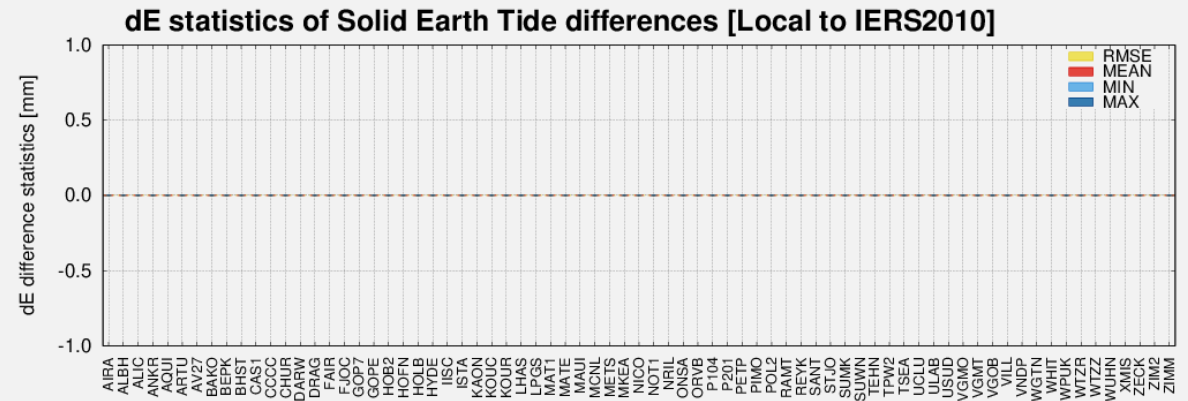
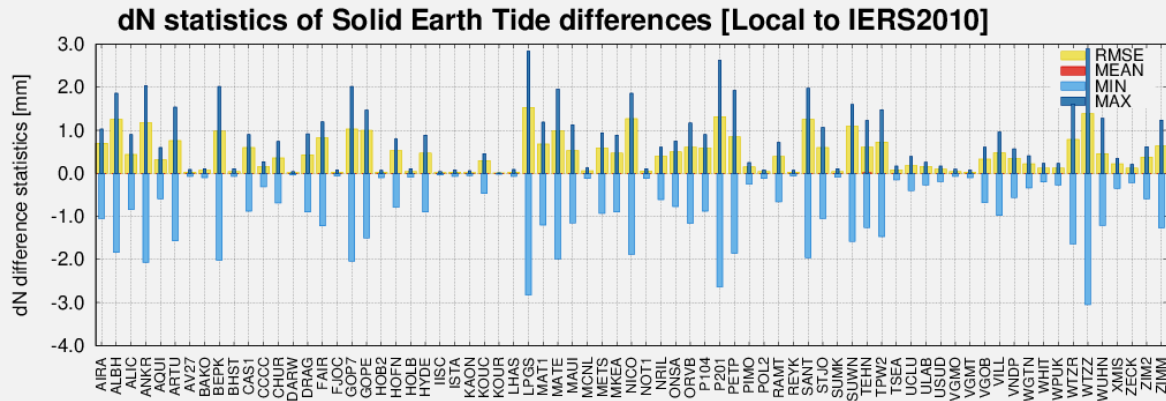


LSET estimates by refining the strategy (fixing initial values of NEU components)



Total

LSET estimates taking into account only the last 5 years of data of the stations



Total

GAGE

EarthScope Consortium

DATA

INSTRUMENTATION

SOFTWARE

KNOWLEDGE BASE

WHAT WE DO

EVENTS

EDUCATION

NEWS

home

gage

software

geodetic utilities

plate motion calculator

Software

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• Plate Motion Calculator

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• Usage

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• References

• Other plate motion calculators

Plate Motion Calculator

Before using, please see: [Overview](#) [Models](#) [Usage](#) [Notes](#) [References](#)

Enter latitude and longitude coordinates (and optionally other selections) and hit *Submit* button:

Latitude:

degrees North

minutes North

seconds North

E.g. enter the latitude as -56.25 degrees or -56 degrees 15 minutes for 56 degrees 15 minutes South.

Longitude:

degrees East

minutes East

seconds East

RGWI
(177,178 -37,524 292,371)
MORVEL 2010
AU
AF

#GNSS_station name
#(Longitude Latitude Height)
Model
Reference plate
Moving plate

www.unavco.org/software/geodetic-utilities/plate-motion-calculator/plate-motion-calculator.html

Tidal Interplate Lithospheric Deformation of Earth (TILDE)

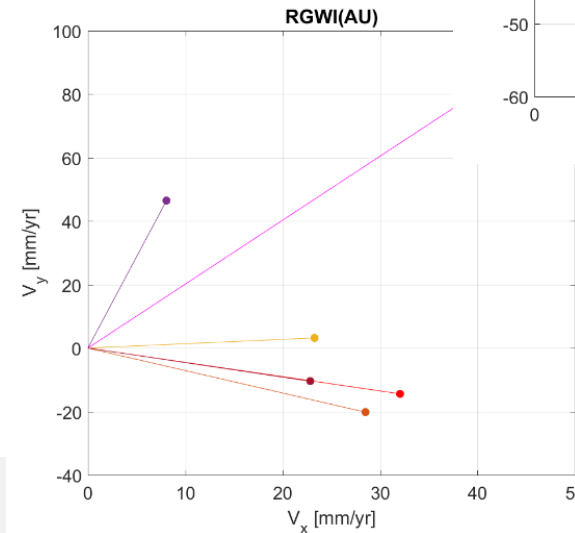
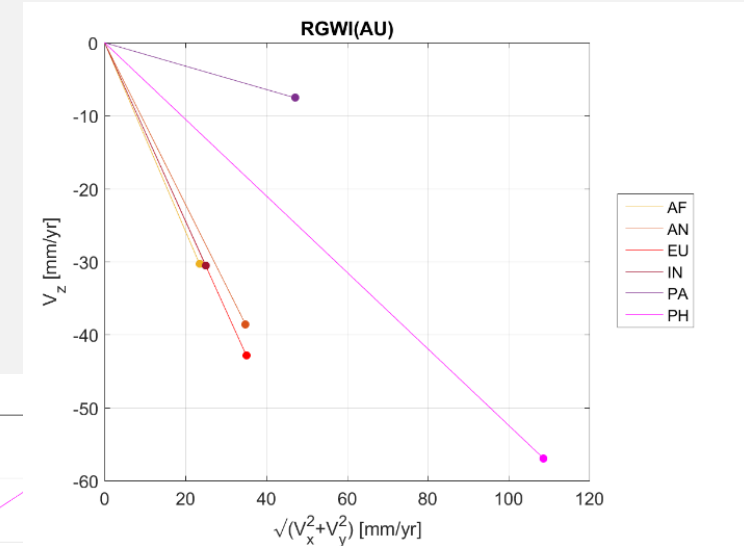
May 1, 2024

© DIAN Srl 2024

64

A script has been written to automatically submit queries to the UNAVCO website and save the output in an excel file

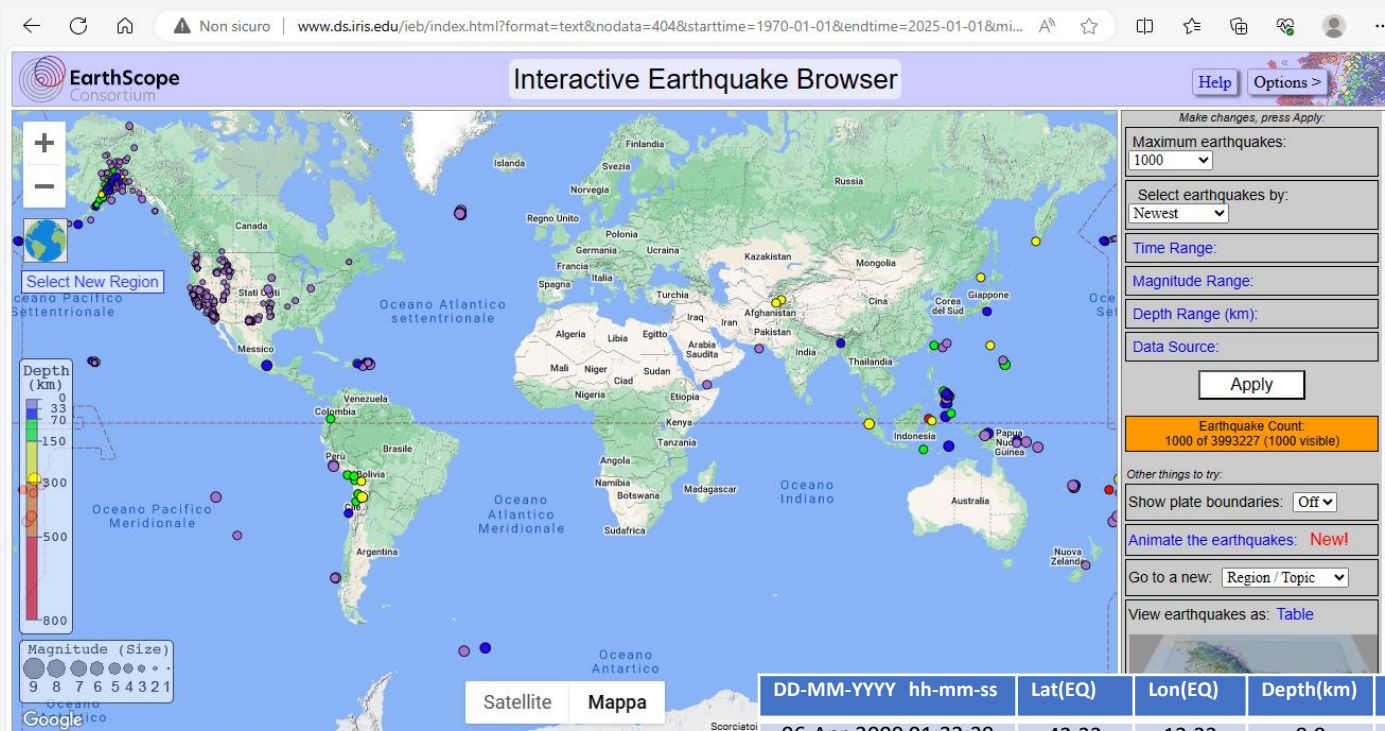
Name	Lon(°E)	Lat(°N)	Height(m)	Xvel(mm/yr)	Yvel(mm/yr)	Zvel(mm/yr)	Plate	Reference	Model Site
ACAE	14,142	40,821	225,7	13,63	-16,73	-10,64	AF	EU	MORVEL 2010
ACAE	14,142	40,821	225,7	1,02	-8,6	1,29	AR	EU	MORVEL 2010
ACAE	14,142	40,821	225,7	29,72	-17,88	-28,49	AU	EU	MORVEL 2010
ACAE	14,142	40,821	225,7	3,55	-7,53	-1,87	IN	EU	MORVEL 2010
ACAE	14,142	40,821	225,7	-0,86	-20,62	6,85	NA	EU	MORVEL 2010
ACAE	14,142	40,821	225,7	44,69	-55,66	-34,66	PA	EU	MORVEL 2010
ACAE	14,142	40,821	225,7	3,32	-109,34	27,38	PH	EU	MORVEL 2010
AIRA	130,6	31,824	315,046	20,26	7,9	11,65	AF	EU	MORVEL 2010
AIRA	130,6	31,824	315,046	-13,17	-39,25	34,43	AR	EU	MORVEL 2010
AIRA	130,6	31,824	315,046	13,78	-37,92	61,25	AU	EU	MORVEL 2010
AIRA	130,6	31,824	315,046	-11,01	-38,11	35,31	IN	EU	MORVEL 2010
AIRA	130,6	31,824	315,046	9,55	7,02	1,44	NA	EU	MORVEL 2010
AIRA	130,6	31,824	315,046	77,52	50,88	19,16	PA	EU	MORVEL 2010
AIRA	130,6	31,824	315,046	48,13	16,76	30,17	PH	EU	MORVEL 2010
ALBH	236,513	48,39	32,205	18,09	2,08	10,47	AF	NA	
ALBH	236,513	48,39	32,205	8,92	-3,78	1,59	CA	NA	
ALBH	236,513	48,39	32,205	-21,46	29,76	11,6	CO	NA	
ALBH	236,513	48,39	32,205	16,81	-1,33	7,3	EU	NA	
ALBH	236,513	48,39	32,205	35,23	-4,7	13,87	JF	NA	
ALBH	236,513	48,39	32,205	3,88	35,92	28,7	PA	NA	
ALBH	236,513	48,39	32,205	7,82	7,03	9,09	SA	NA	
ALIC	133,886	-23,67	603,803	40,2	6,52	-53,22	AF	AU	
ALIC	133,886	-23,67	603,803	27,56	-11,74	-63,31	AN	AU	
ALIC	133,886	-23,67	603,803	34,11	-7,19	-66,22	EU	AU	
ALIC	133,886	-23,67	603,803	10,29	-7,72	-29,17	IN	AU	
ALIC	133,886	-23,67	603,803	71,37	42,36	-43,51	PA	AU	
ALIC	133,886	-23,67	603,803	102,94	76,78	-36,81	PH	AU	
ANKR	32,759	39,888	975,217	17,74	-15,02	-8,18	AF	EU	
ANKR	32,759	39,888	975,217	-5,6	-10,55	12,55	AR	EU	
ANKR	32,759	39,888	975,217	24,35	-19,08	-12,23	AU	EU	



www.ds.iris.edu/ieb/index.html

<https://www.globalcmt.org/CMTsearch.html>

A script has been written to automatically submit queries, save the output in an excel file, compute the geodetic distance between the hypocentre of a EQ and each GNSS station



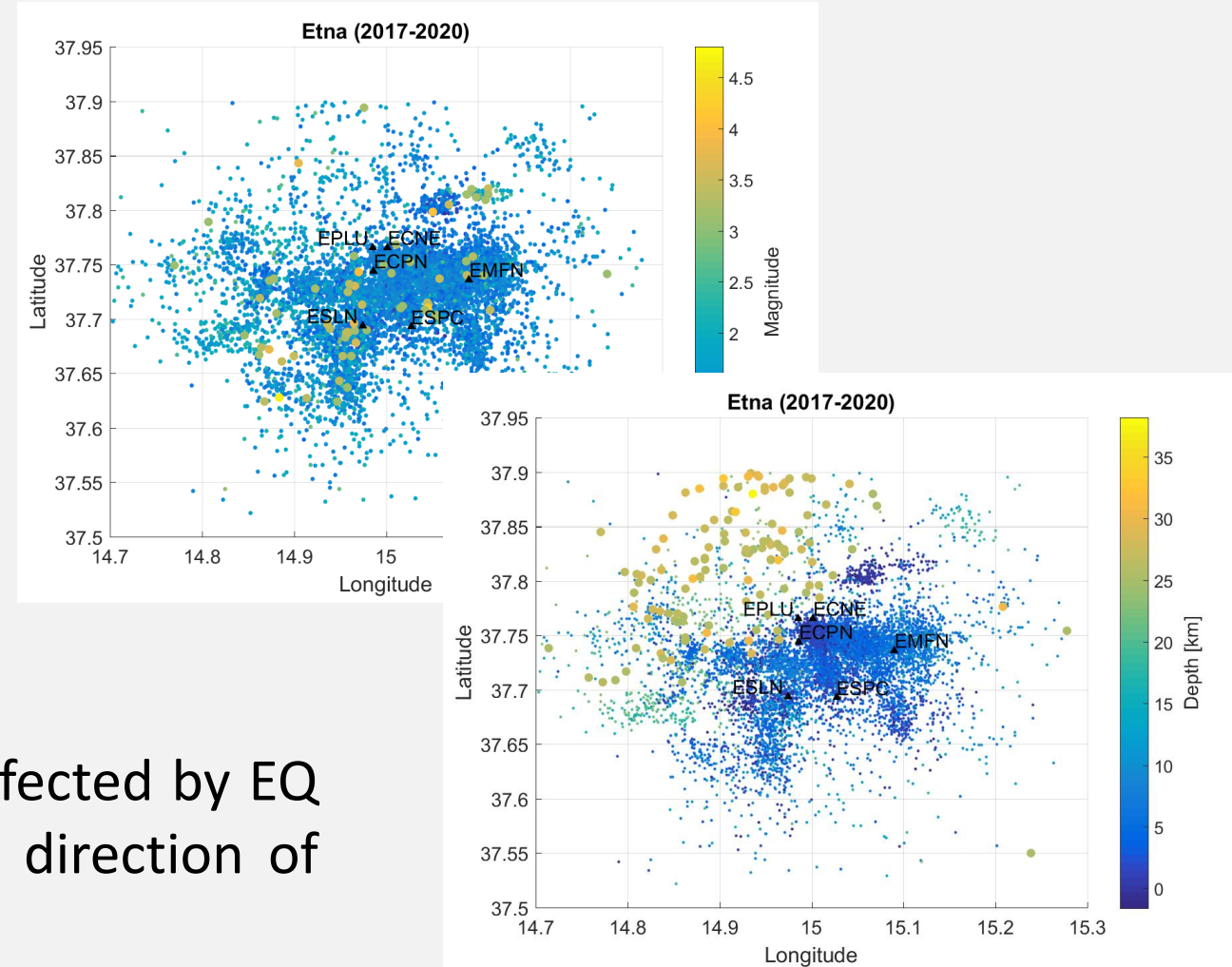
DD-MM-YYYY hh-mm-ss	Lat(EQ)	Lon(EQ)	Depth(km)	Magnitude	GNSS	Lat(GNSS)	Lon(GNSS)	Z(GNSS)	dist(km)	EQ type component
06-Apr-2009 01:32:39	42.33	13.33	8.8	6.3	AQUI	13.35	42.368	713.399	12.80402	extension
21-Jun-2000 00:51:46	63.98	-20.75	10	6.5	REYK	-21.955	64.139	93.496	70.86671	strike-slip+extension
21-Jul-2013 05:09:31	-41.7	174.33	17	6.5	WGTM	174.806	-41.323	26.535	74.63544	compression
17-Jun-2000 15:40:41	63.96	-20.48	10	6.5	REYK	-21.955	64.139	93.496	83.98976	strike-slip+extension
11-Mar-2011 19:46:50	40.48	139.05	10	6.2	P104	139.703	39.942	45.056	91.55179	strike-slip+extension
...	...	...	...	...	...	...	...	...	...	

sismoweb.ct.ingv.it/Etna/catalogs/EtnaRCSC/catalogue.php

A script has been written to compute the geodetic distance between the hypocentre of a EQ and each GNSS station and identify the GNSS sample closest in time (< 15 min) to the occurrence time of EQ



Identify GNSS samples which could be affected by EQ to investigate statistical changes (e.g. in direction of displacement and spectral properties)

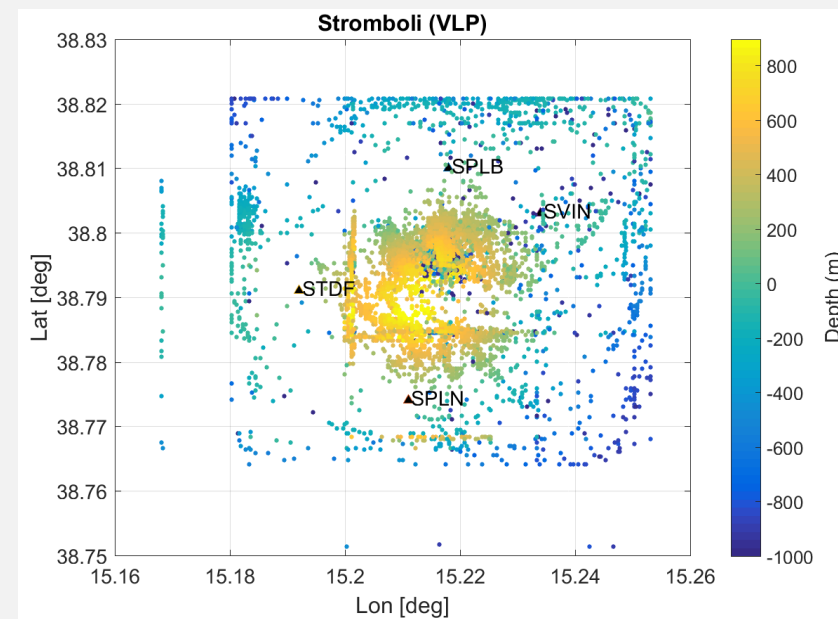


<http://eolo.ov.ingv.it/eolo/>

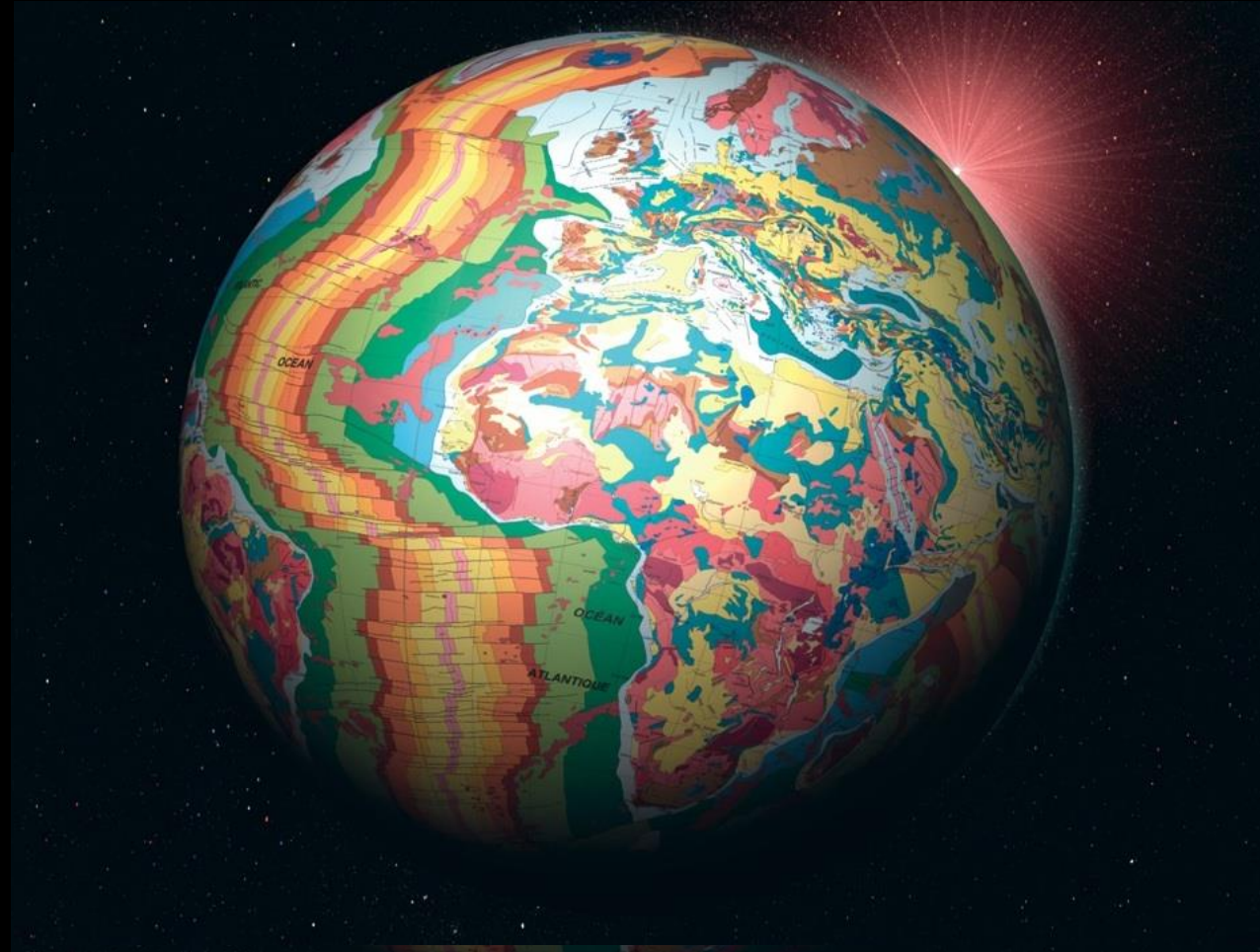
A script has been written to identify the GNSS sample closest in time (< 15 min) to the occurrence time of VLP event



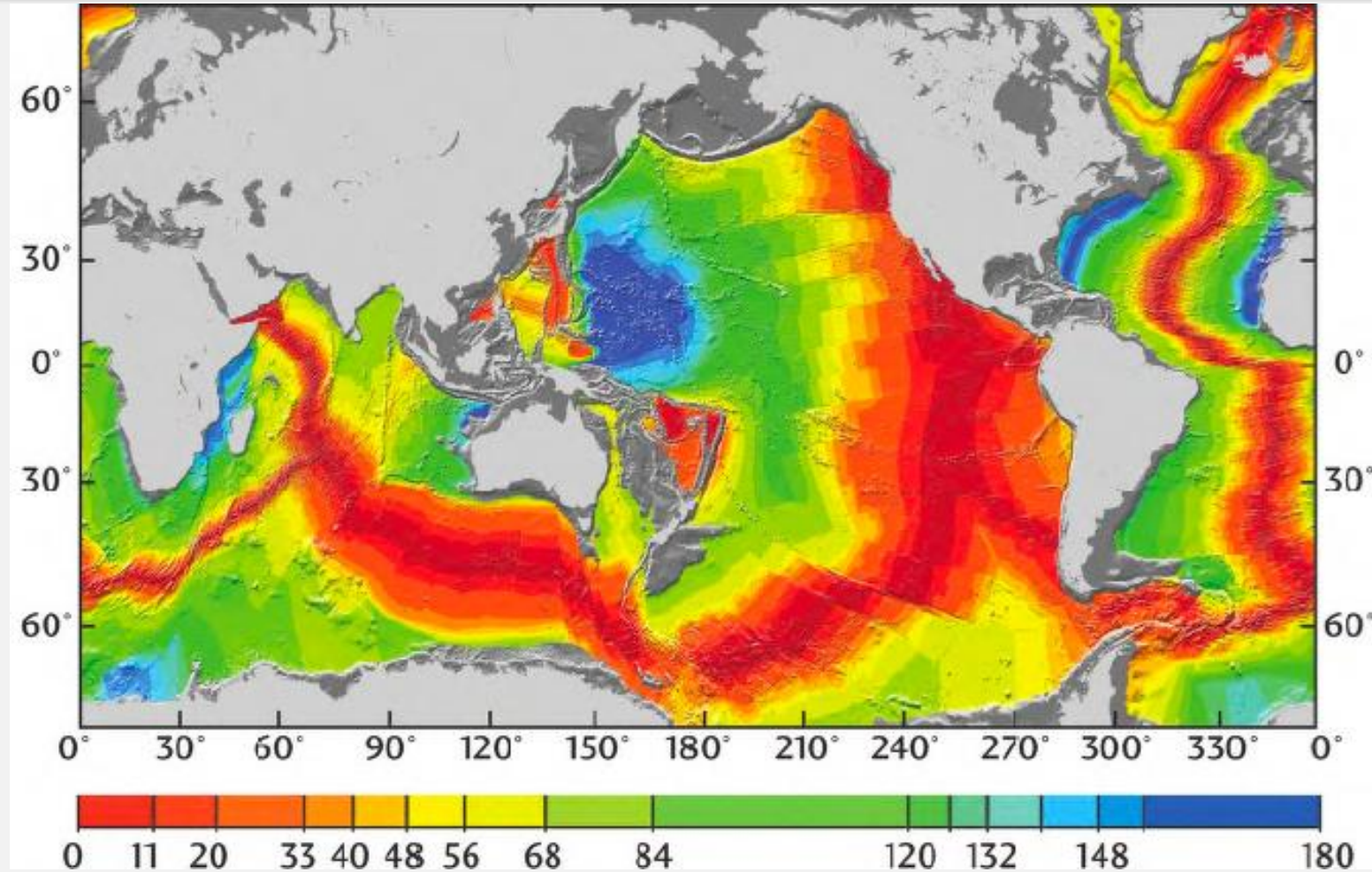
Identify GNSS samples which could be affected by the VLP event to investigate statistical changes (e.g. in direction of displacement and spectral properties)



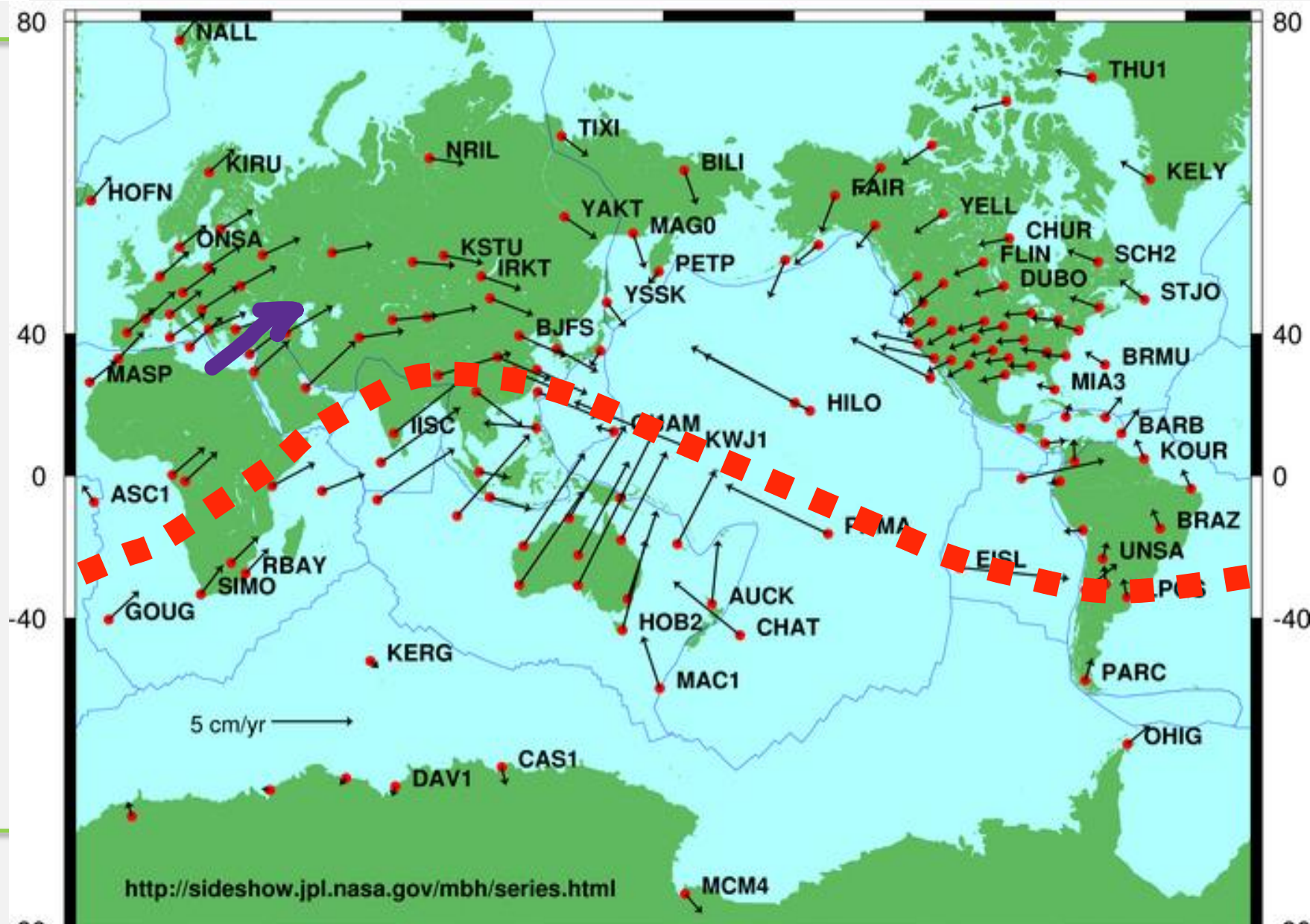
Oscillating tidal stress loading on the lithosphere



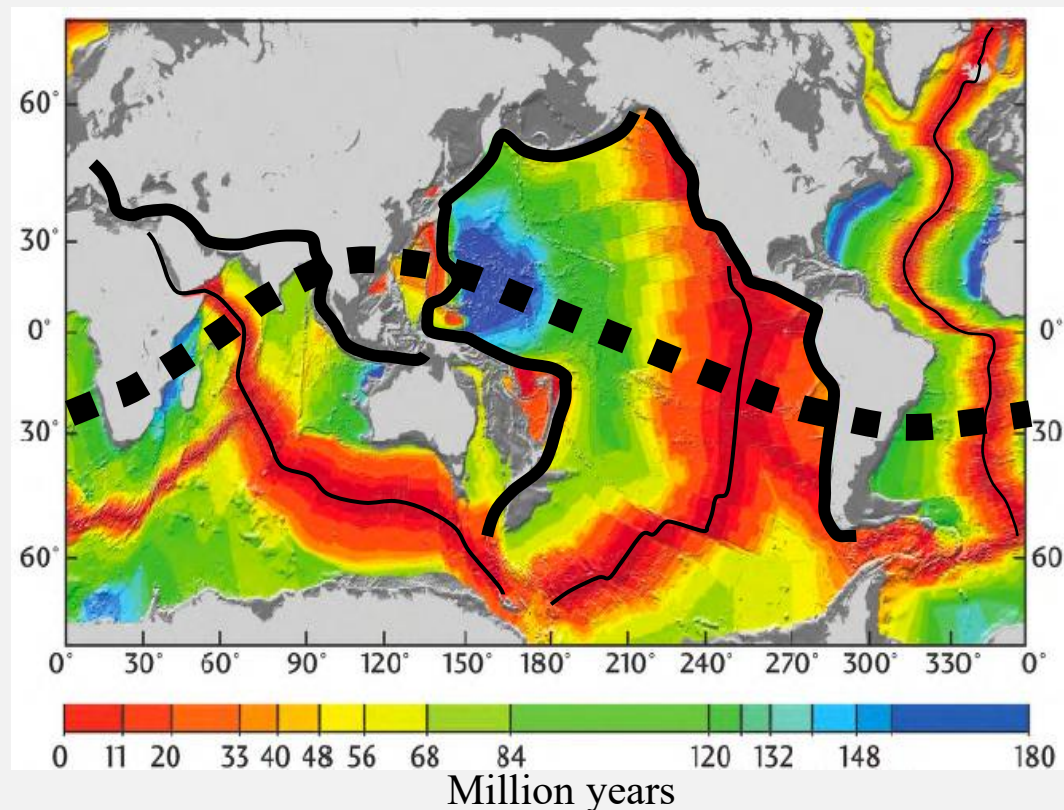
It is the asymmetry that generates the phenomenon
PIERRE CURIE



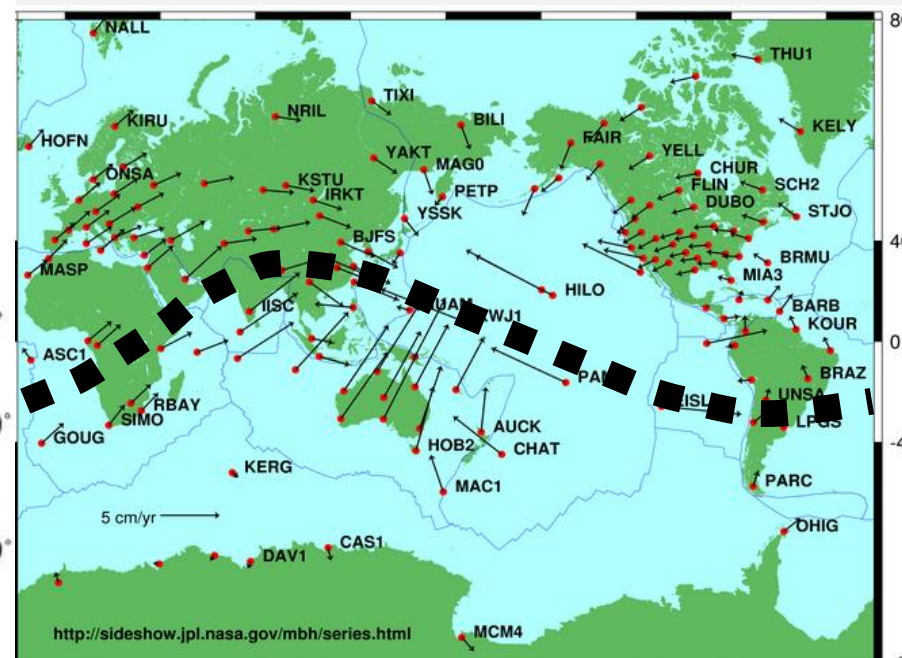
Million years



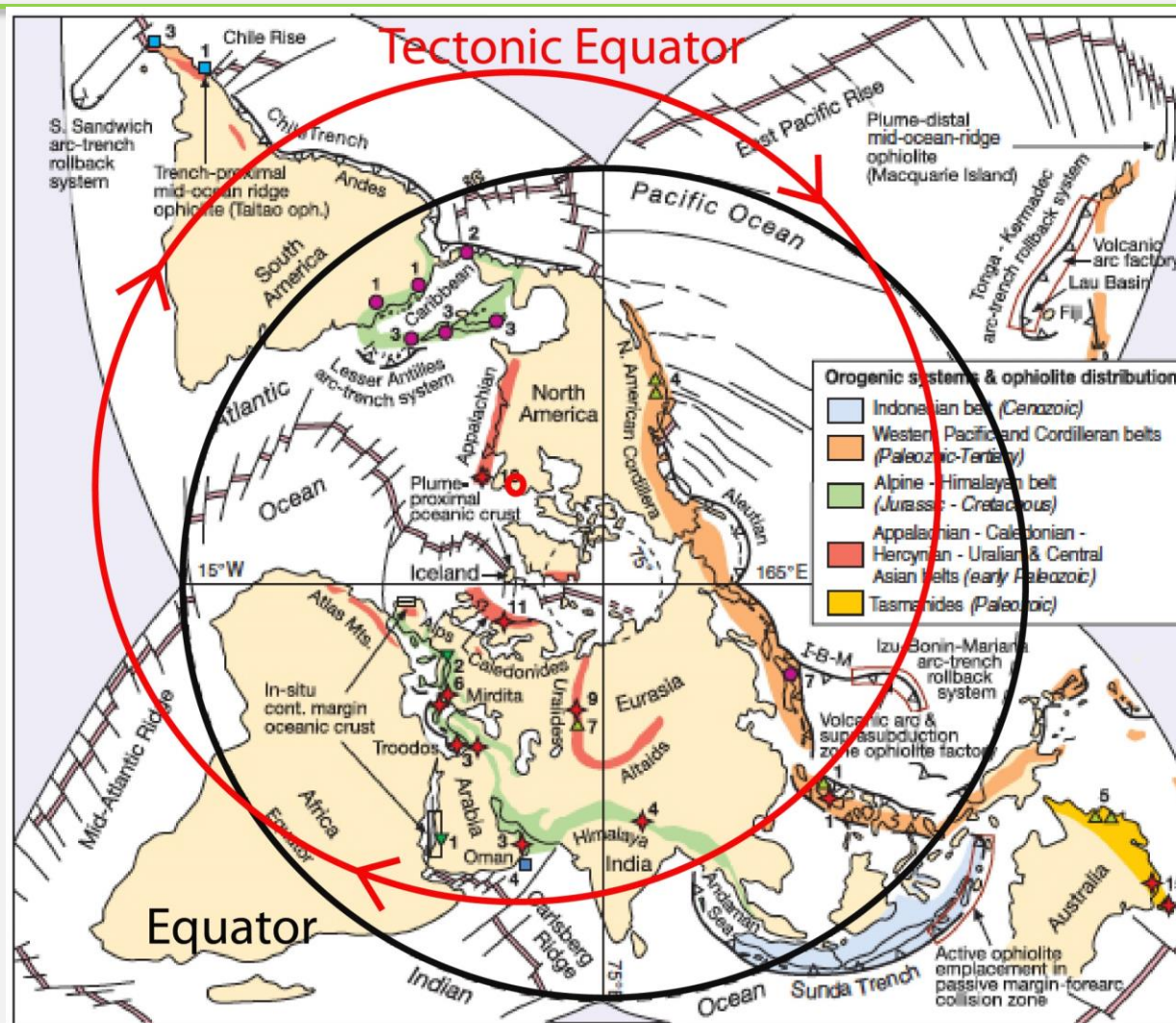
Past 100 Ma movements

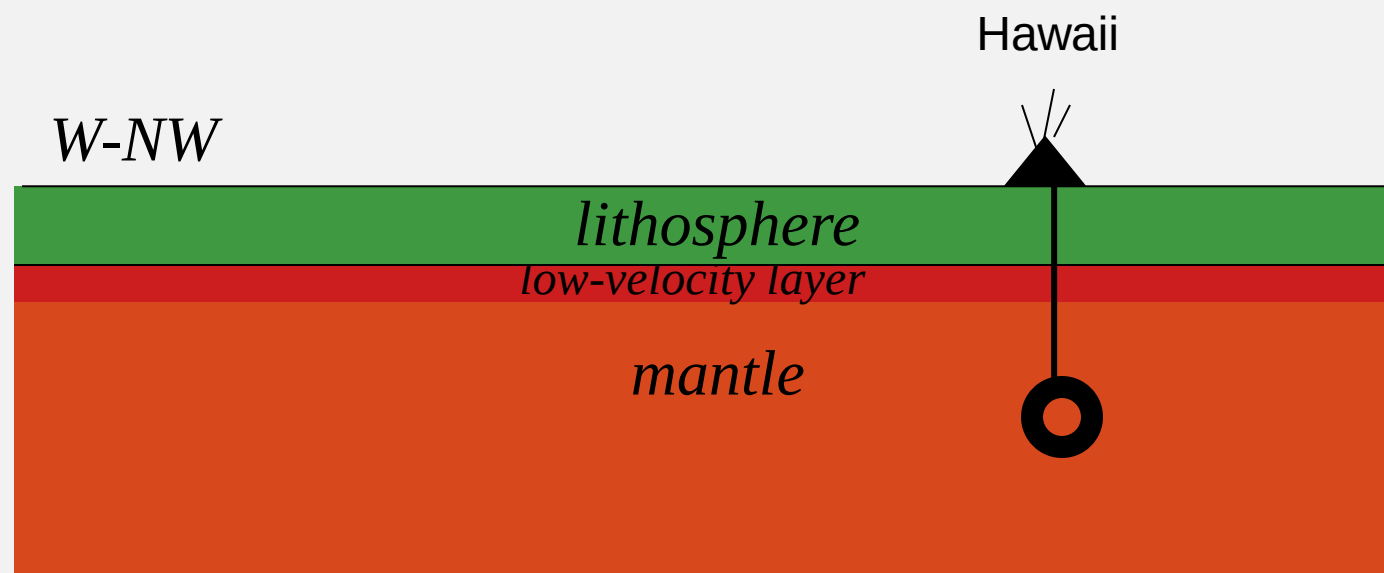


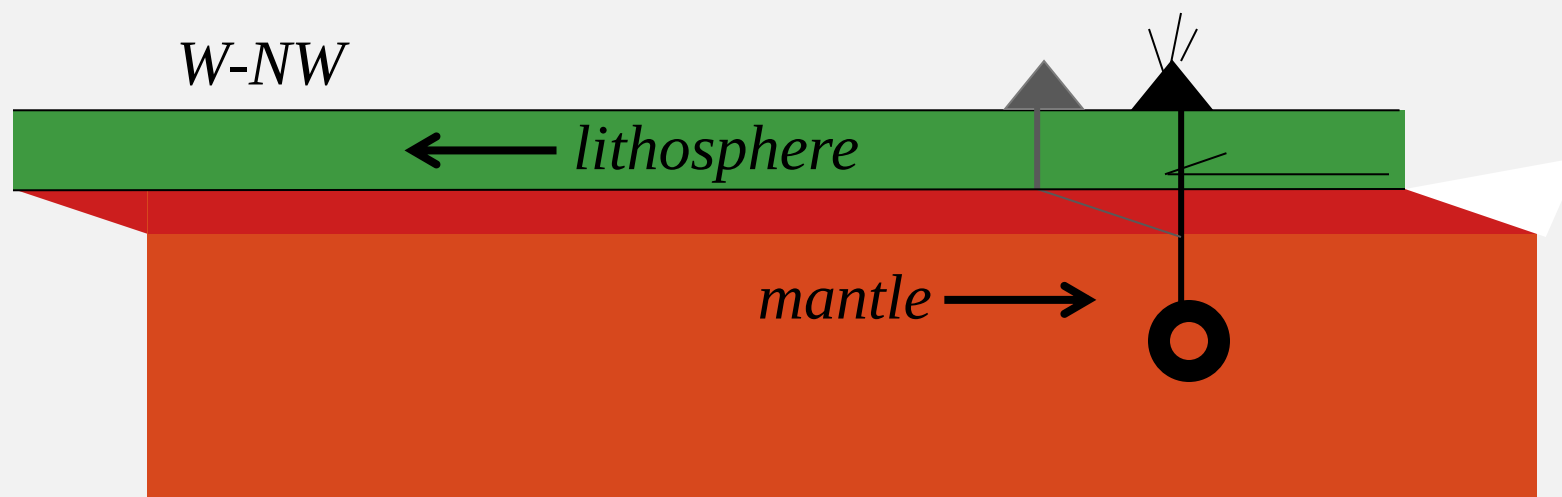
Present movements

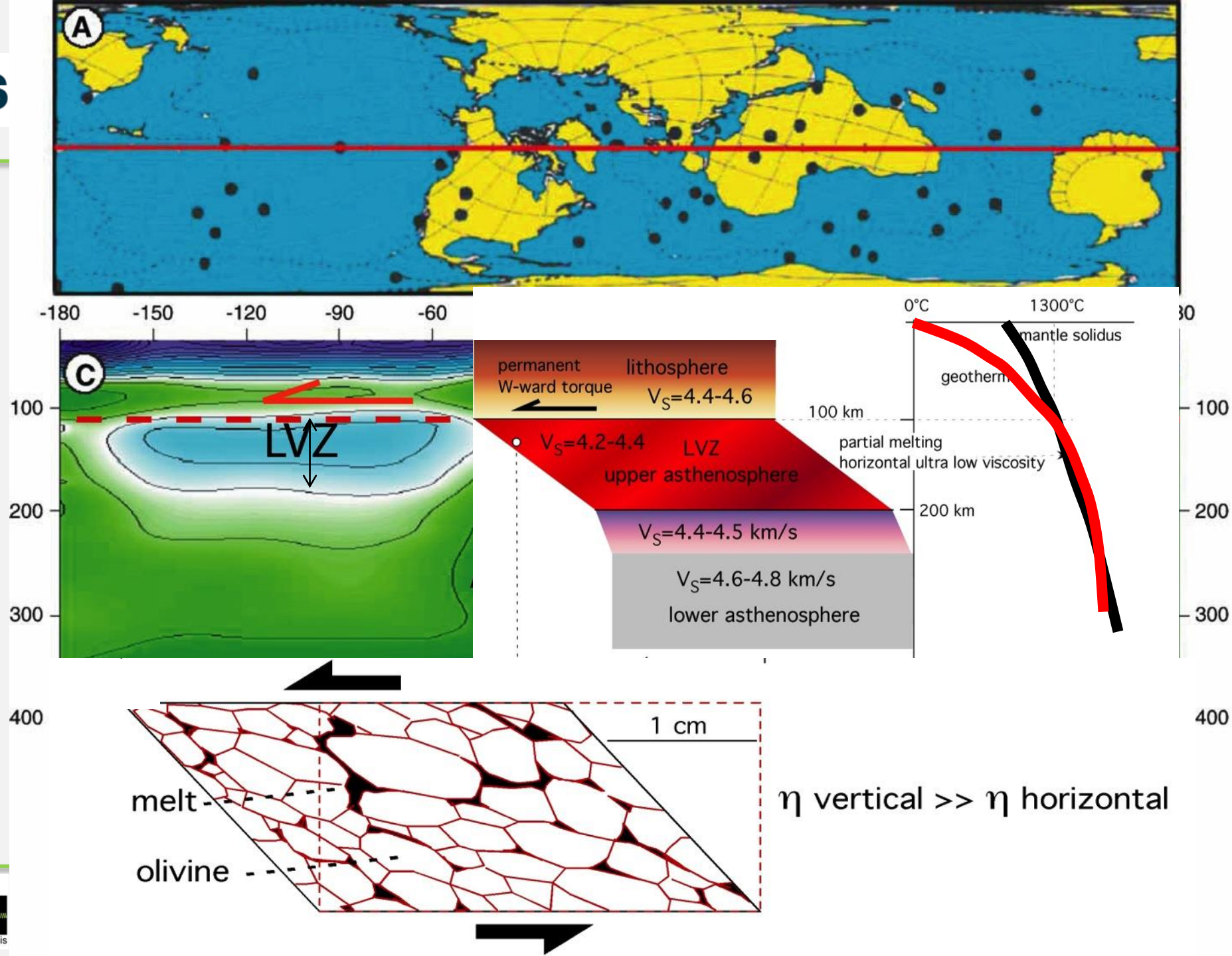


Dogliani & Panza 2015 Advances Geophys.









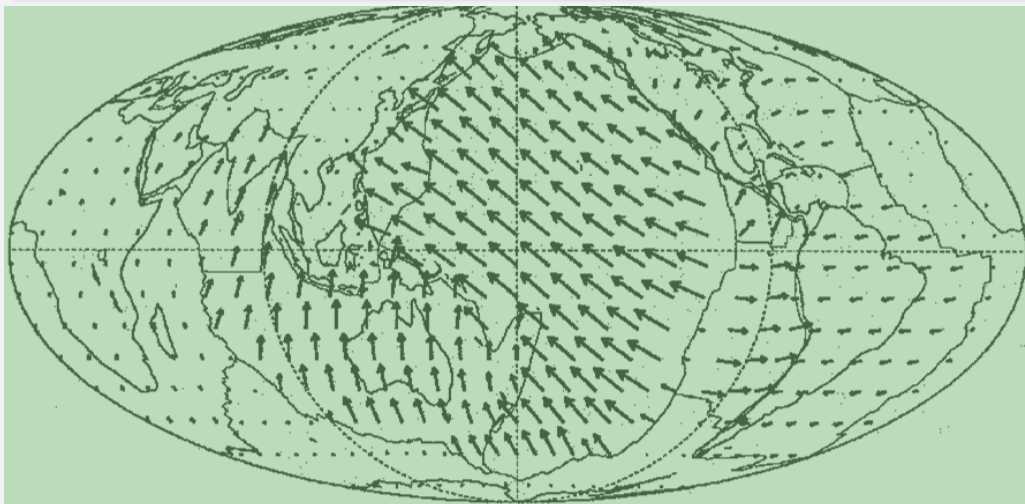
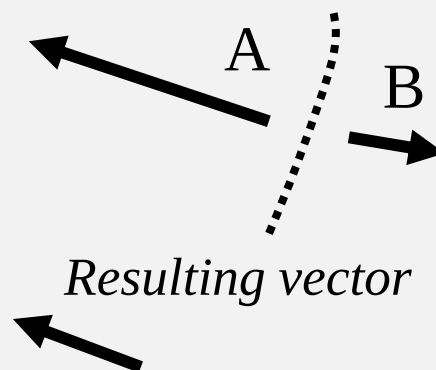
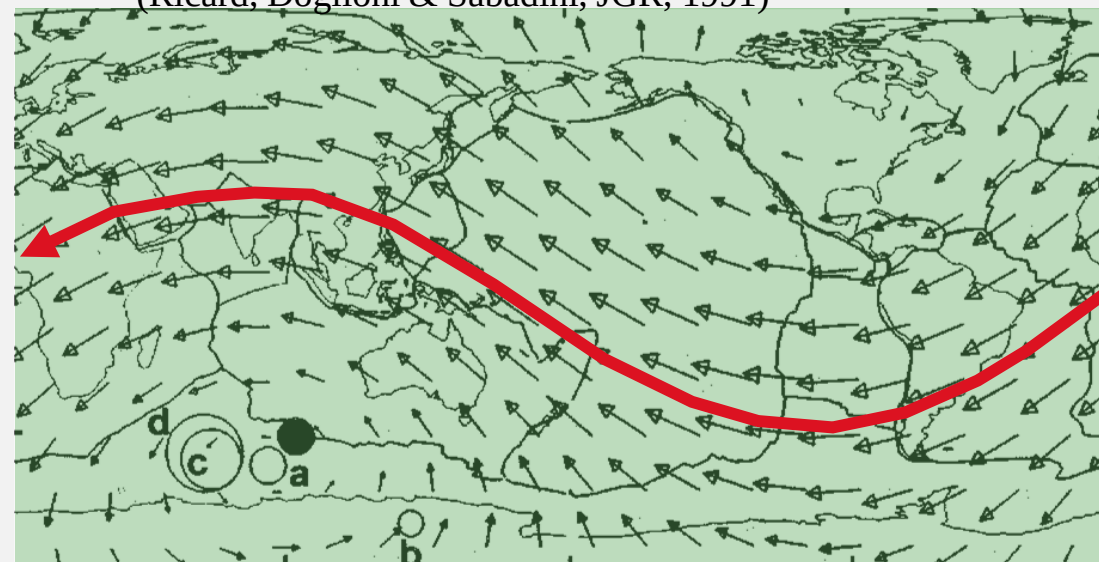


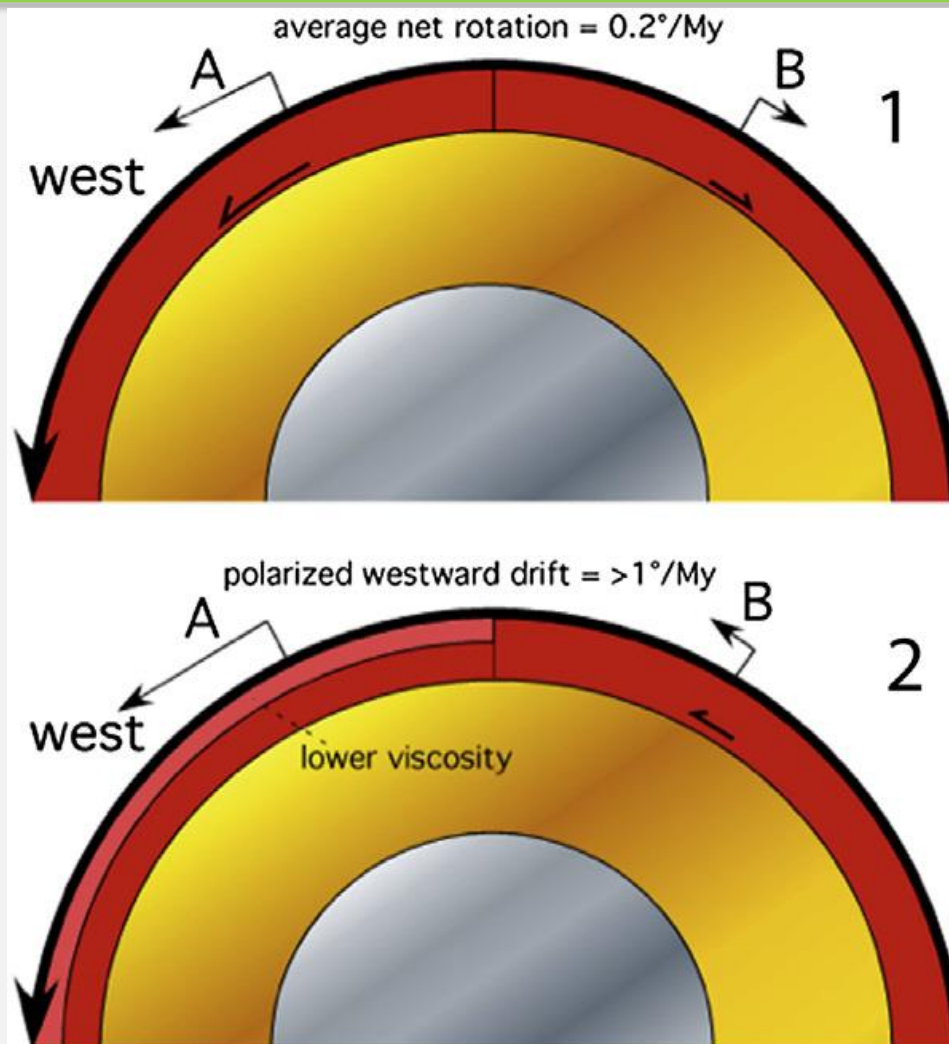
Plate motions based on the Hotspot Reference Frame

(O'Connell, Gable & Hager, 1991)

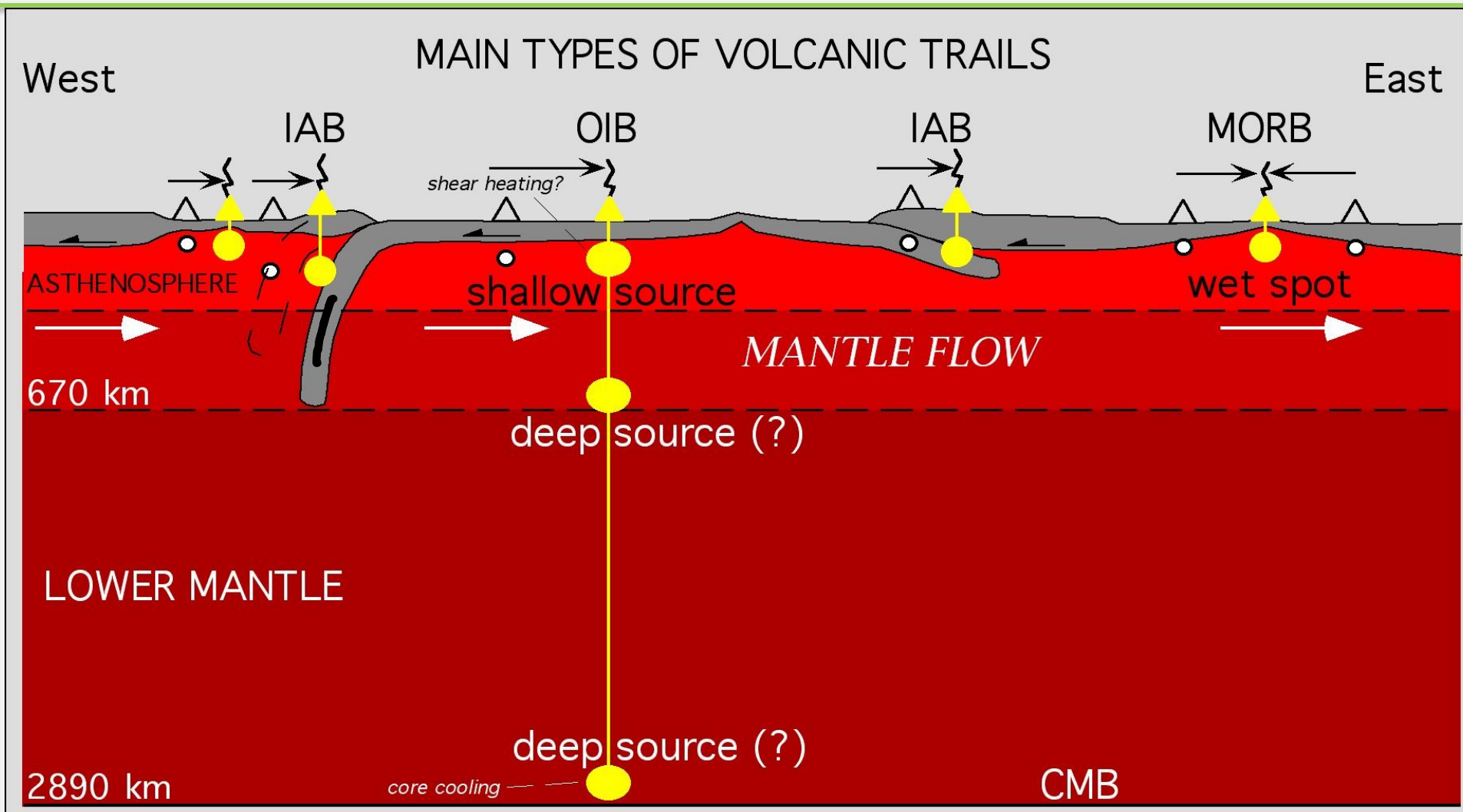
(Ricard, Doglioni & Sabadini, JGR, 1991)

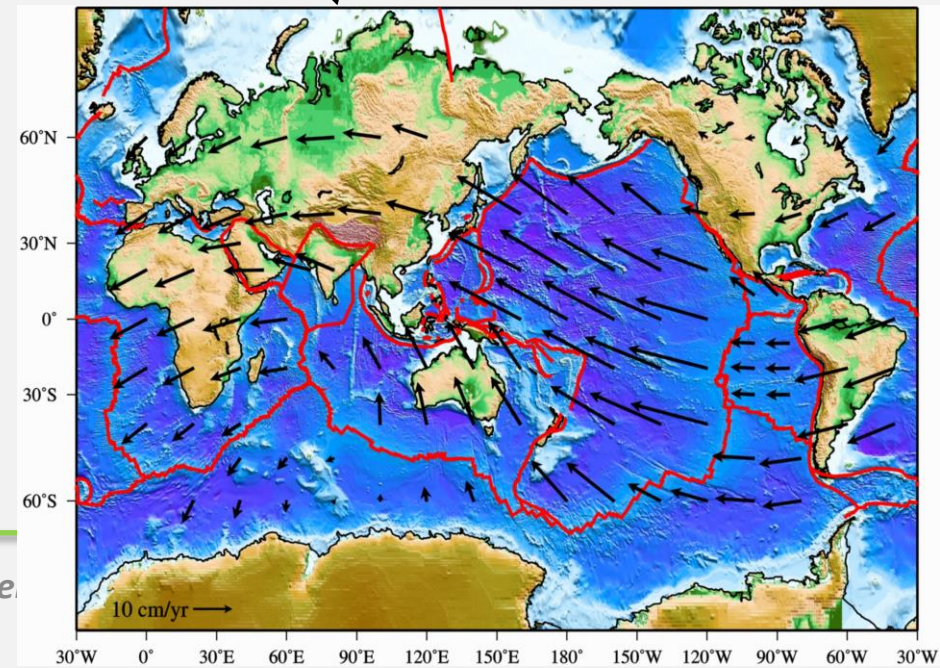
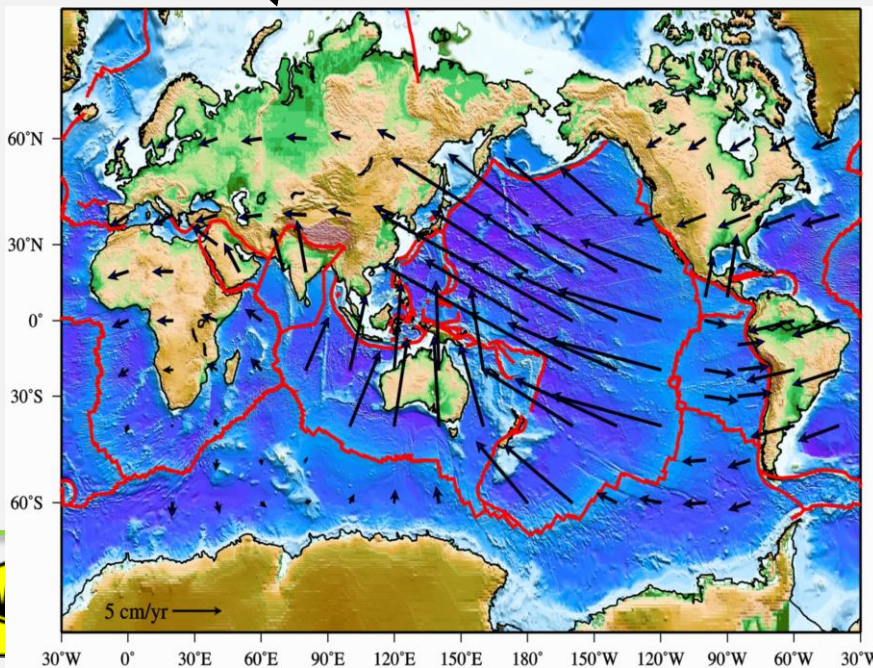
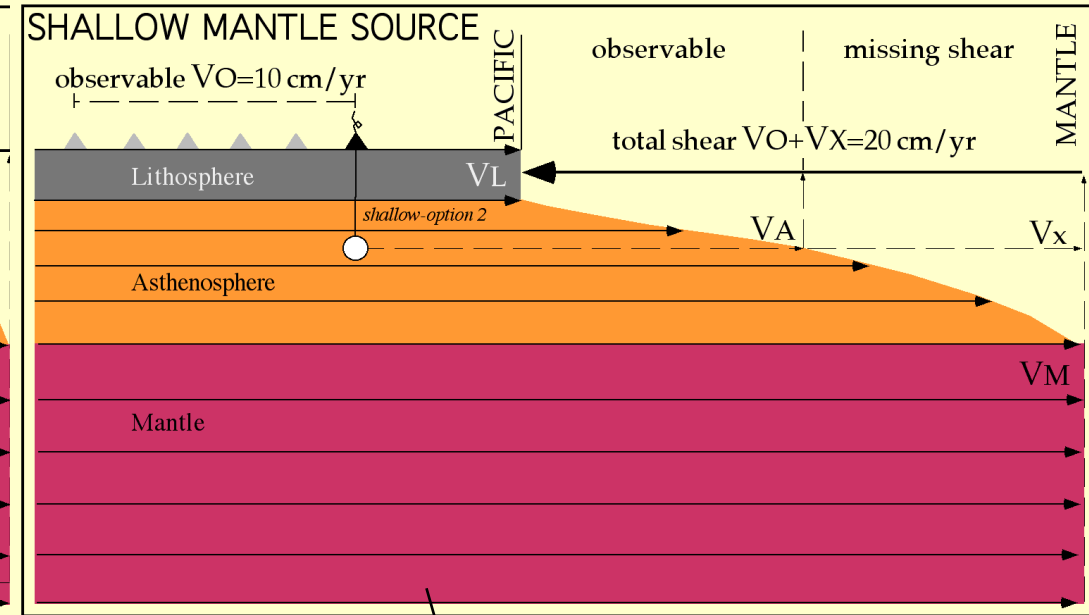
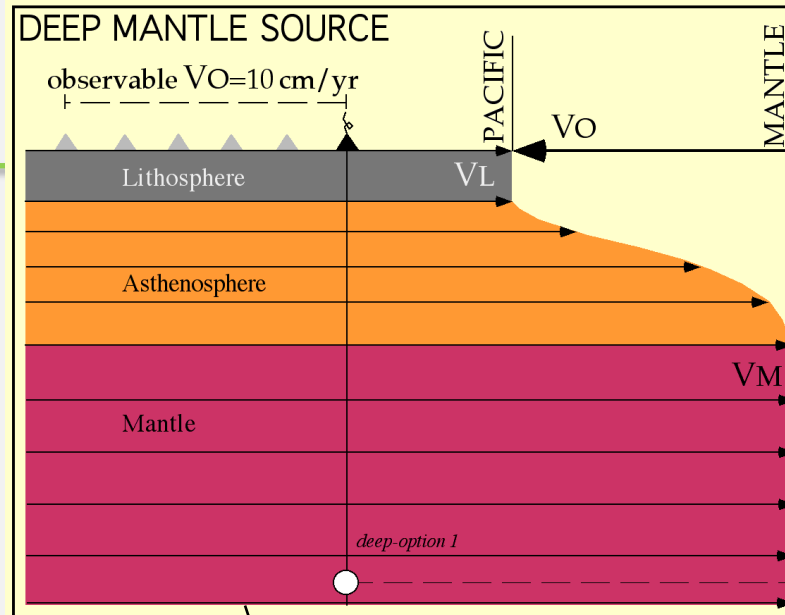


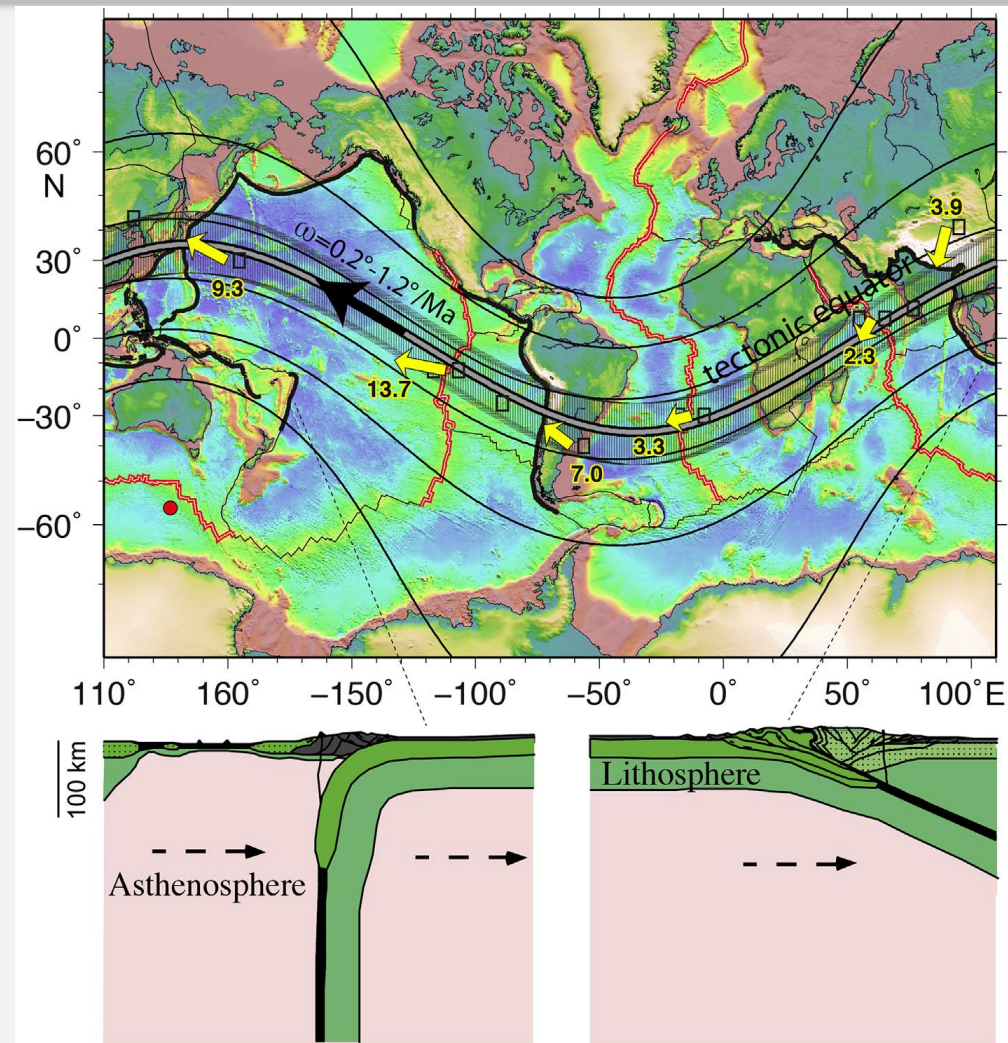
Westward drift of the lithosphere:
an small temporal
accident or a larger
permanent phenomenon?



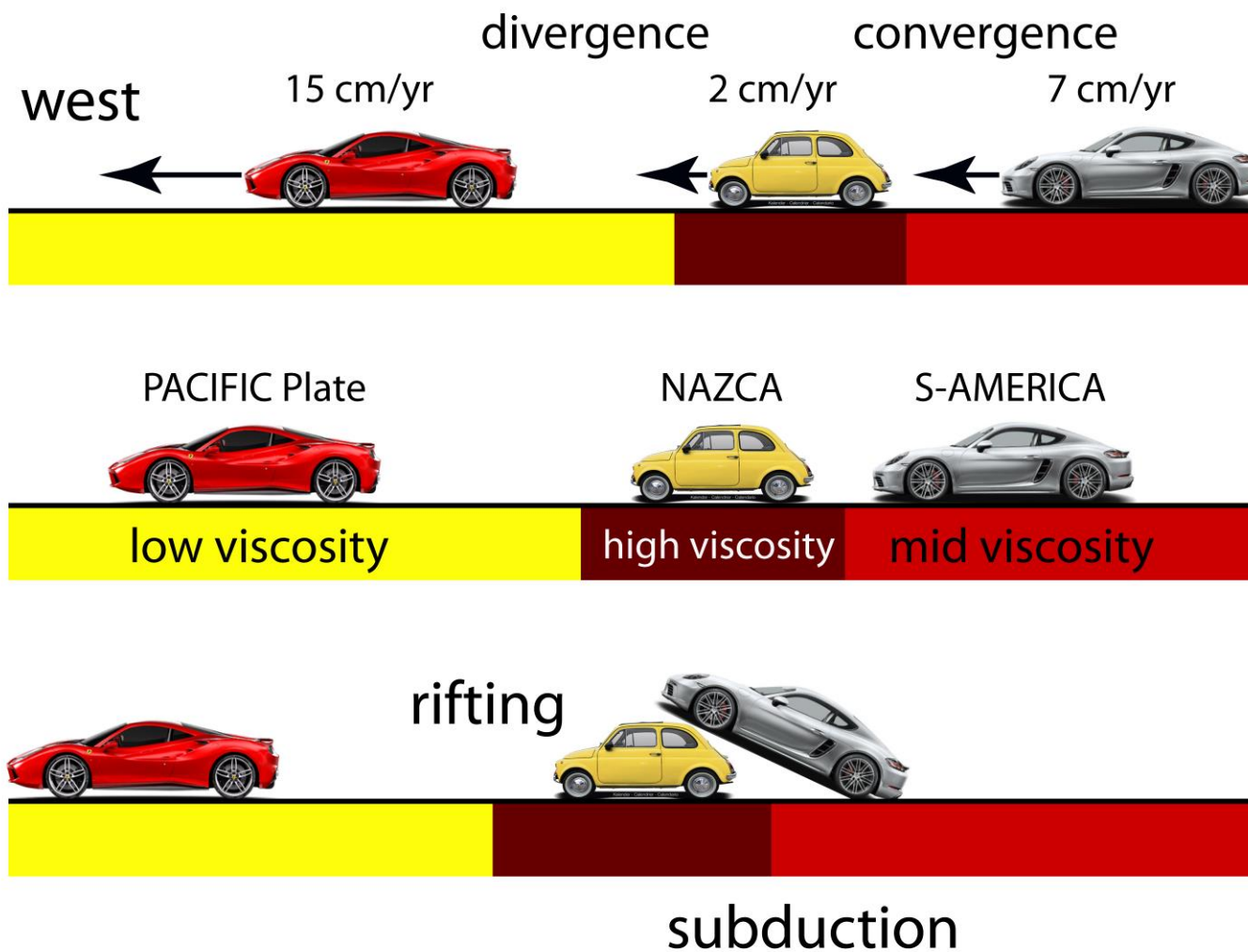
Doglioni & Panza 2015
Advances in Geophysics



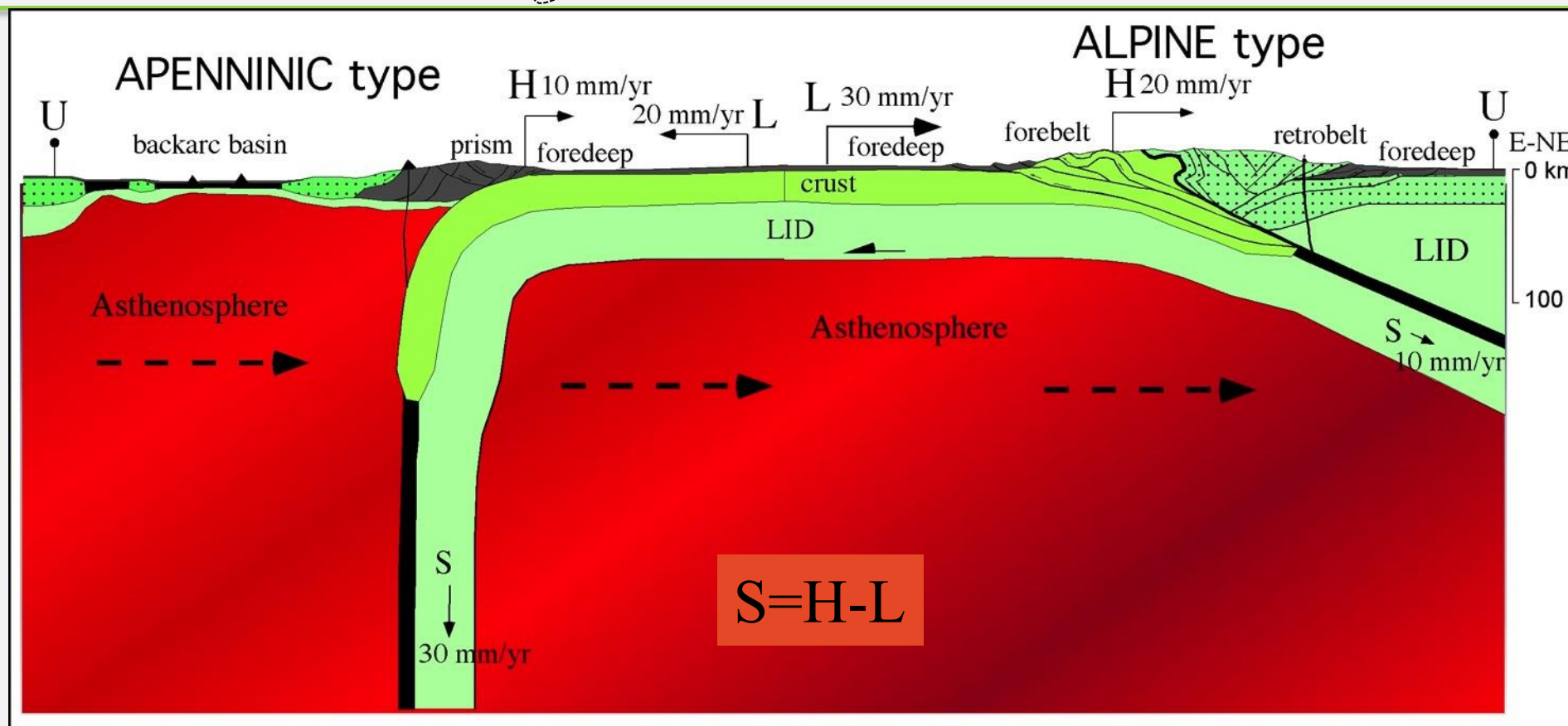




Cuffaro & Doglioni 2018 Gondw. Res.



heat flow



convergence < subduction

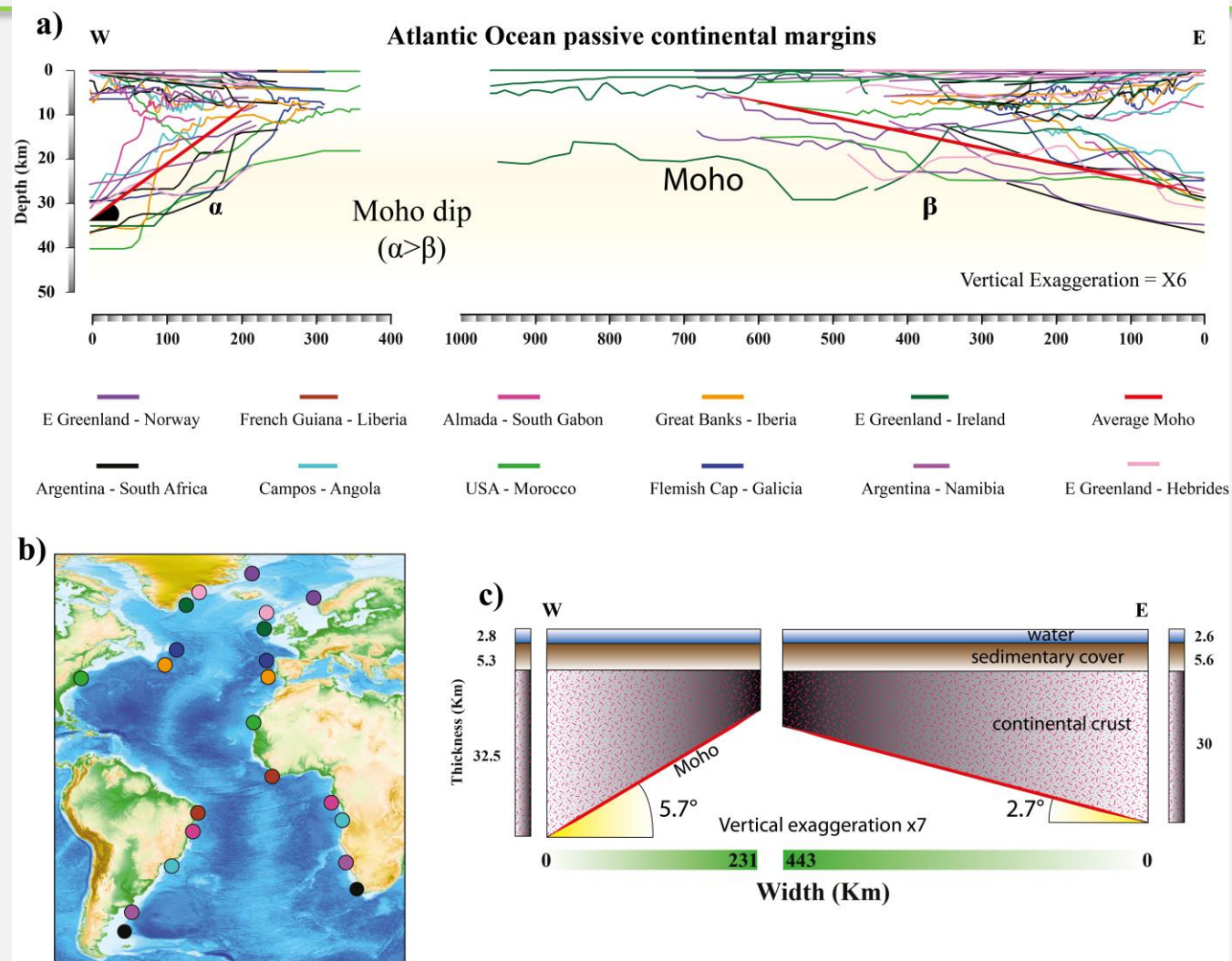
CONVERGENCE
SHORTENING

convergence > subduction

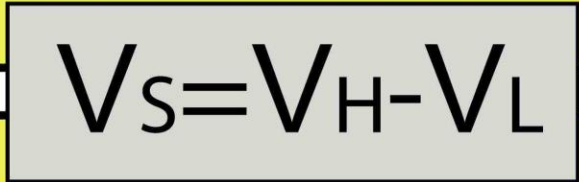
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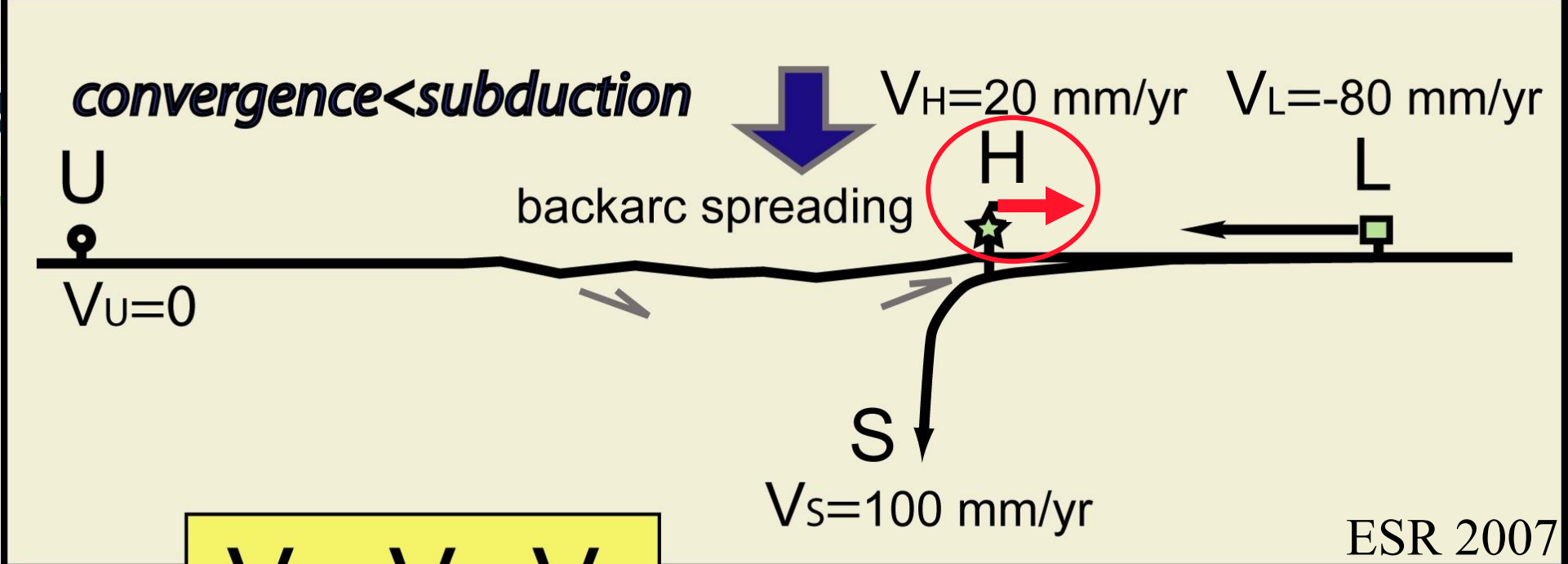
> 1

Dogliani et al. 2007 ESR

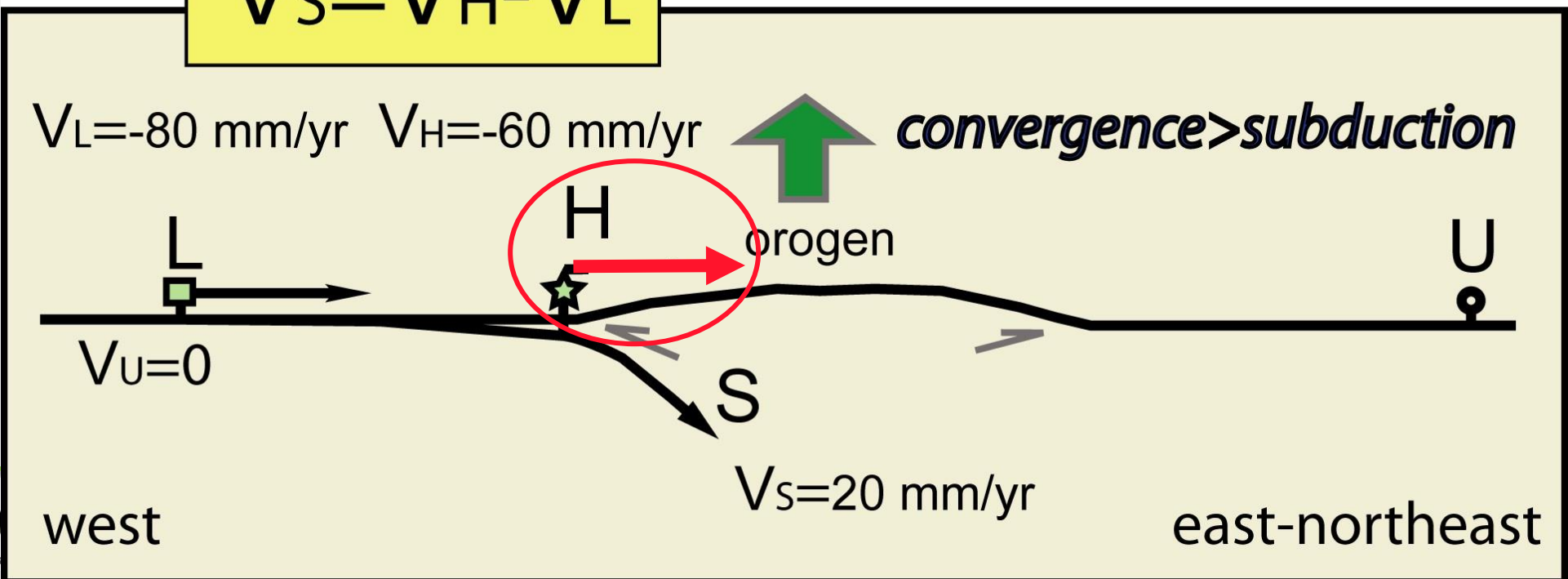


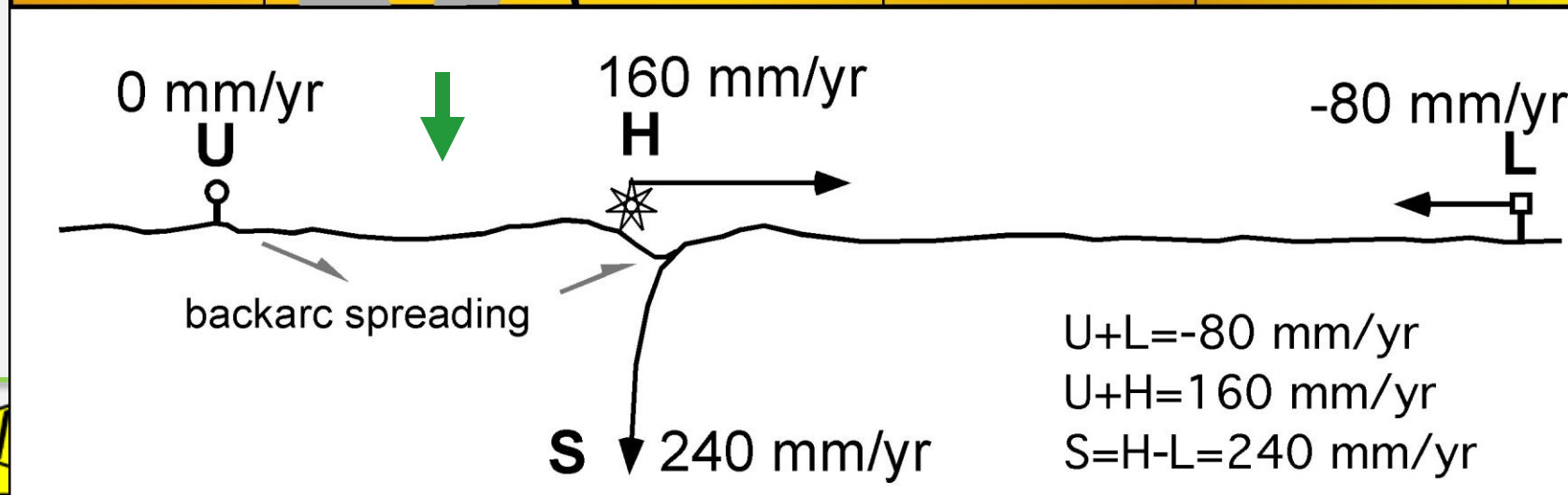
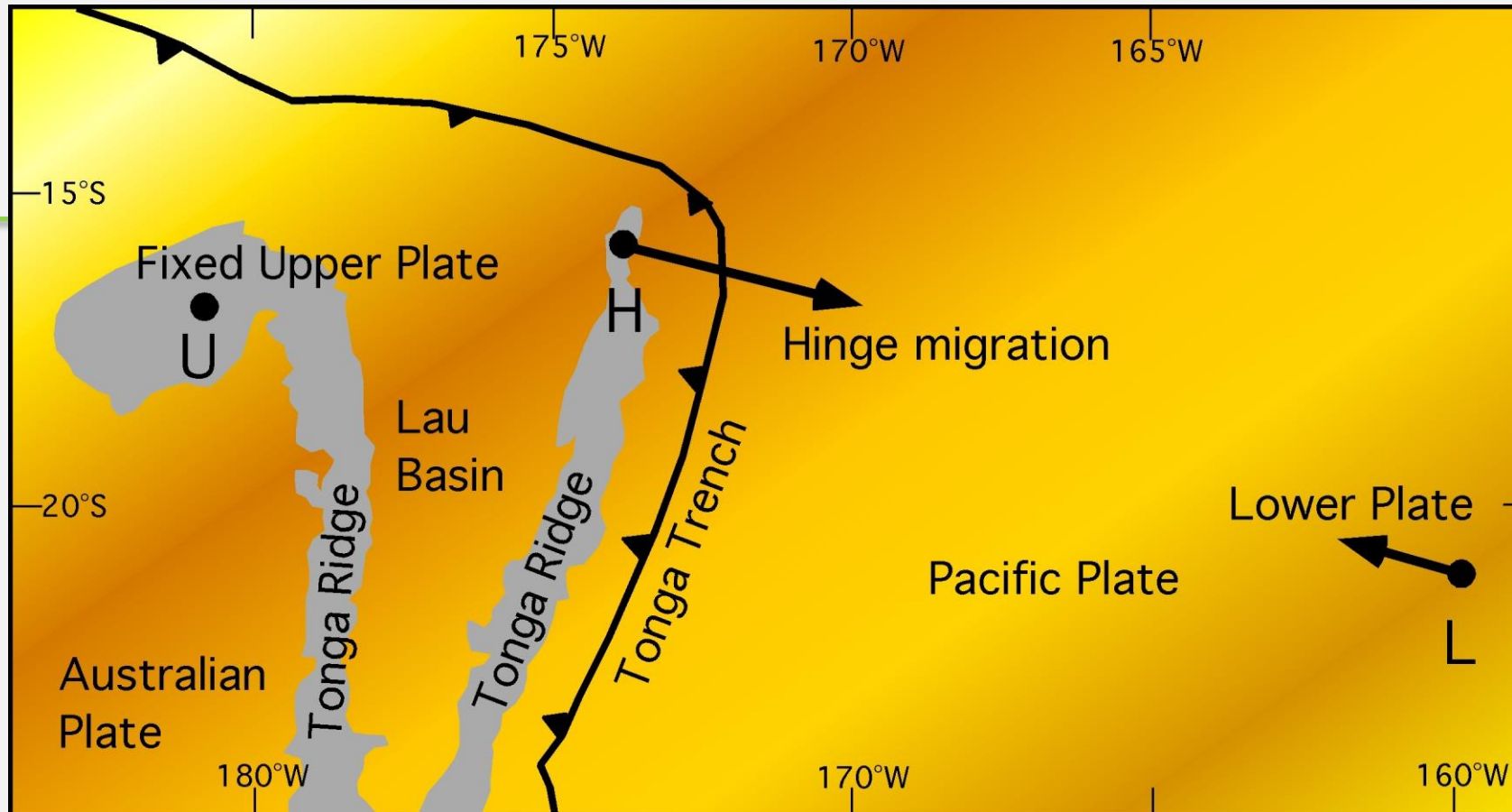
Vangone & Doglioni 2021

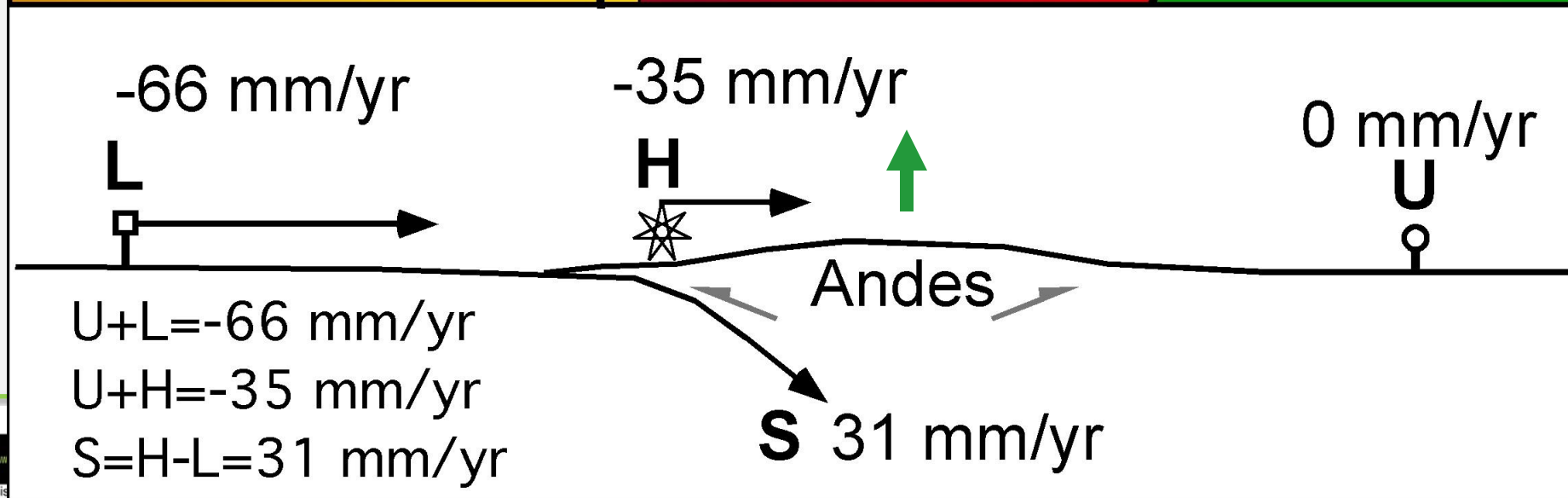
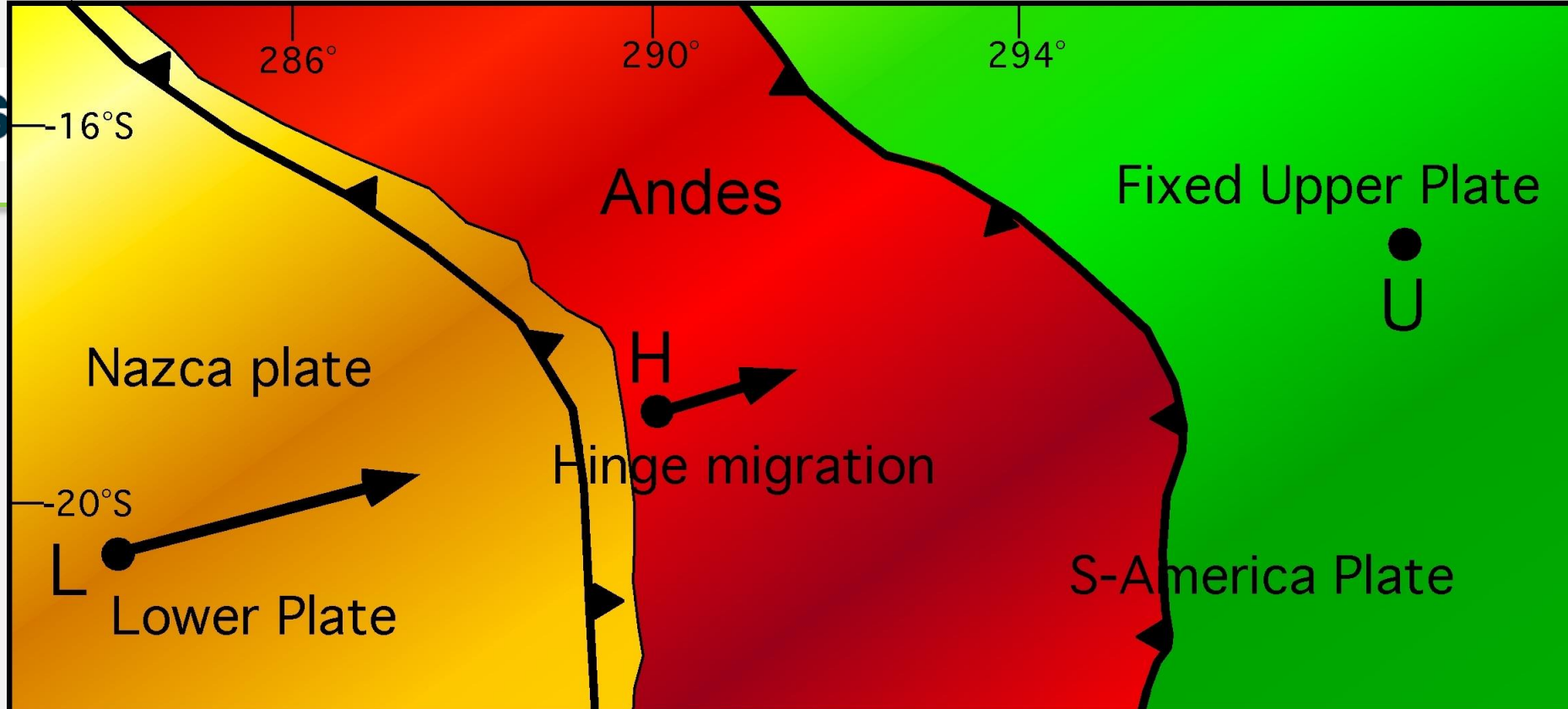




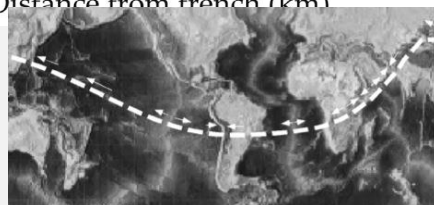
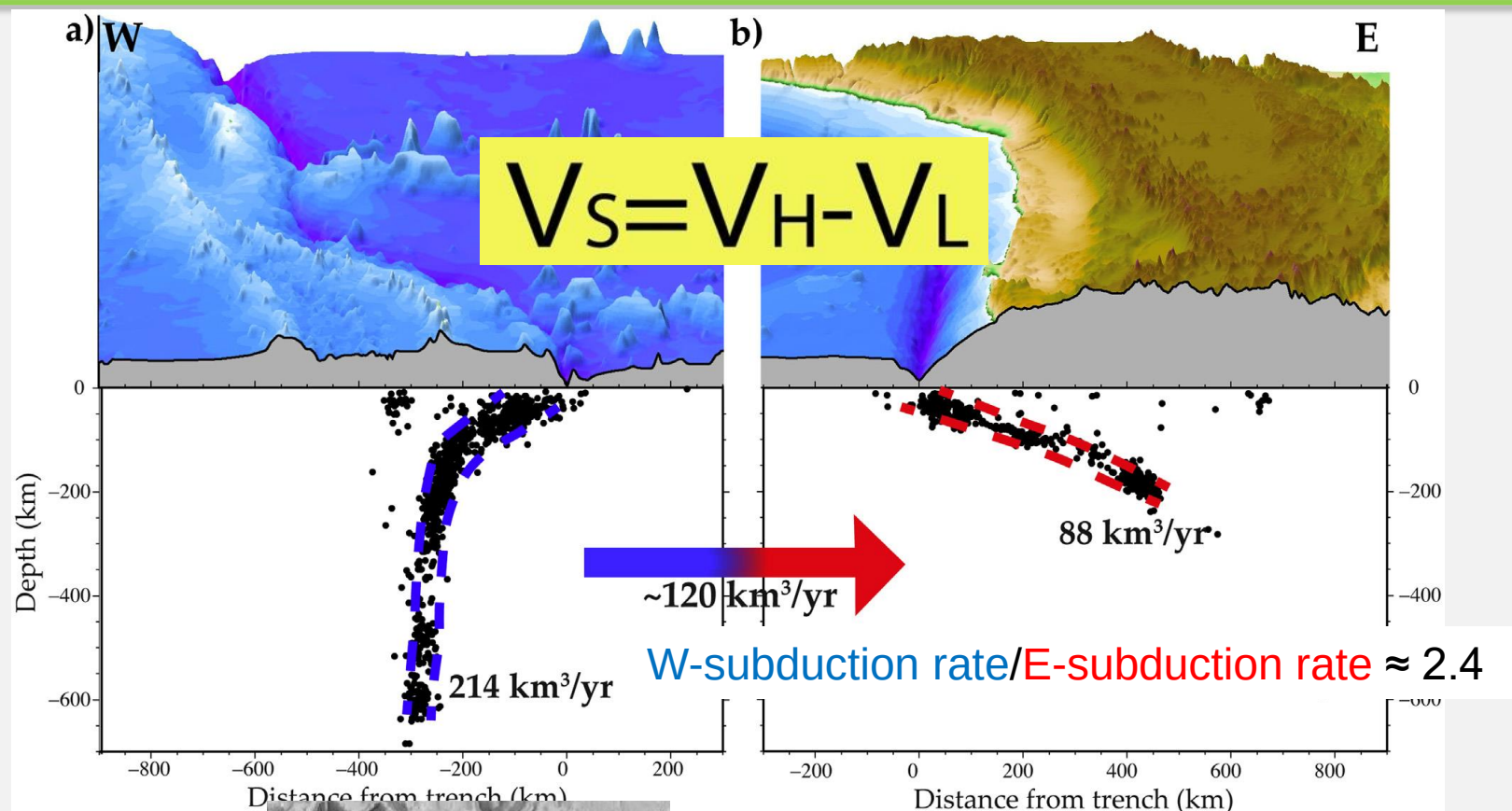
$$V_S = V_H - V_L$$



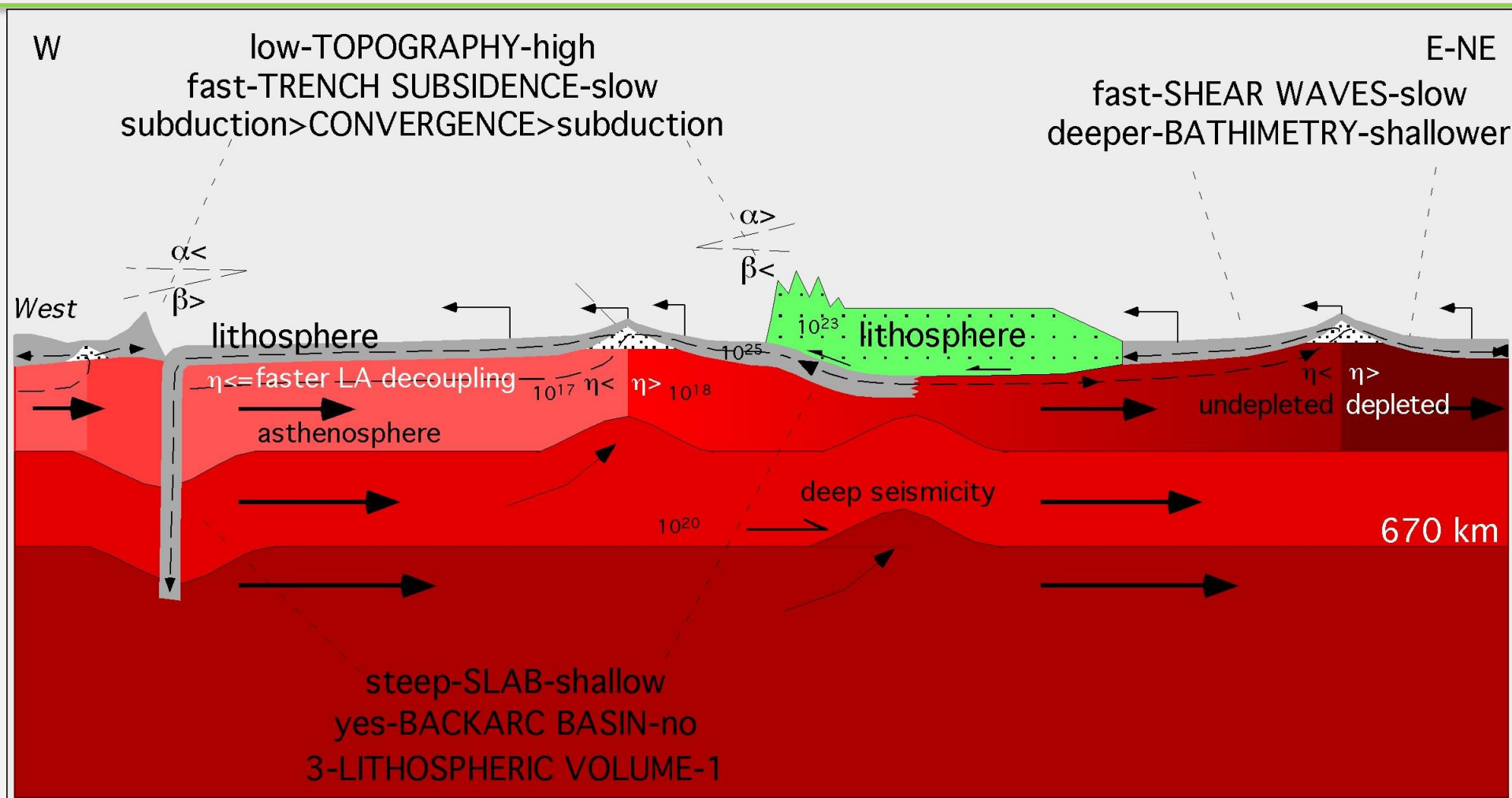




Slab recycling
volumes ≈ 306
 km^3/yr (180 Ma)

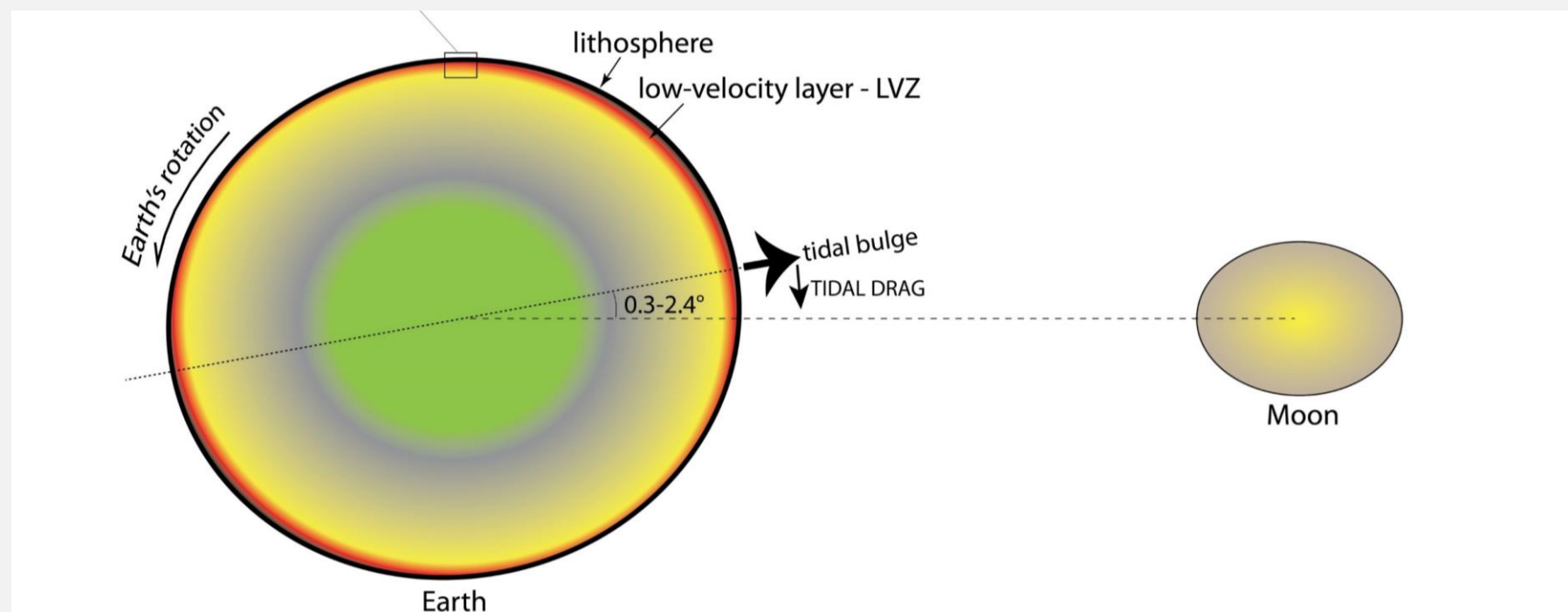


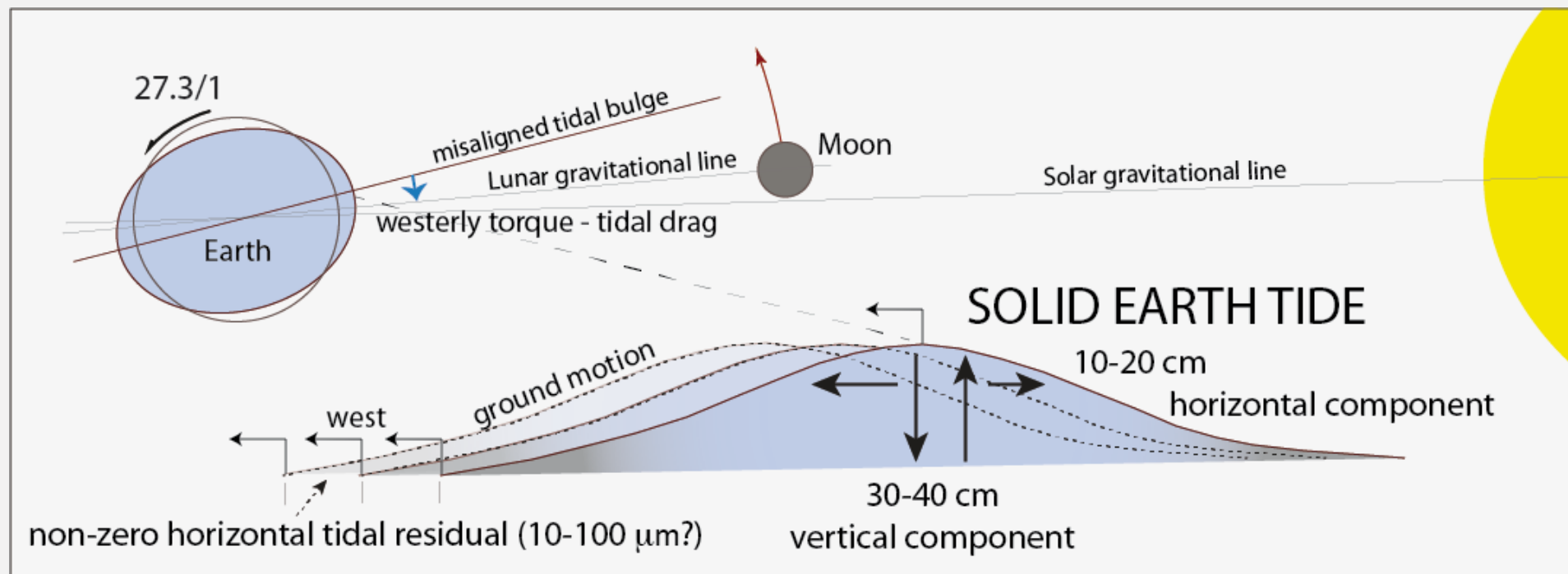
Ficini et al. 2020 Gondwana Res.



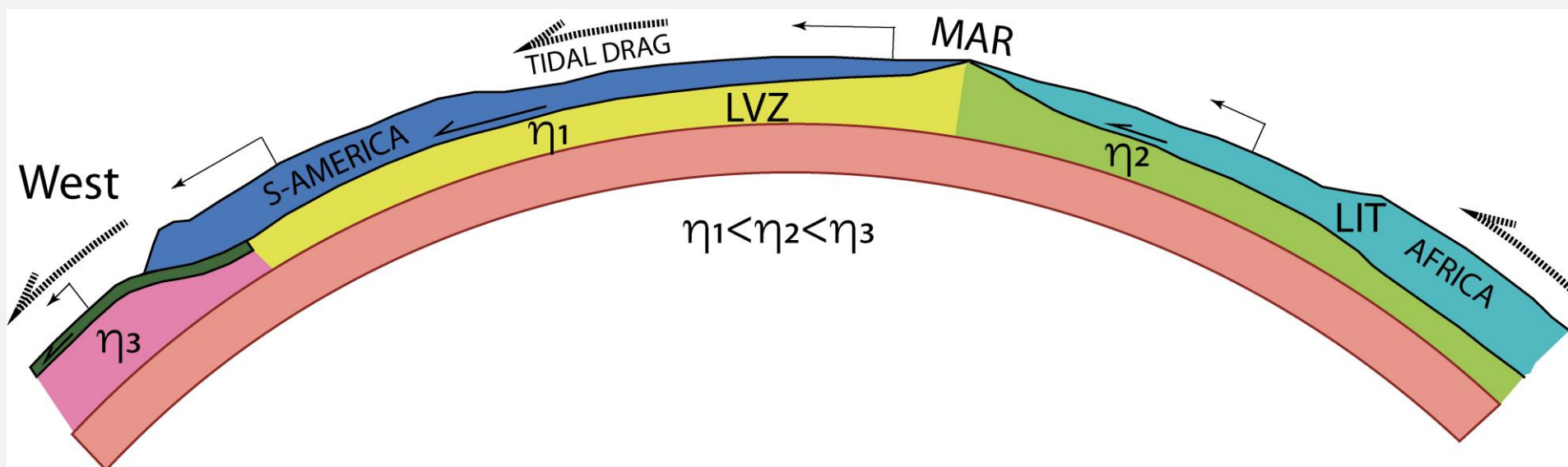
Doglioni & Panza 2015 Advances Geophys.

- Earth's rotation is slowing: with dinosaurs the day was of 22h
- Moon receding at 38 mm/year
- Tidal friction 10^{20-21} J/yr
- Tectonic moment 10^{21} J/yr

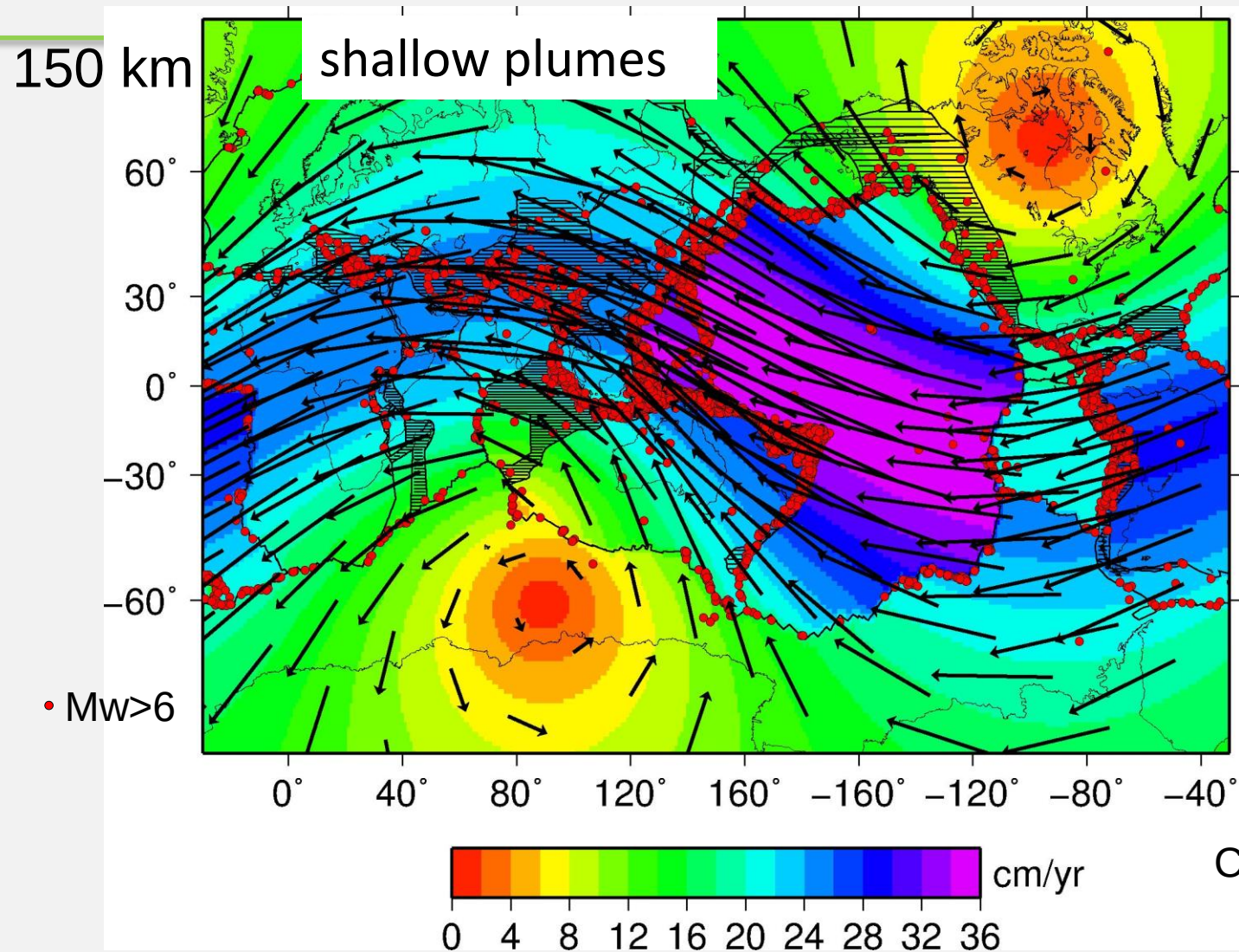




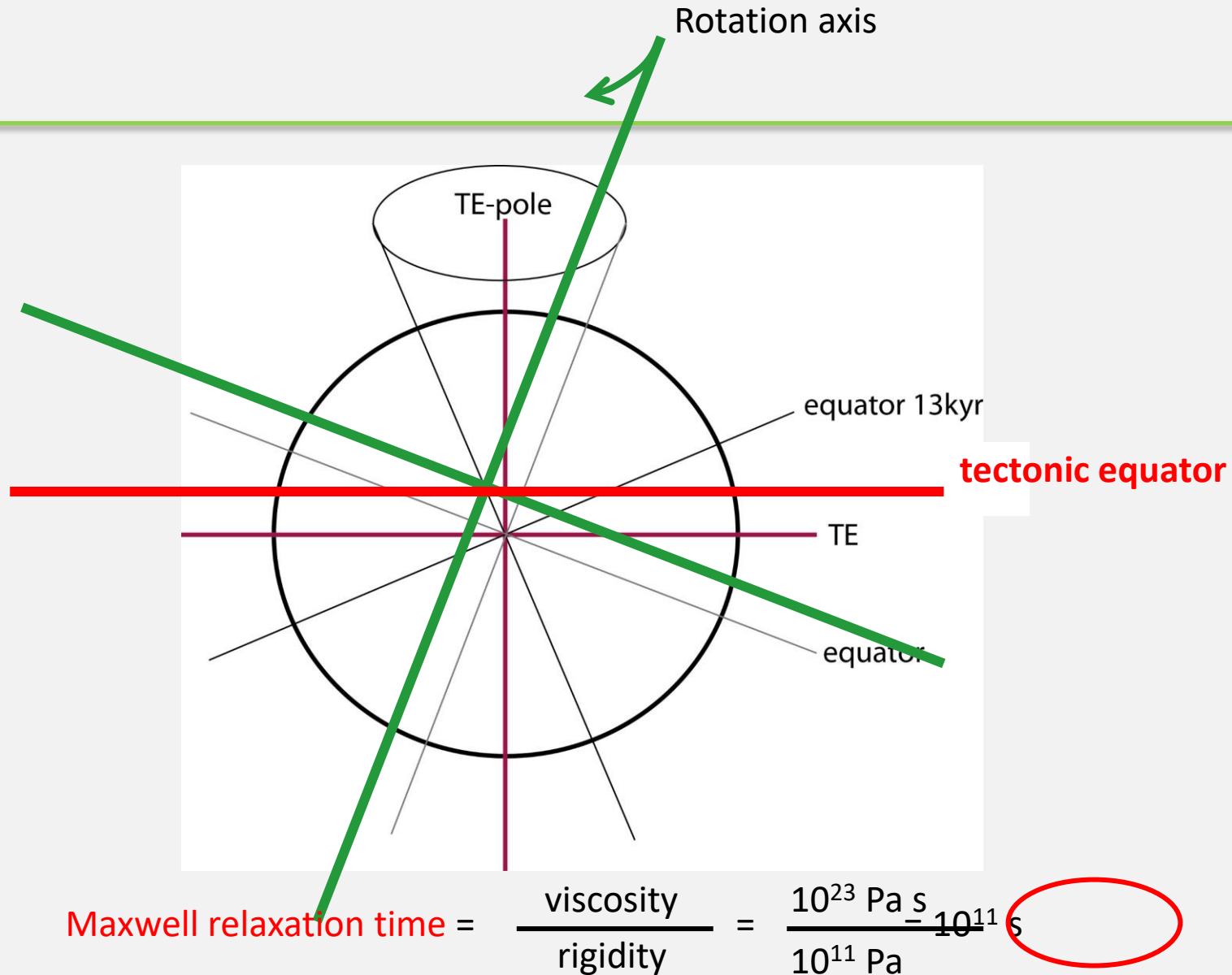
Zaccagnino et al. 2020

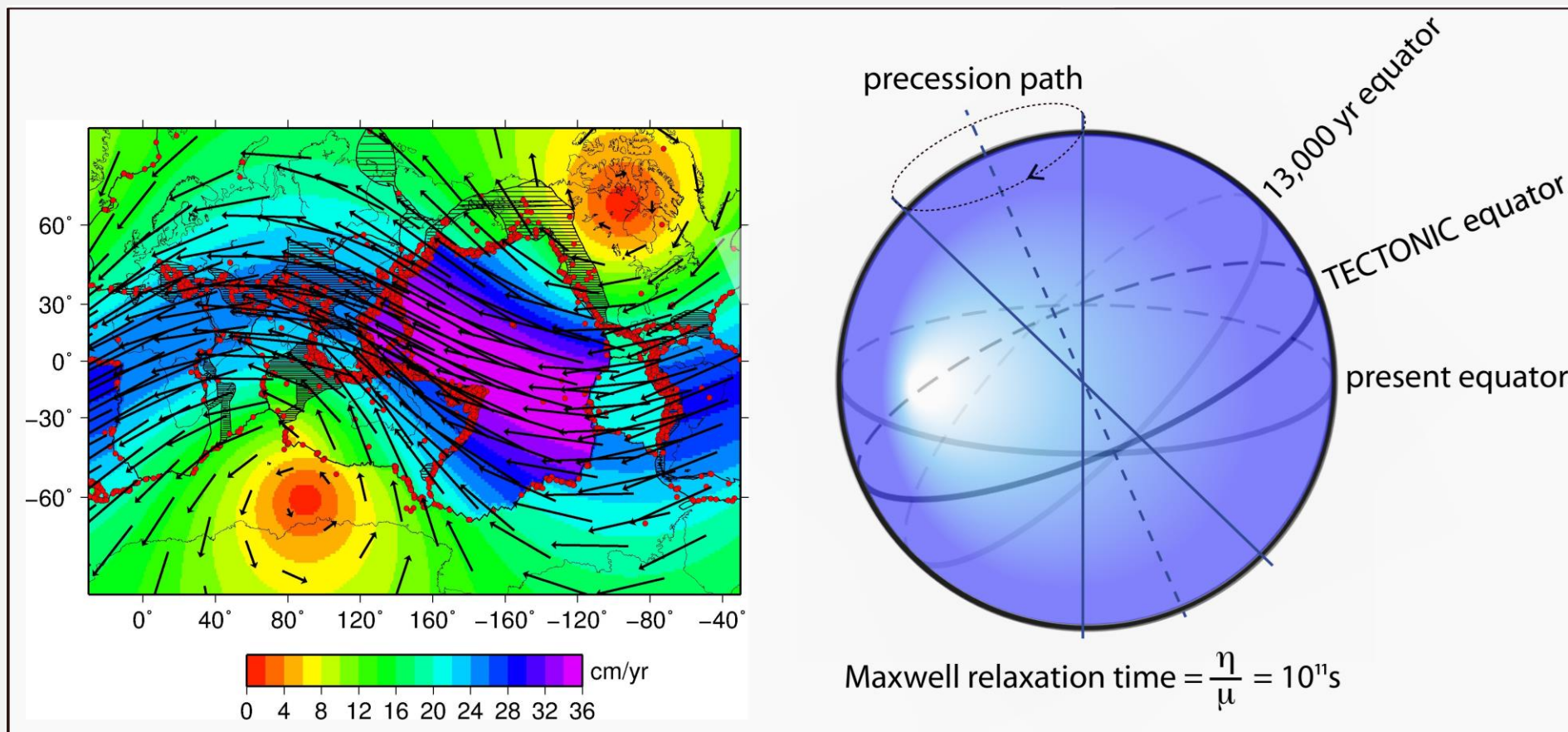


Zaccagnino et al. 2020

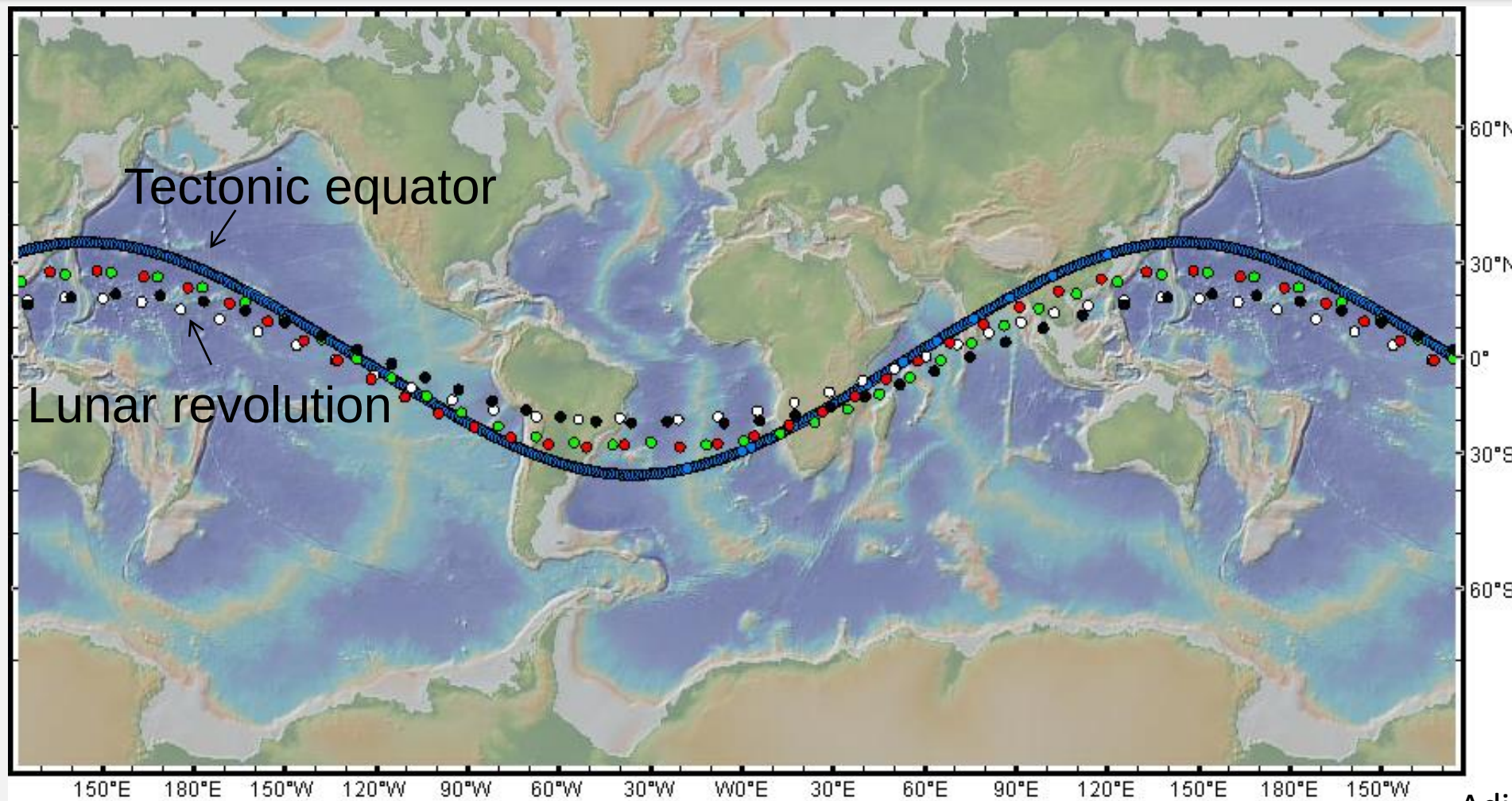


Cuffaro & Doglioni 2018 GR

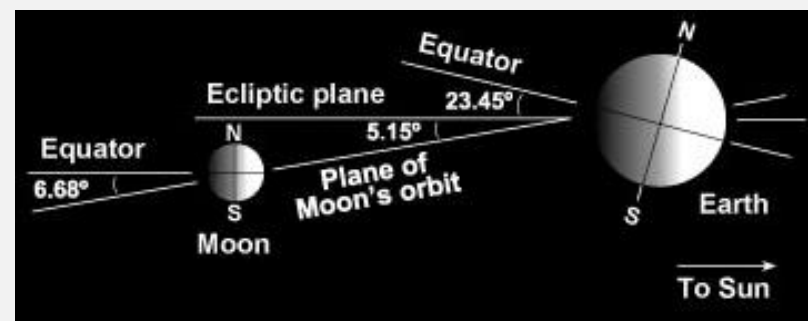
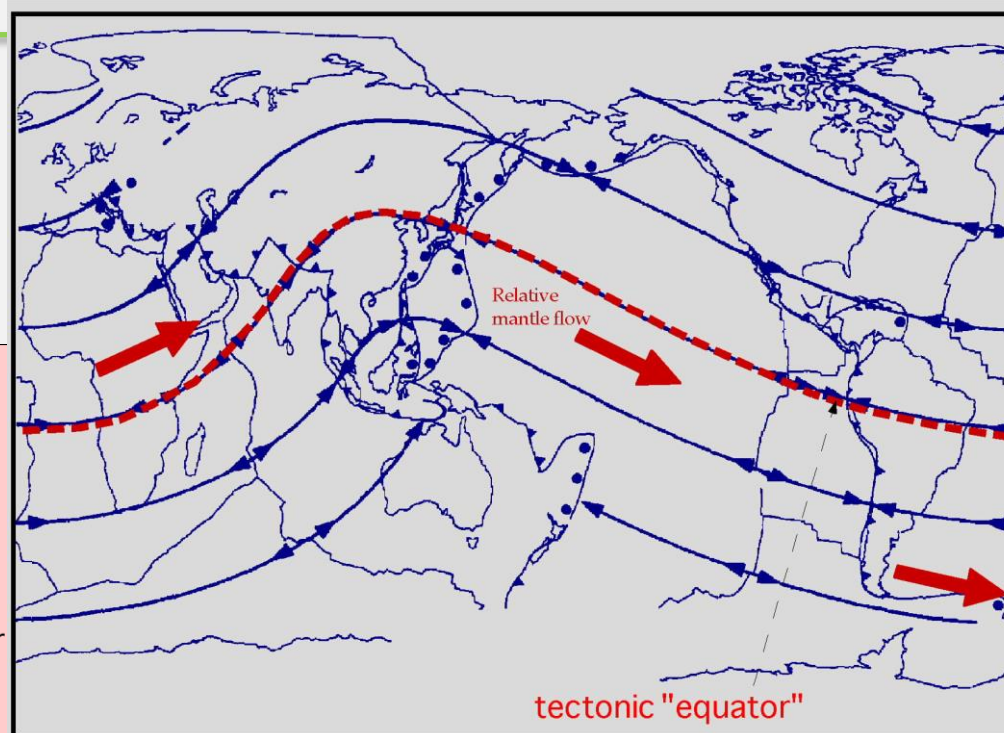
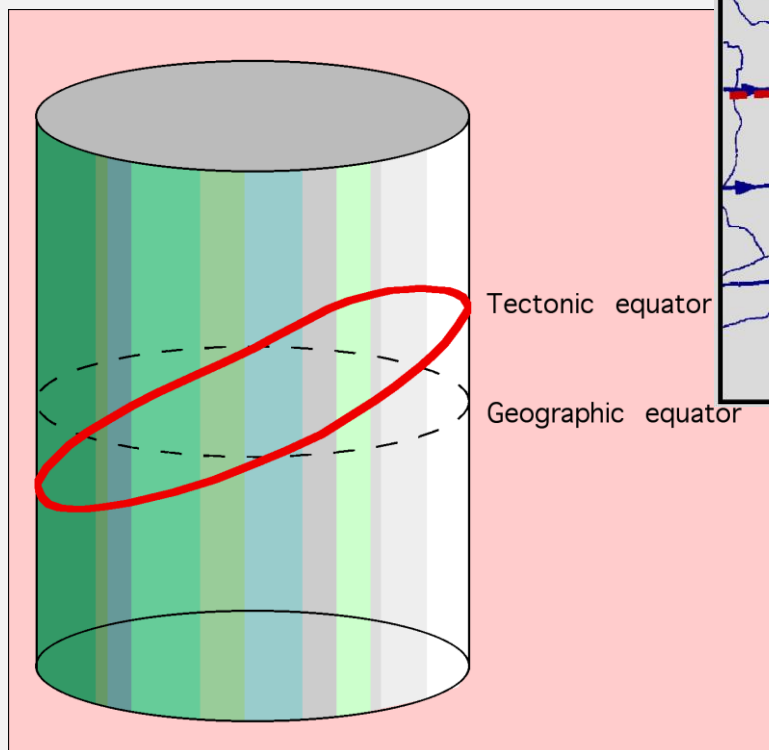


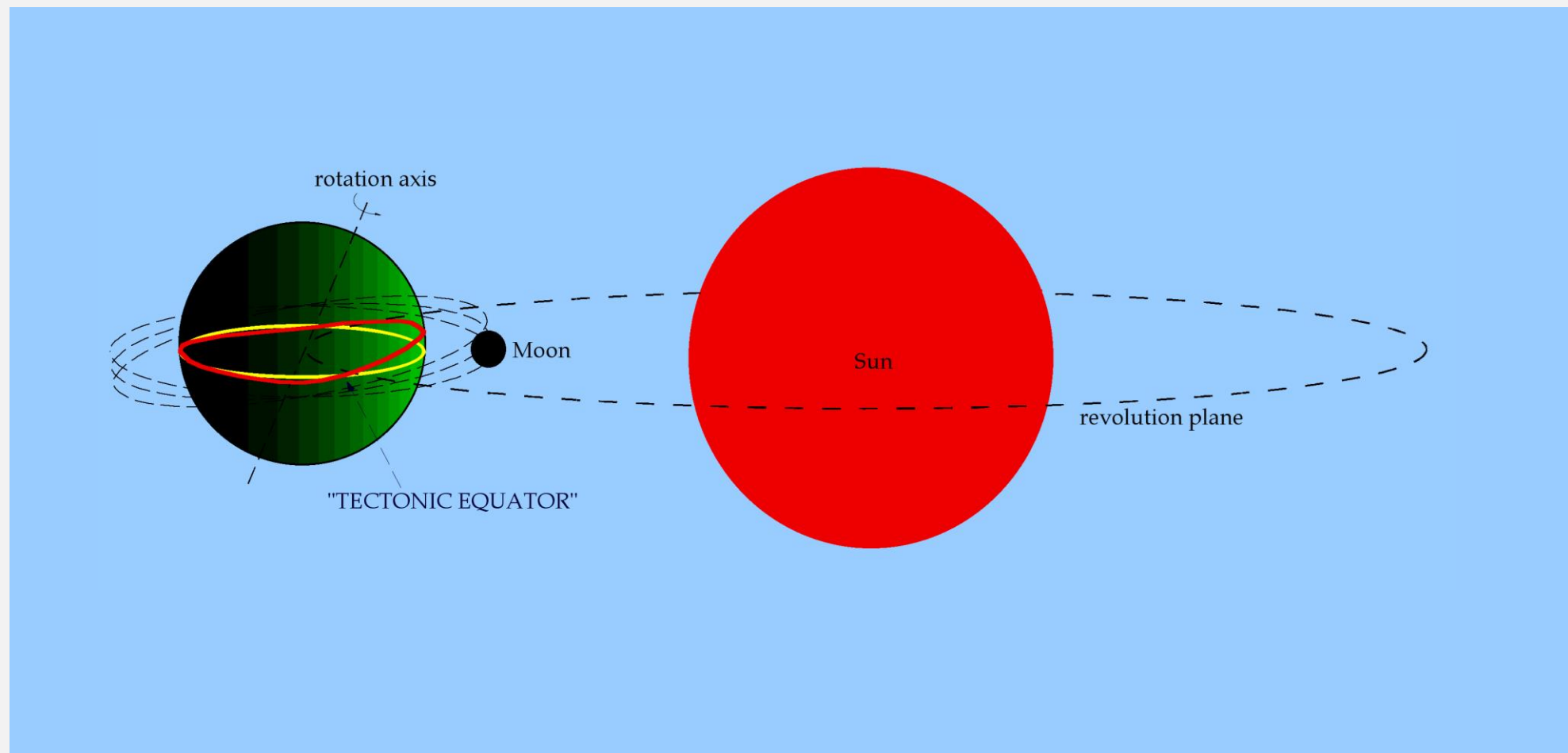


Zaccagnino et al. 2020

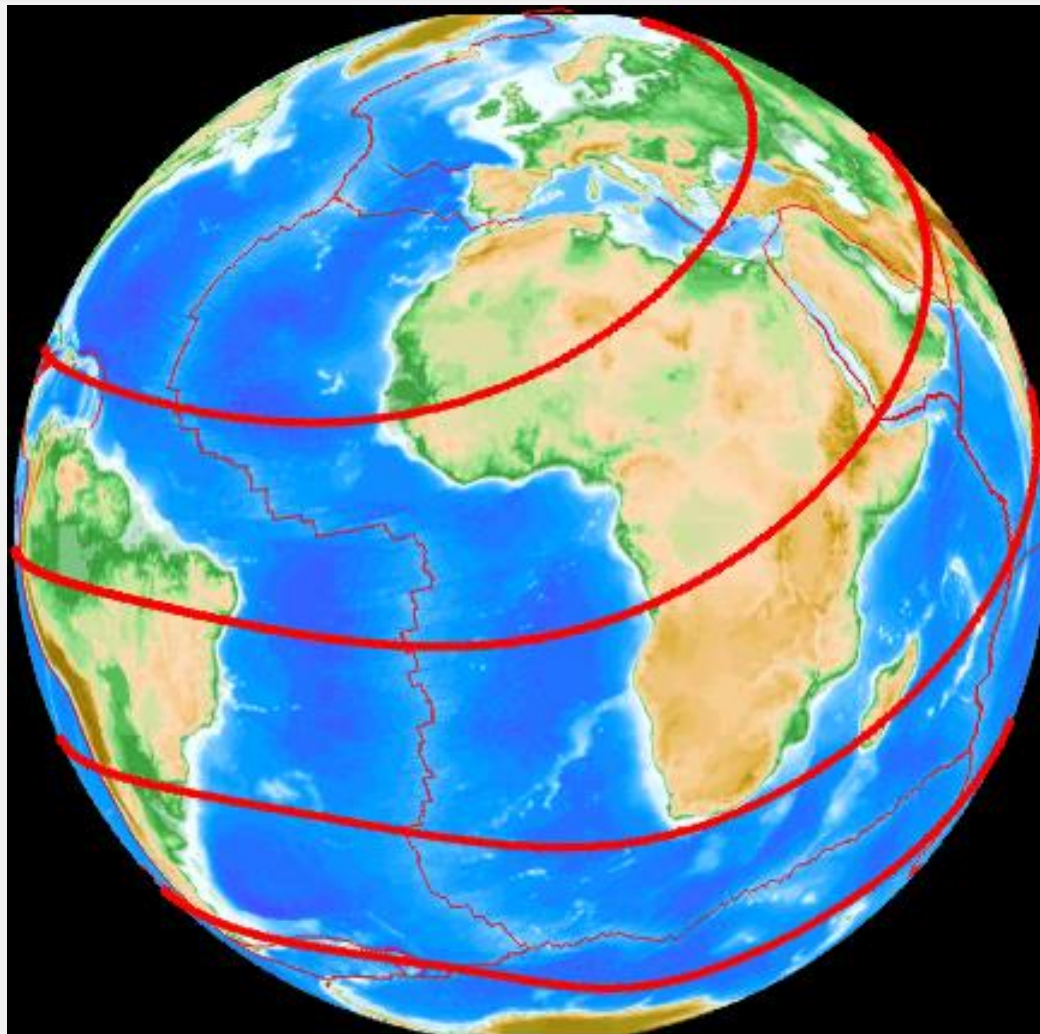


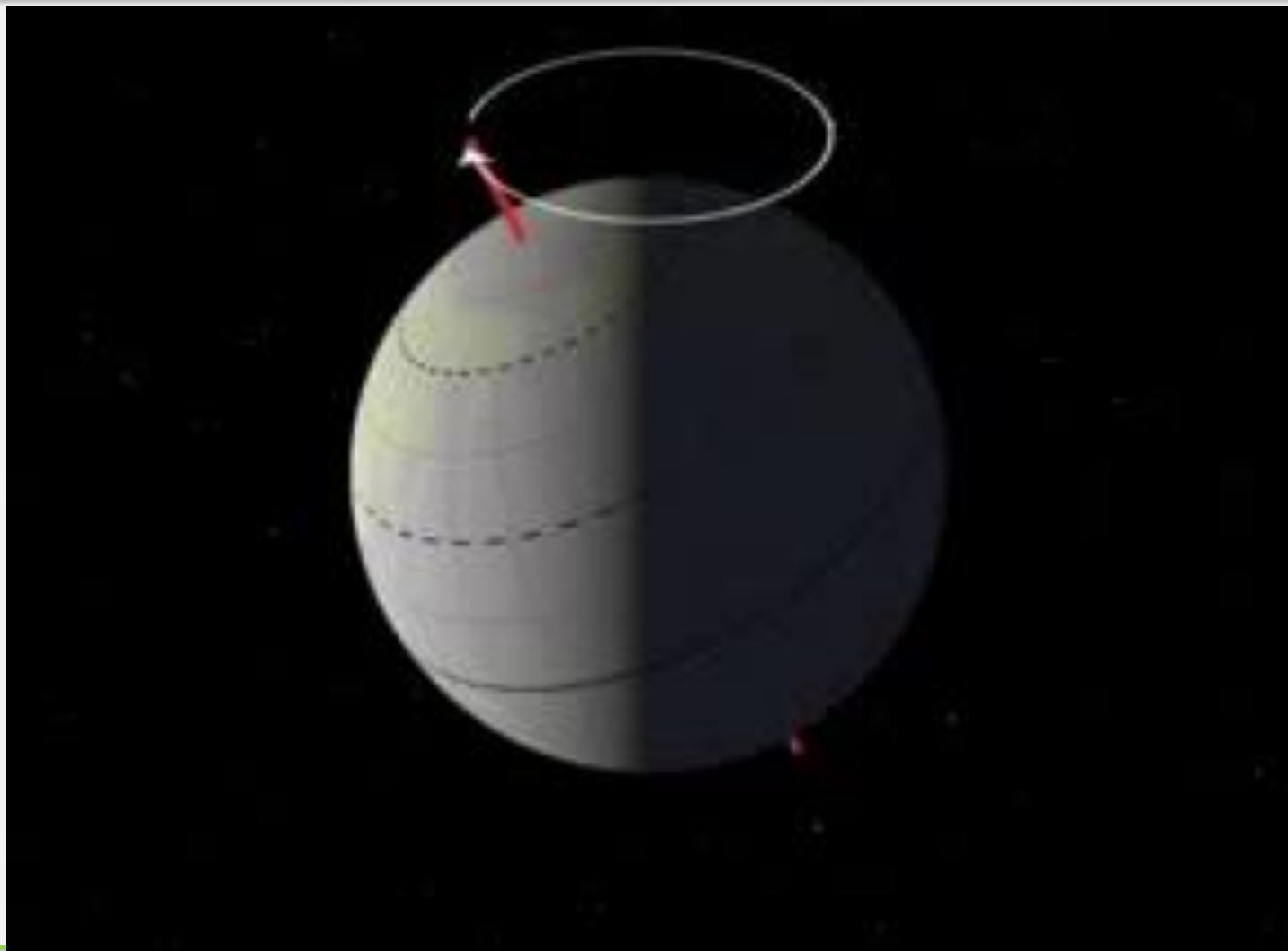
Adinolfi et al. in prep.

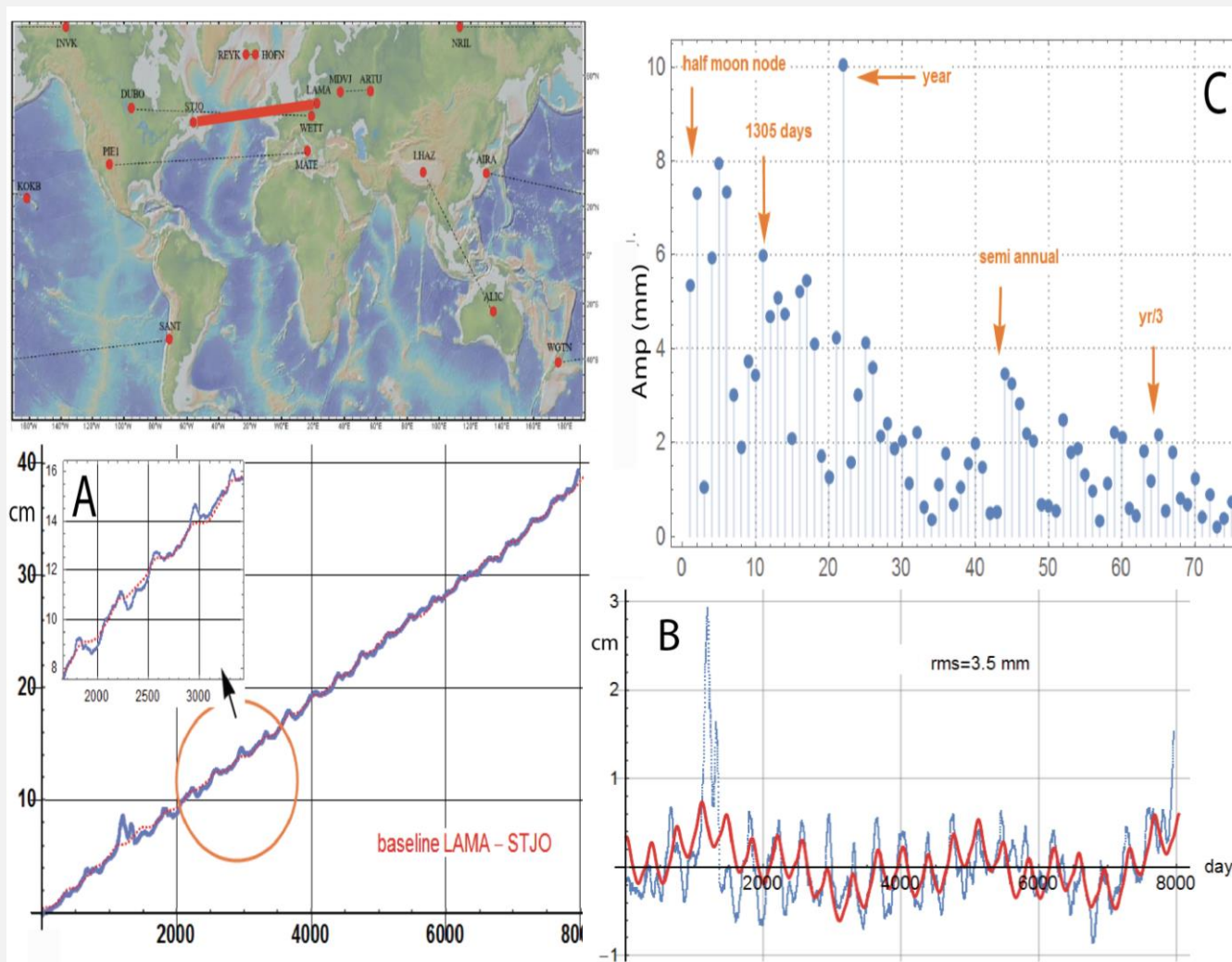




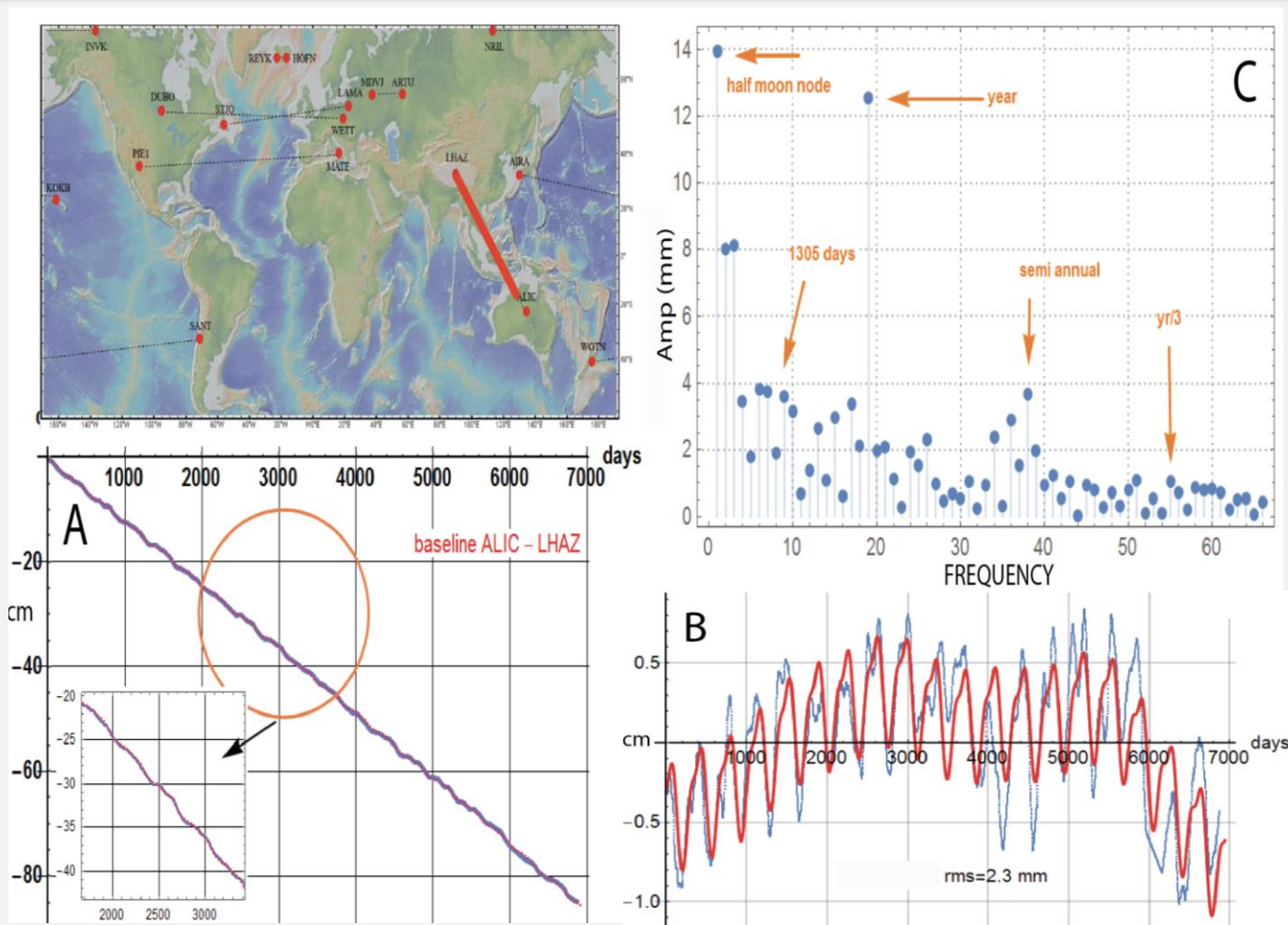




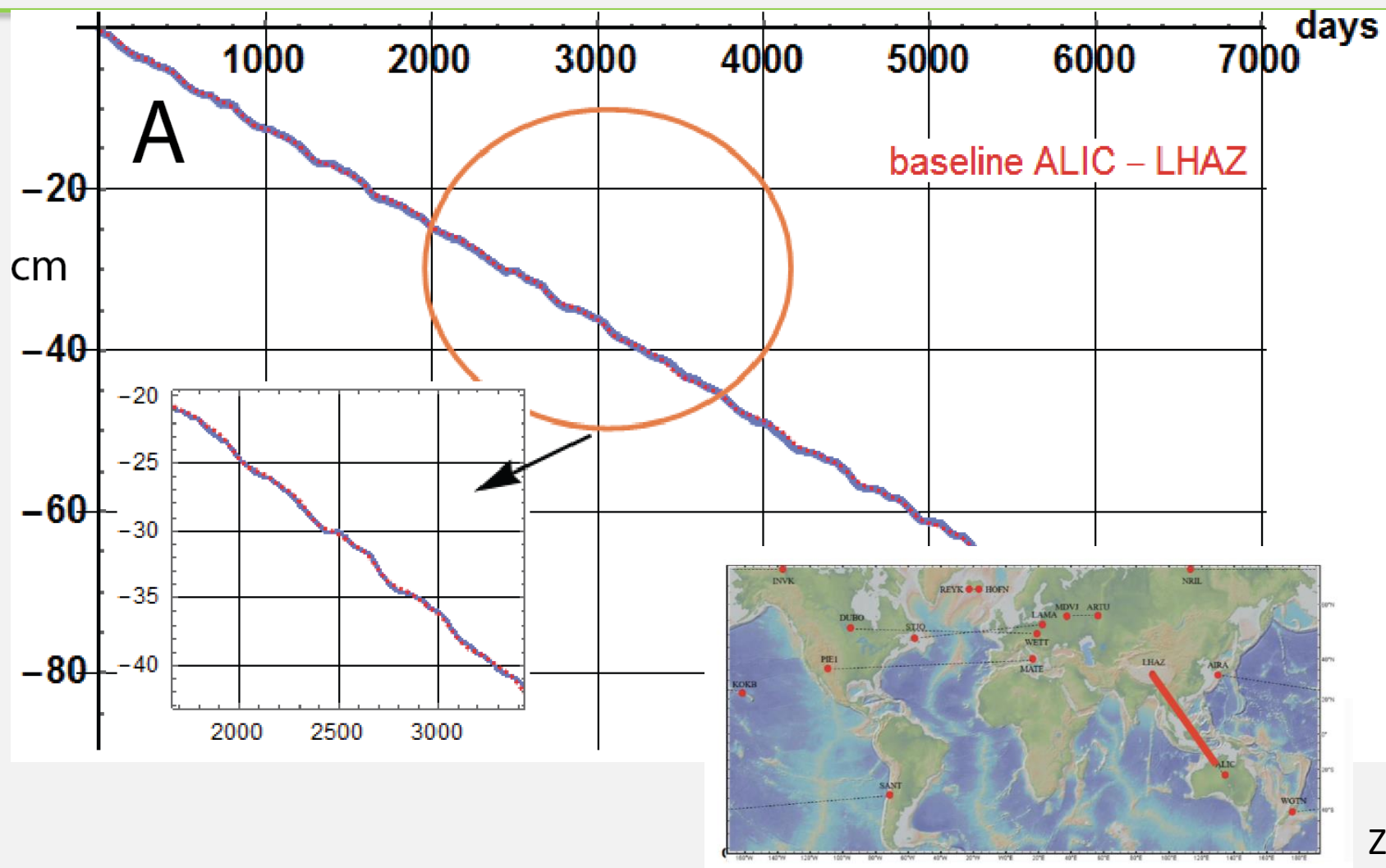




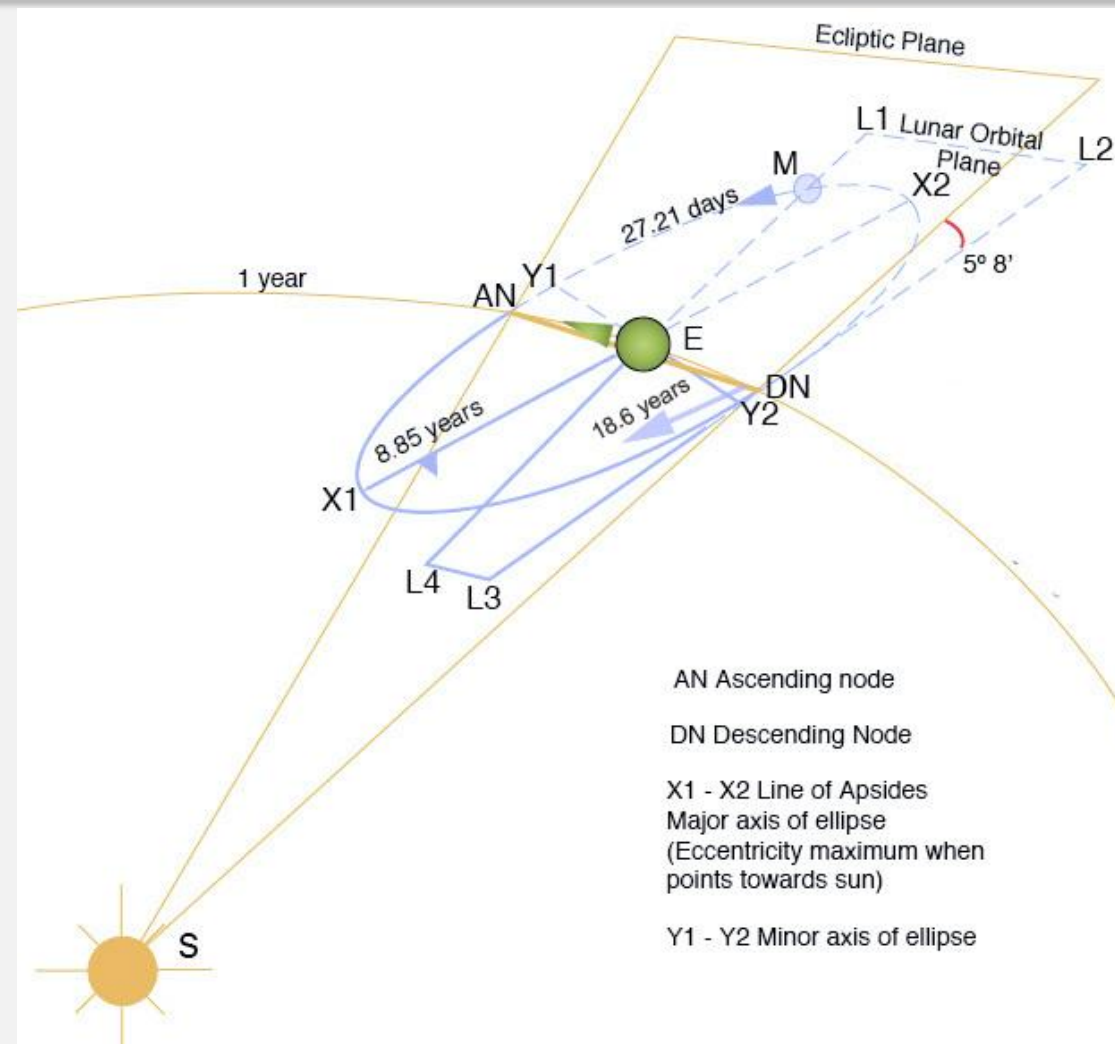
Zaccagnino et al. 2020



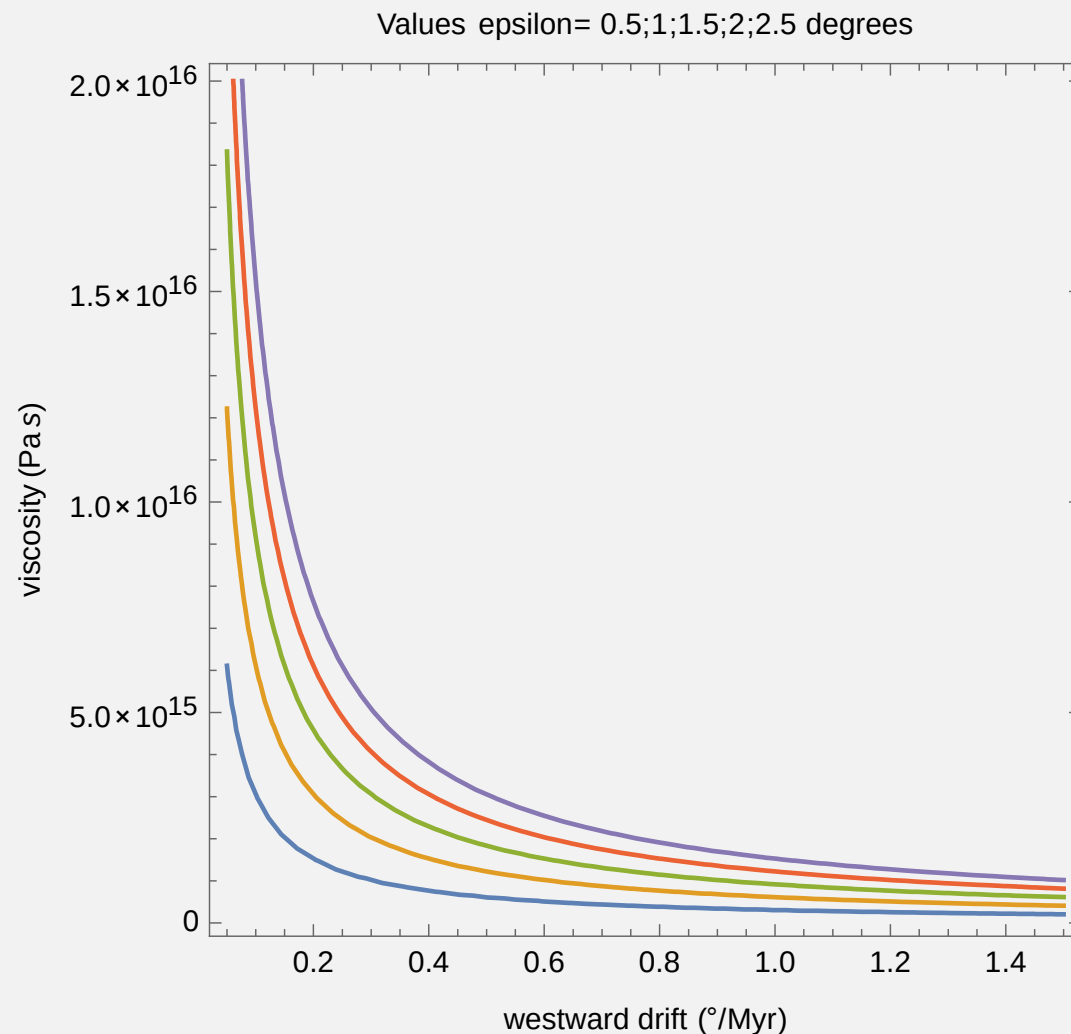
Zaccagnino et al. 2020 ESR



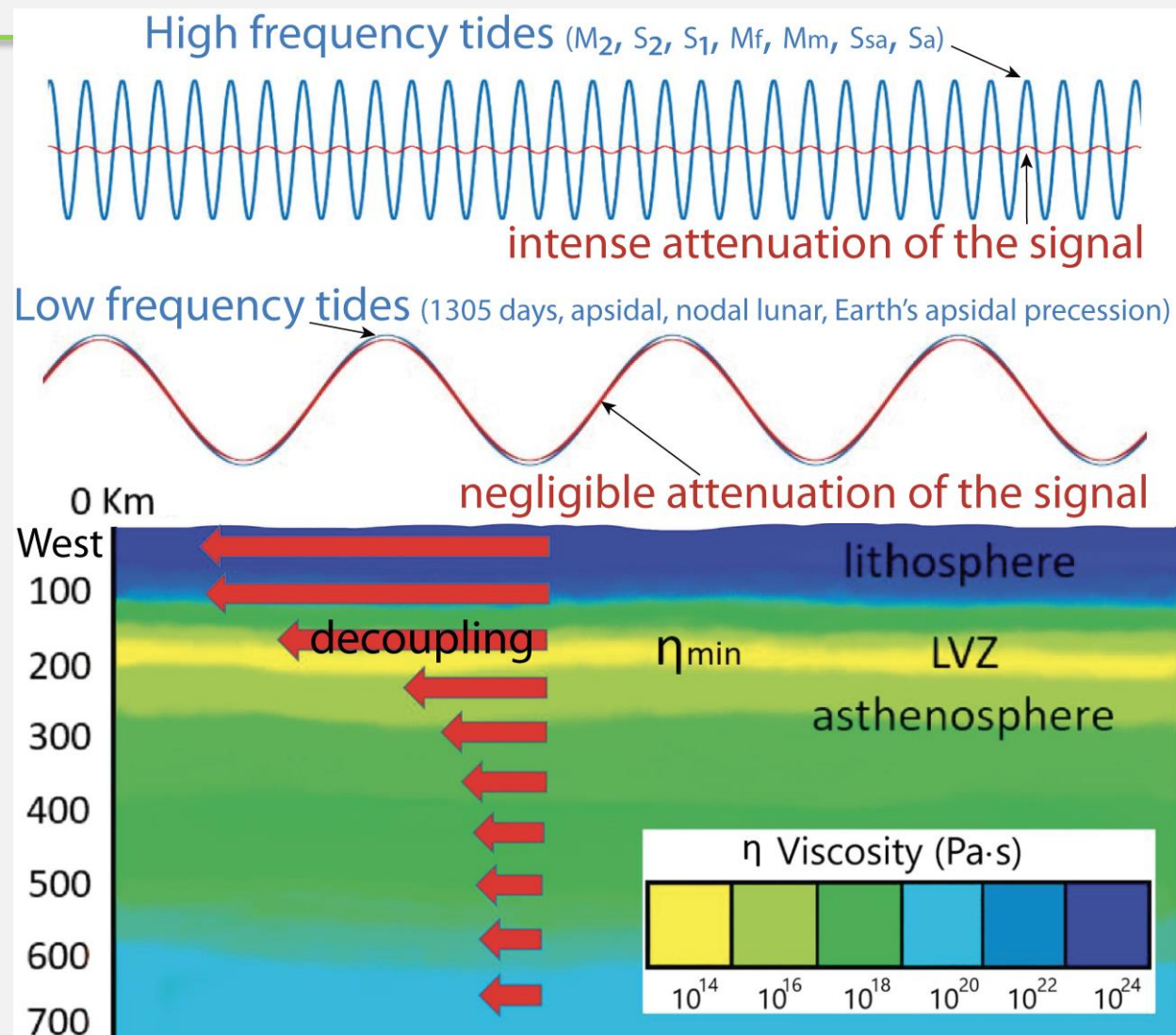
Zaccagnino et al. 2020 ESR



AN Ascending node
 DN Descending Node
 X1 - X2 Line of Apsides
 Major axis of ellipse
 (Eccentricity maximum when
 points towards sun)
 Y1 - Y2 Minor axis of ellipse

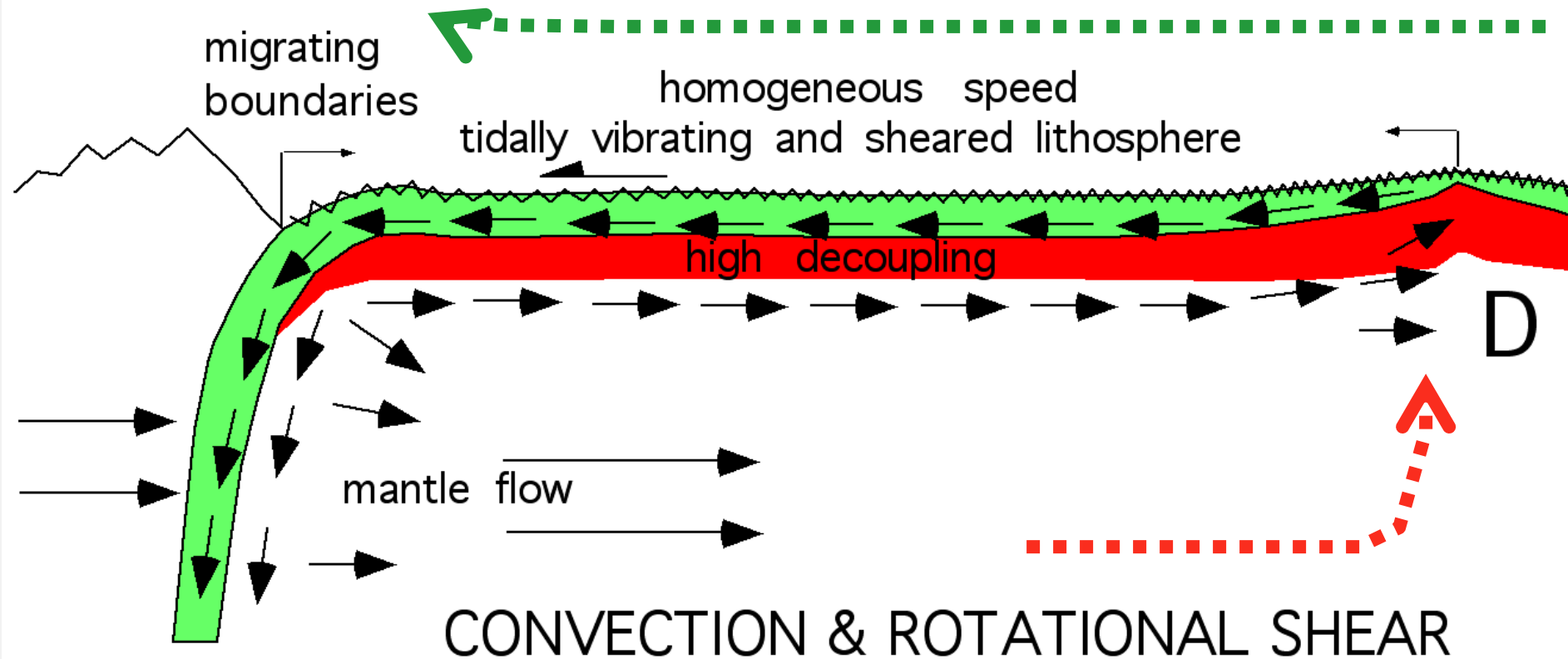


Nesi et al. 2023 Geoscience Frontiers



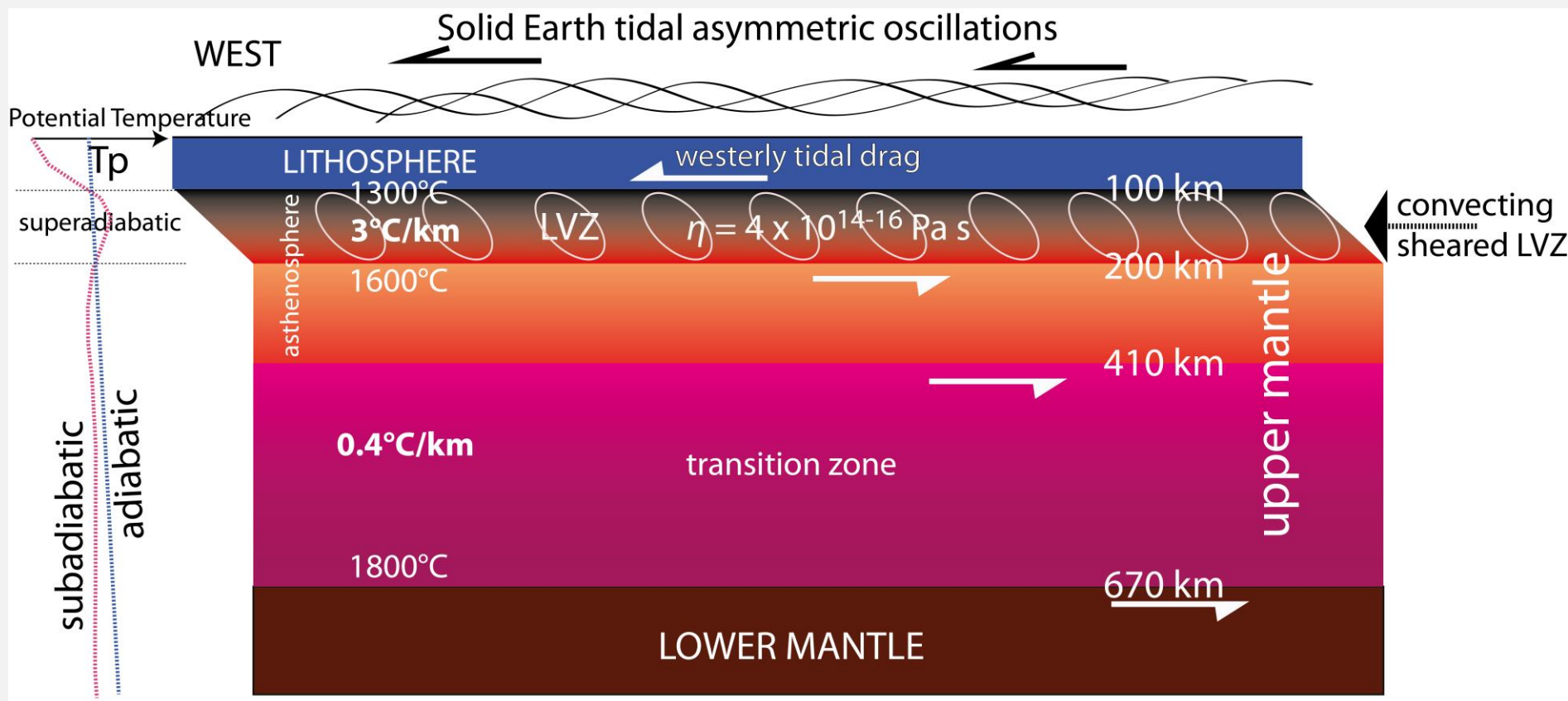
Zaccagnino et al. 2020

ASTRONOMICAL TUNING

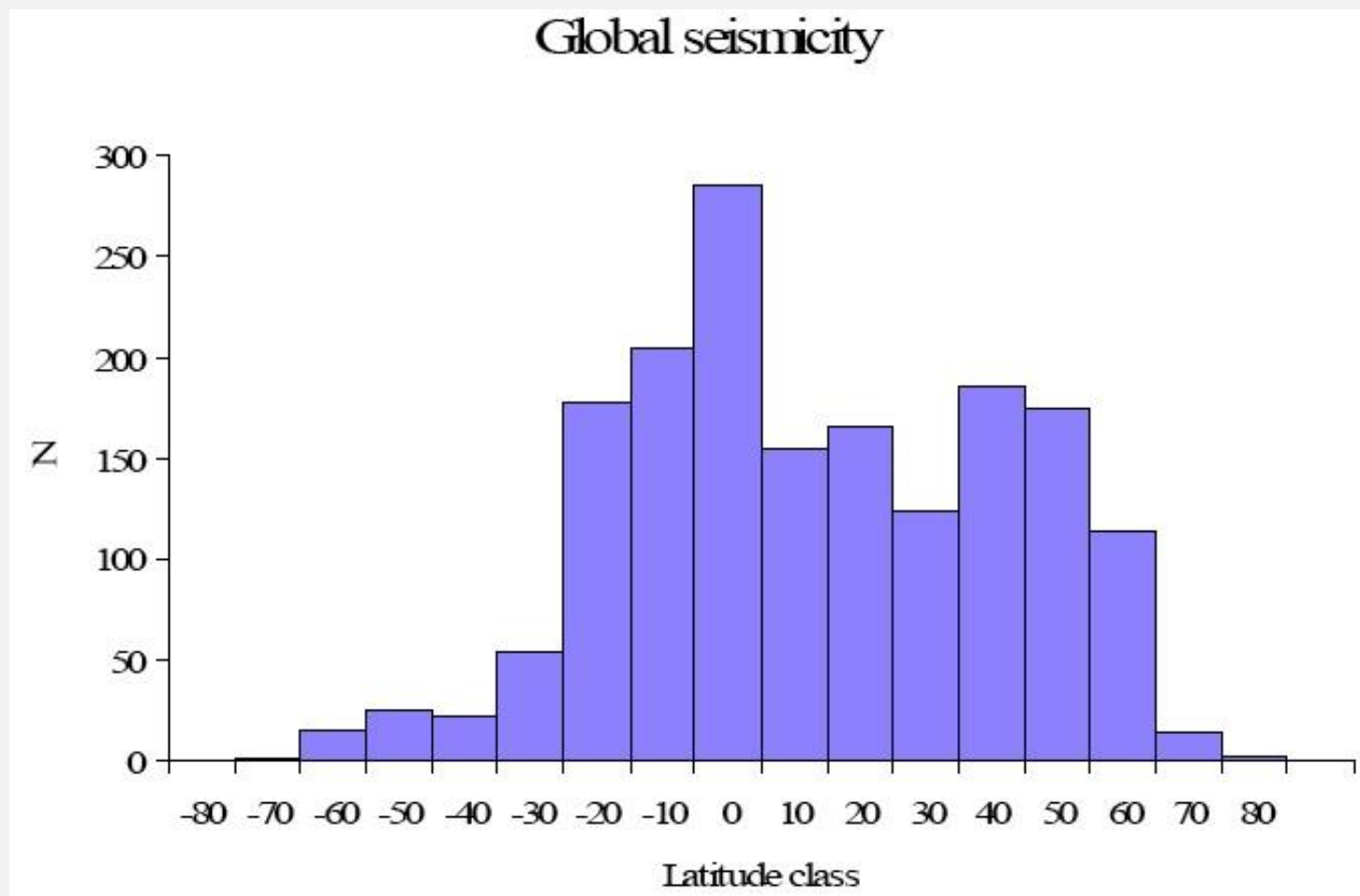


THERMAL COOLING

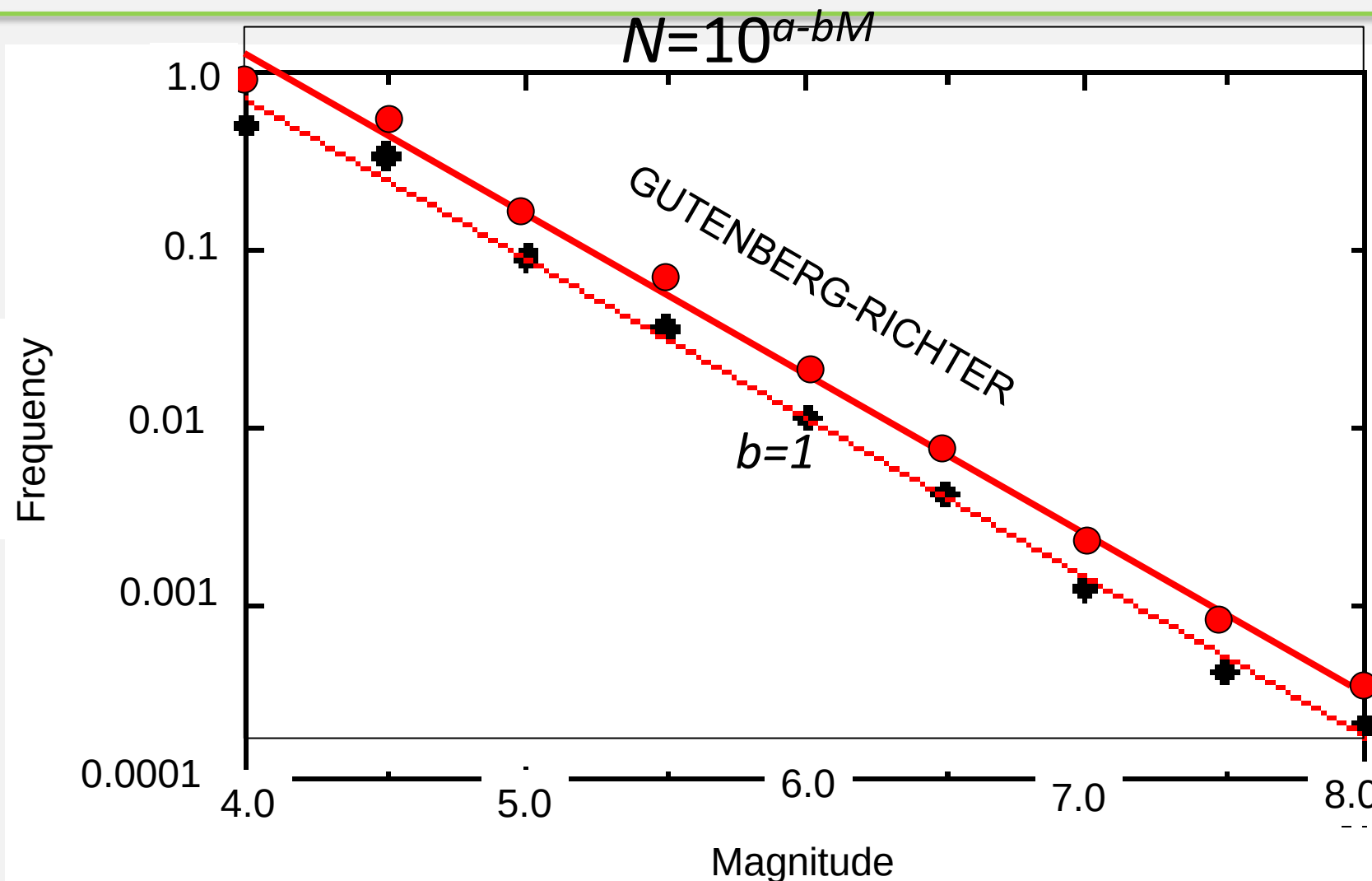
ASTRONOMICAL TUNING



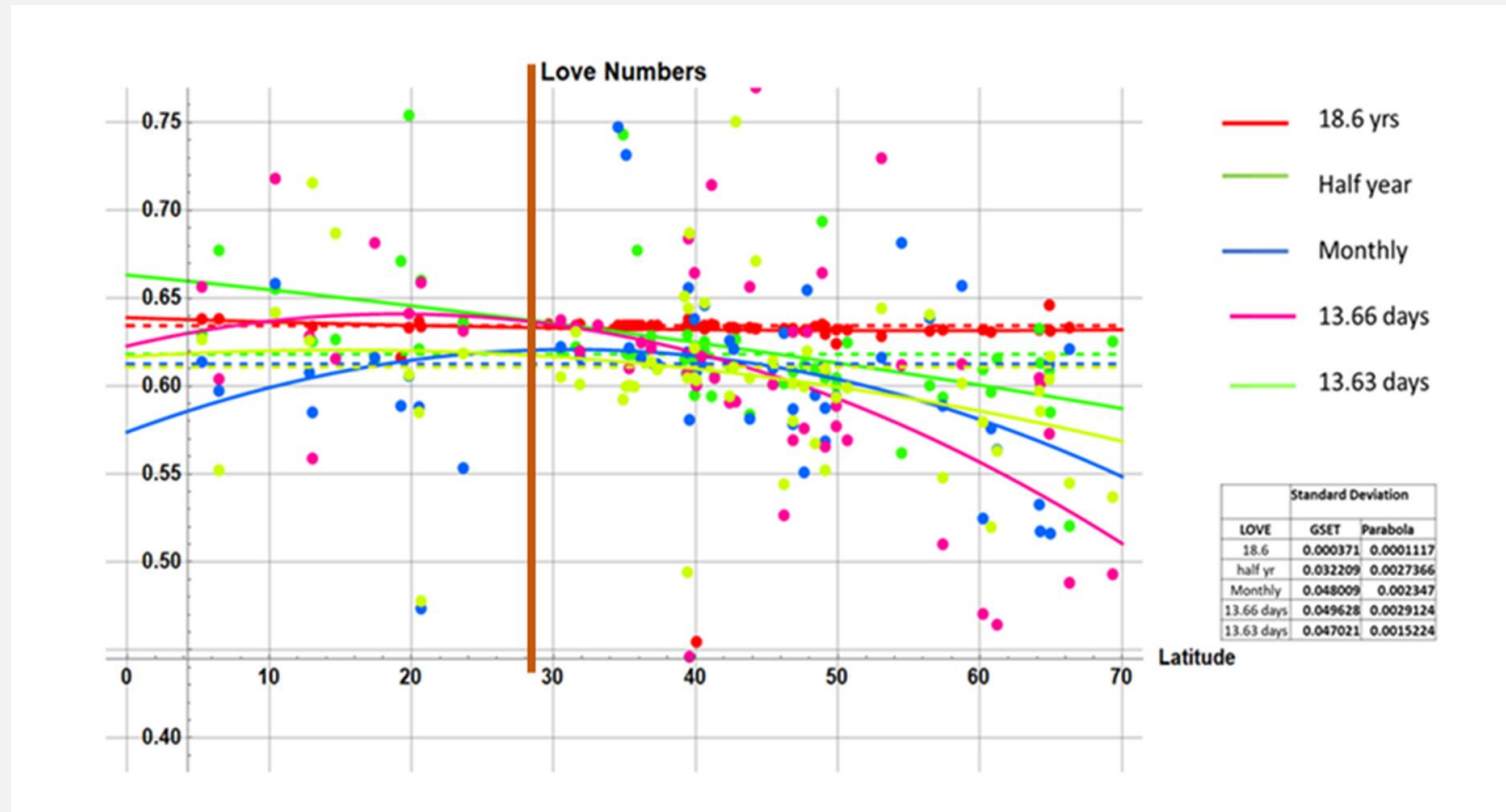
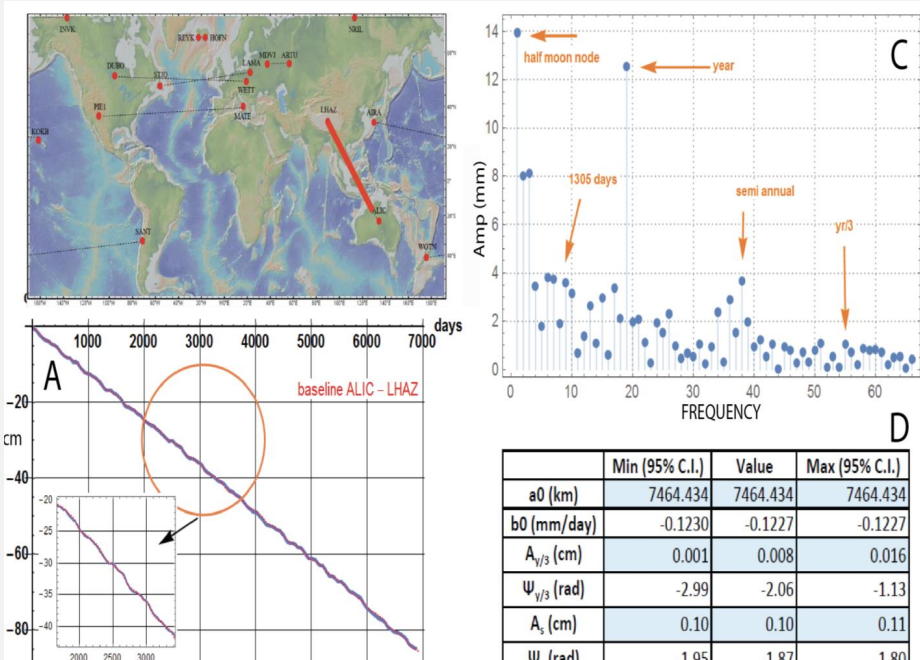
THERMAL COOLING



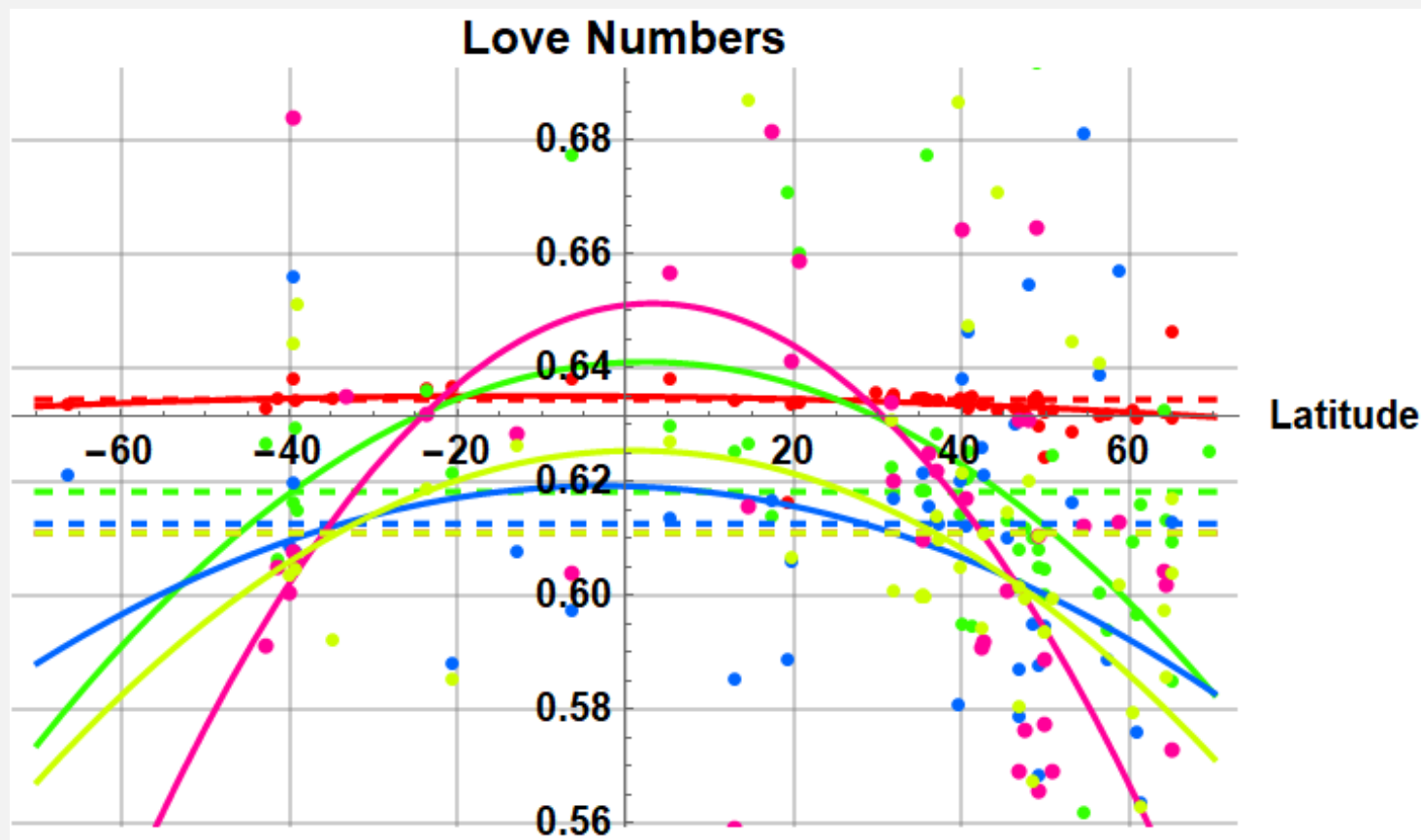
Riguzzi et al., 2010 Tectonophysics



- For Tectonics
 - Global network with a sampling rate of 1 day with LPT switched off and SPT switched on (Should reduce the noise level)
 - Global network with a sampling rate of 3H with all the Tides model Switched off for SPT: K1 & M2
- For Earthquakes
 - Global network with a sampling rate of 3H with all the Tides model Switched off looking at SPT: K1 & M2
- For Volcanoes
 - Regional network with a sampling rate of 3H. Time span as long as possible (more than a couple of years at least). Tides model Switched Off looking at SPT: K1 & M2



Values of Love Numbers with respect the Tectonic Equator: Where did we stand ?

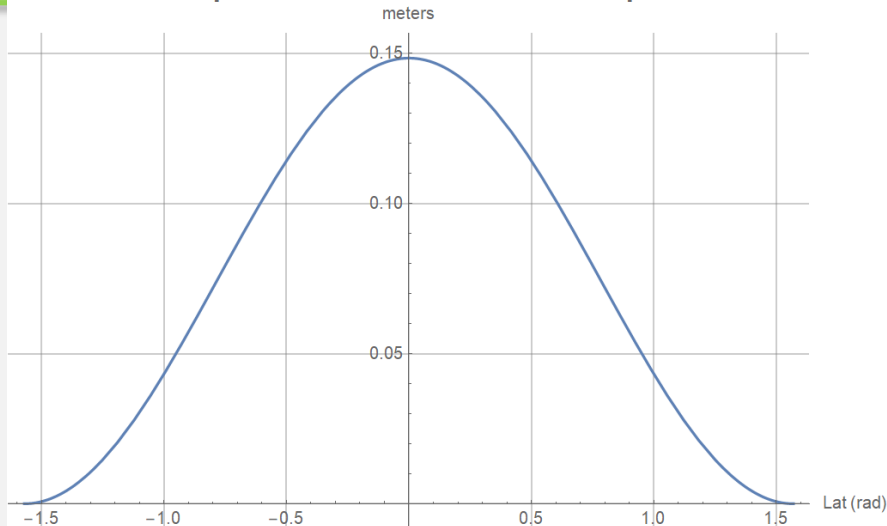


Pole of TE:
Lat.= -56.4°
Lon.=136.7°

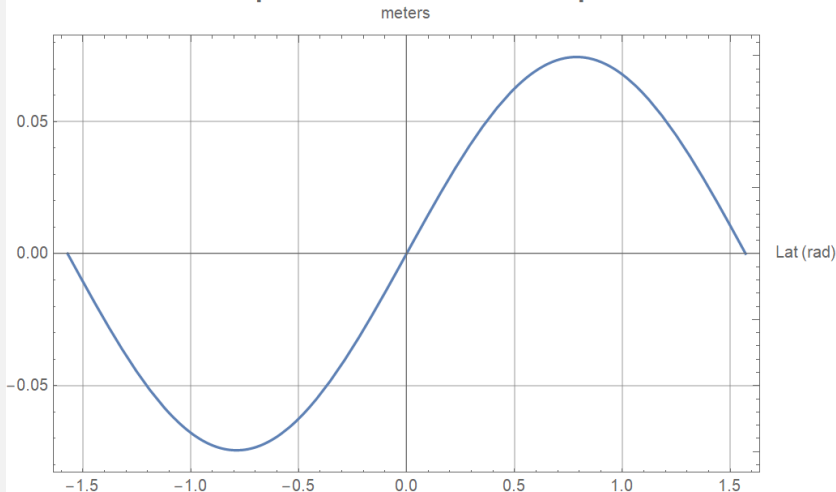


Tidal Friction → Higher Temperature of Mantle/Crust → More Fluidity → Bigger L_{Sn}

amplitudes of semidiurnal tides: Up

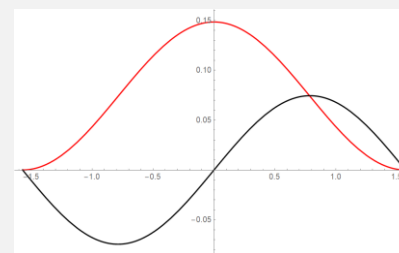


amplitudes of diurnal tides: Up

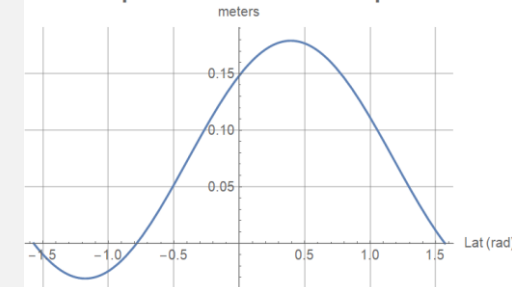


For Semidiurnal Tides:

$$\Delta \mathbf{r}_f = \sqrt{\frac{5}{96\pi}} \cdot H_f \cdot \left\{ \begin{array}{l} 3h(\phi) \cos^2 \phi \cdot \cos(\theta_f + 2\lambda) \hat{\mathbf{r}} + \\ -6 [l(\phi) + l^{(1)}] \cdot \sin \phi \cdot \cos \phi \cdot \cos(\theta_f + 2\lambda) \hat{\mathbf{n}} + \\ -6 [l(\phi) + l^{(1)} \cdot \sin^2 \phi] \cdot \cos \phi \cdot \sin(\theta_f + 2\lambda) \hat{\mathbf{e}} \end{array} \right\}$$



amplitudes of short tides: Up



For Diurnal Tides:

$$\Delta \mathbf{r}_f = \sqrt{\frac{5}{24\pi}} \cdot H_f \cdot \left\{ \begin{array}{l} 3h(\phi) \cdot \sin \phi \cdot \cos \phi \cdot \sin(\theta_f + \lambda) \hat{\mathbf{r}} + \\ \left[3l(\phi) \cdot \cos 2\phi - 2l^{(1)} \cdot \sin^2 \phi + \sqrt{\frac{24\pi}{5}} l' \right] \cdot \sin(\theta_f + \lambda) \hat{\mathbf{n}} + \\ \left[\left(3l(\phi) - \sqrt{\frac{24\pi}{5}} l' \right) \cdot \sin \phi - 3l^{(1)} \cdot \sin \phi \cdot \cos \phi \right] \cdot \cos(\theta_f + \lambda) \hat{\mathbf{e}} \end{array} \right\}$$

- Focus only on the main tidal constituents:

Period (days)	Amp. (m)	Freq	$h^{(0)R}$	$h^{(0)I}$	$h^{(2)}$	h'	$l^{(0)R}$	$l^{(0)I}$	$l^{(1)}$	$l^{(2)}$	l'
0.99727	-0.3678	1.0027	0.5236	0.0030	0.0030	0.0007	0.0870	-0.0006	0.0011	0.0002	-0.0003
0.517526	0.6319	1.9323	0.6079	-0.0022	-0.0006	0.0000	0.0847	0.0007	0.0024	0.0002	0.0000

- 12^h 25' (M2) with $H_f=0.632$ (m)
- 23^h 56.07' (K1) with $H_f= -0.3678$ (m)
- Estimated **one by one**every 15 days
- With only the offset to be estimated:

$$\Delta r[t]=A_d * \text{Cos}[2 * \text{Pi} * t / T_d + \text{ph}_d] \text{ or } A_{sd} * \text{Cos}[2 * \text{Pi} * t / T_{sd} + \text{ph}_{sd}] + b$$
- one by one as done for LPT, not Removing the slope
- For LPT we have used the new DI release of GNSS data processing:
 - LPT switched off
 - ST switched on

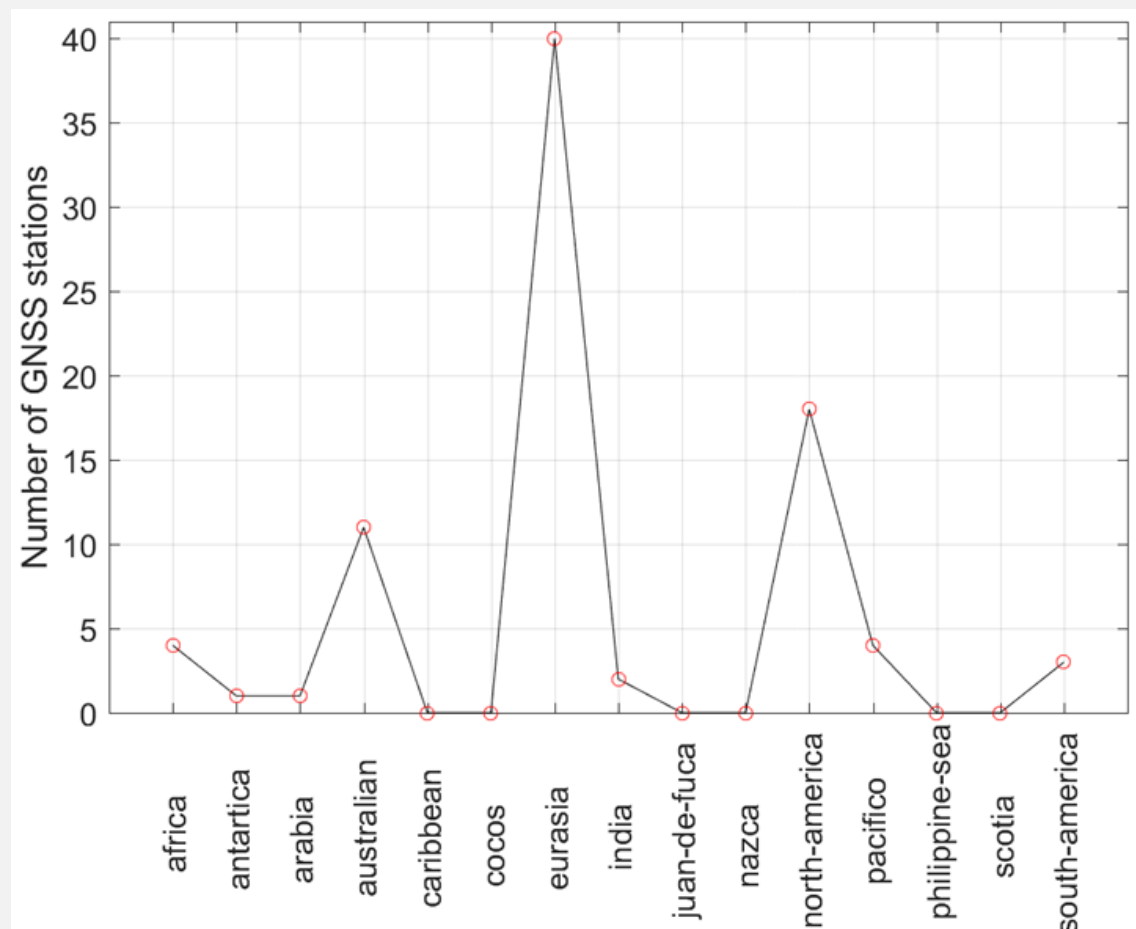


The Table of Love Numbers



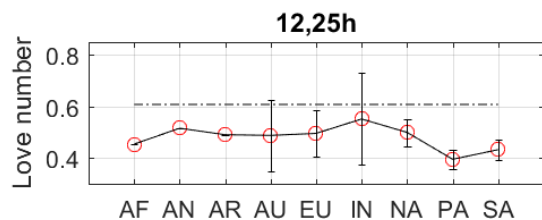
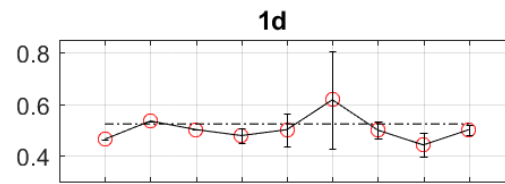
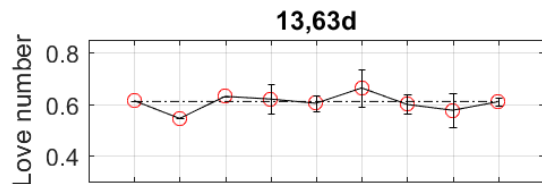
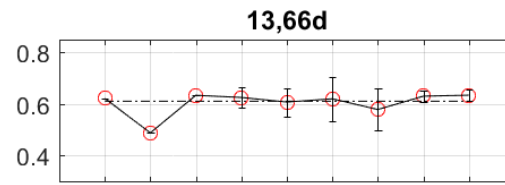
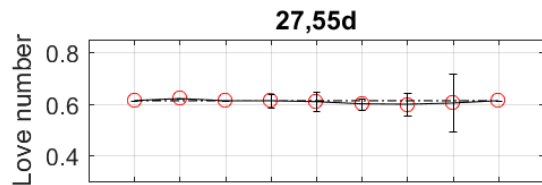
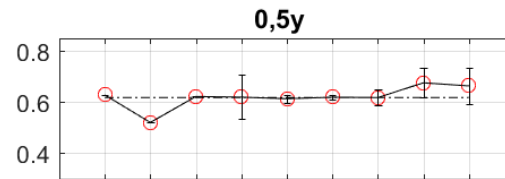
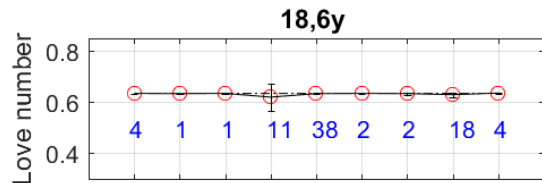
LOVE Nrs	Lat	Lon		18.6y			half_yr			27.55 d			13.66d			13.63d		1 Day	12.25 h	TE
CI (95%)			Min	Value	Max	Min	Value	Max	Min	Value	Max	Min	Value	Max	Min	Value	Max	Value	Value	
AIRA	31,8241	130,5996	0,590007	0,635336	0,680665	0	0,6182	0	0,493233	0,588439	0,683645	0	0,6109	0	0	0,6109	0	0,464568	0,395668	-1,62331
ALBH	48,3898	236,5125	0,586834	0,638161	0,689488	0,527508	0,595937	0,664366	0,503712	0,578691	0,653671	0,442511	0,507008	0,571505	0,409706	0,592308	0,774909	0,52538	0,577094	43,26604
ALIC	-23,6701	133,8855	0,594692	0,638243	0,681795	0	0,6182	0	0,353283	0,437361	0,521438	0,473752	0,541492	0,609233	0,480275	0,62011	0,759944	0,487152	0,441707	-57,2054
ANKR	39,8874	32,7585	0	0,6344	0	-0,17349	0,550304	1,274095	-1,37178	0,628332	2,628447	-0,5753	0,579155	1,733611	-2,38906	0,627341	3,64374	0,495384	0,535717	39,52693
AQUI	42,3682	13,3502	0,542732	0,638308	0,733884	0	0,6182	0	0,525235	0,596441	0,667648	0,452112	0,51475	0,577388	0,442924	0,601277	0,759629	0,493464	0,503364	51,81982
ARTU	56,4298	58,5605	0,593232	0,63622	0,679208	0,525693	0,606227	0,686761	0	0,6126	0	0	0,6109	0	0	0,6109	0	0,515101	0,561329	39,13172
AV27	54,4924	195,2768	0,383676	0,694336	1,004995	0,302932	0,619358	0,935784	0,306234	0,591611	0,876987	0,258019	0,523395	0,788771	0,010401	0,619452	1,228504	0,451677	0,51532	30,69432
BAKO	-6,4911	106,8489	0,580486	0,635267	0,690047	0,525806	0,59697	0,668134	0,502836	0,580222	0,657608	0,474644	0,534097	0,59355	0	0,6109	0	0,560318	0,375738	-34,8236
BEPK	35,8784	241,9259	0,581465	0,635829	0,690192	0,518072	0,590714	0,663356	0,513793	0,57993	0,646066	0,508717	0,550181	0,591645	0,535738	0,630147	0,724556	0,44507	0,406574	37,29412
BHST	-39,4892	176,0632	0,377916	0,63848	0,899044	0,509008	0,594914	0,68082	0,512416	0,584536	0,656657	0	0,6109	0	0,510214	0,621568	0,732921	0,463584	0,465318	-59,3023
CAS1	-66,2834	110,5197	0,587543	0,637779	0,688014	0	0,6182	0	0	0,6126	0	0	0,6109	0	0,350232	0,468062	0,585893	0,535073	0,515808	-74,2224
CCCC	35,5653	242,3288	0,587294	0,636545	0,685795	0,480672	0,559995	0,639318	0	0,6126	0	0	0,6109	0	0	0,6109	0	0,483072	0,467118	37,28118
CHUR	58,7591	265,9113	0,586714	0,637661	0,688608	0,073713	0,567132	1,060551	-0,75792	0,58914	1,9362	0	0,6109	0	-2,40773	0,576057	3,559843	0,561417	0,565315	63,32726
DARW	-12,8437	131,1327	0	0,6344	0	0,477045	0,596281	0,715517	0,481378	0,591236	0,701093	0,478767	0,557308	0,635849	0	0,6109	0	0,5236	0,907899	-46,2325
DRAG	31,5932	35,3921	0,572182	0,636521	0,70086	0	0,6182	0	0,469739	0,589343	0,708947	0	0,6109	0	0,34992	0,582926	0,815932	0,501831	0,490576	31,92323
FAIR	64,978	212,5008	0,576294	0,63748	0,698666	0,461124	0,597297	0,73347	0,481839	0,601184	0,720528	0,493518	0,560115	0,626713	0,410198	0,623355	0,836513	0,511832	0,448506	44,2134
FIOC	64,8749	341,994	0	0,6344	0	0,424375	0,550743	0,677112	0,34742	0,599988	0,852557	0	0,6109	0	0,276559	0,622486	0,968412	0,468477	0,415784	75,13959
GOP7	49,9137	14,7856	-3,70156	0,634025	4,969611	0	0,6182	0	0,389366	0,481602	0,573838	0,457898	0,568597	0,679295	0,308664	0,599087	0,889511	0,472087	0,532522	55,65273
GOPE	49,9137	14,7856	0,559318	0,63715	0,714983	0,53179	0,607467	0,683143	0,510916	0,600443	0,688997	0,464459	0,539657	0,614855	0,382511	0,585652	0,788792	0,49711	0,510711	55,65274
HOB2	-42,8047	147,4387	0,593541	0,636922	0,680304	0,518053	0,609061	0,700069	0,491225	0,599956	0,708686	0,451049	0,549924	0,648798	0,392426	0,585509	0,778591	0,51579	0,533144	-74,768
HOFN	64,2673	344,8021	0,481797	0,637432	0,793067	0,5283	0,614366	0,700432	0	0,6126	0	0,52942	0,579758	0,630096	0	0,6109	0	0,490429	0,463147	74,20937
HOLB	50,6404	231,865	0,56618	0,636599	0,707019	0,405569	0,605511	0,805453	0,390845	0,59244	0,794036	0	0,6109	0	0,137447	0,605171	1,072895	0,517112	0,550673	42,50019
HYDE	17,4173	78,5509	0,350987	0,442923	0,534859	0,506604	0,617244	0,727883	0	0,6126	0	0,501425	0,585432	0,669438	0,267544	0,474126	0,680707	0,484541	0,425623	-1,68038
IISC	13,0212	77,5704	0,585791	0,634845	0,6839	0,326	0,442684	0,559368	0,501503	0,608038	0,714572	0,415977	0,513169	0,610361	0,392873	0,610327	0,827781	0,750181	0,677566	-5,10473
ISTA	41,1044	29,0193	0,509713	0,634055	0,758397	0,504891	0,61317	0,721448	0	0,6126	0	0,504635	0,587144	0,669653	0,391343	0,608803	0,826264	0,491741	0,523676	42,39472
KAON	19,2779	204,7176	-8,22049	0,623446	9,467379	0,06588	0,616167	1,166454	0,150602	0,627112	1,103623	0,149763	0,629841	1,10992	-0,43532	0,619902	1,675124	0,470196	0,395955	4,557371
KOUC	-20,5587	164,2873	0,565354	0,635873	0,706393	0	0,6182	0	0,50019	0,641492	0,782794	0,497694	0,582471	0,667249	0,375839	0,594809	0,813779	0,505408	0,39065	-48,7406
KOUR	5,2522	307,194	0,566599	0,634512	0,702425	0,449009	0,615255	0,781501	0,397285	0,575315	0,753345	0,421995	0,597295	0,772594	0,221663	0,607845	0,994026	0,498909	0,389932	38,29761
LHAS	29,6573	91,104	-9,38242	0,635543	10,65351	-4,16295	0,618981	5,400912	0	0,6126	0	-13,9705	0,606963	15,18443	0	0,6109	0	0,510324	0,442444	4,338518
LPGS	-34,9067	302,0677	-0,11875	0,635006	1,388761	0	0,6182	0	0	0,6126	0	0	0,6109	0	0	0,6109	0	0,482863	0,437569	-2,15048
MAT1	40,6491	16,7045	0,571075	0,635162	0,699249	0,53801	0,708631	0,879251	0	0,6126	0	0,430937	0,606091	0,781245	0	0,6109	0	0,451757	0,440437	48,80645
MATE	40,6491	16,7045	0,571354	0,635019	0,698685	0,374318	0,549807	0,725296	0	0,6126	0	0,477521	0,604231	0,730942	0	0,6109	0	0,440749	0,409133	48,80654
MAUI	20,7067	203,743	0,51405	0,634389	0,754729	0,189576	0,404065	0,618553	0,271346	0,614295	0,957245	0,358718	0,555676	0,752634	0	0,6109	0	0,375246	0,358463	5,313488
MCNL	-39,4442	176,6965	-0,54348	0,634311	1,812106	-0,12769	0,533913	1,195512	0	0,6126	0	0	0,6109	0	0	0,6109	0	0,4827	0,489246	-58,933
METS	60,2175	24,3953	-1,13071	0,634452	2,399616	-1,87915	0,618619	3,116384	-2,21958	0,61264	3,444859	-1,09404	0,610503	2,315049	-3,6745	0,610884	4,896268	0,490988	0,518158	55,81525
MKEA	19,8014	204,5437	0,090039	0,634258	1,178477	-0,17292	0,541111	1,25514	-0,59885	0,409373	1,417597	-0,16535	0,437664	1,040675	-1,11416	0,451624	2,017405	0,44945	0,379052	4,921867
NICO	35,141	33,3964	0,492653	0,634059	0,775466	0,14777	0,509014	0,870258	0,30981	0,715276	1,120742	0	0,6109	0	-0,12592	0,473129	1,072175	0,477707	0,49015	35,70083
NOT1	36,8758	14,9898	0,512263	0,634332	0,756401	0	0,6182	0	0	0,6126	0	0,133508	0,606504	1,0795	0	0,6109	0	0,464451	0,453967	47,09674
NRIL	69,3618	88,3598	0,585225	0,634365	0,683505	0,364901	0,618538	0,872175	0,259146	0,534378	0,80961	0	0,6109	0	0	0,6109	0	0,518584	0,456919	40,52779
ONSA	57,3953	11,9255	0,585046	0,633455	0,681865	0,48023	0,615885	0,751541	0,411412	0,558133	0,704855	0	0,6109	0	0	0,6109	0	0,507122	0,537478	60,66046
ORVB	39,5546	238,4997	0,55545	0,633244	0,711038	0,359526	0,616945	0,874364	0,430387	0,676418	0,922449	0	0,6109	0	0,020336	0,603995	1,187655	0,479708	0,481472	38,14595

LOVE Nrs	Lat	Lon		18.6y			half_yr			27.55 d			13.66d			13.63d		1 Day	12.25 h	TE
CI (95%)			Min	Value	Max	Mjn	Value	Max	Mjn	Value	Max	Min	Value	Max	Mjn	Value	Max	Value	Value	
P104	39,9421	139,7035	-5780,16	0,634418	5781,429	0,339979	0,596221	0,852463	0,400243	0,621937	0,843632	0,131607	0,620736	1,109866	-0,392	0,613934	1,619863	0,499066	0,504177	6,375707
P201	45,4078	141,6853	0	0,6344	0	0	0,6182	0	0,50562	0,606035	0,706451	0,493648	0,587944	0,68224	0,398054	0,605361	0,812668	0,521438	0,514139	11,89386
PETP	53,0667	158,6071	-0,53854	0,631605	1,80175	0	0,6182	0	-0,78545	0,738694	2,262841	-0,91895	0,454009	1,826966	-2,43373	0,584095	3,601921	0,553675	0,527817	20,93269
PIMO	14,6357	121,0777	0,516078	0,632382	0,748686	0	0,6182	0	0,474583	0,598471	0,722359	0,466626	0,590255	0,713885	0,334837	0,605502	0,876167	0,823599	0,907894	-17,7701
POL2	42,6798	74,6943	0,55187	0,632184	0,712498	0,539034	0,613338	0,687643	0	0,6126	0	0	0,6109	0	0,431748	0,584574	0,737401	0,525441	0,546896	21,9427
RAMT	35,3387	242,3167	0,589823	0,63375	0,677678	0,509937	0,60963	0,709324	0	0,6126	0	0,512266	0,576519	0,640773	0,491357	0,617713	0,744069	0,473003	0,4577	37,10613
REYK	64,1388	338,0445	0,468014	0,635306	0,802598	0,505302	0,596888	0,688475	0,346464	0,440507	0,53455	0	0,6109	0	0,48592	0,621472	0,757023	0,5133	0,498718	76,99116
SANT	-33,1503	289,3314	0,580546	0,634214	0,687883	0,512065	0,60243	0,692794	0,519076	0,598381	0,677686	0,47975	0,56195	0,644151	0,425862	0,60456	0,783258	0,522496	0,46979	-2,5225
STJO	47,5952	307,3223	0,574499	0,63132	0,688142	0,522049	0,604657	0,687265	0,521094	0,594782	0,668469	0,497234	0,559103	0,620972	0,447891	0,609894	0,771897	0,524784	0,546511	79,49161
SUMK	44,2081	73,9971	0,547402	0,632208	0,717015	0,480823	0,601554	0,722284	0,492246	0,595883	0,699519	0,492881	0,554988	0,617096	0,50266	0,629443	0,756226	0,47893	0,452612	23,50632
SUWN	37,2755	127,0542	0,582669	0,633425	0,684181	0,534047	0,607496	0,680944	0,52148	0,590333	0,659186	0,488453	0,539338	0,590222	0,496401	0,610538	0,724675	0,465315	0,438198	4,033016
TEHN	35,6973	51,3341	0	0,6344	0	0,546746	0,649566	0,752386	0,501152	0,585784	0,670416	0,450733	0,524727	0,59872	0,393394	0,597443	0,801492	0,464515	0,444752	26,7246
TPW2	46,2074	236,2316	0,588287	0,630584	0,672882	0,515721	0,615927	0,716134	0,523993	0,581621	0,63925	0	0,6109	0	0,55764	0,631674	0,705709	0,480461	0,470709	41,65634
TSEA	61,1873	210,105	0,575021	0,630298	0,685576	0,496601	0,580124	0,663648	0,490525	0,571113	0,651701	0,47178	0,545448	0,619115	0,436429	0,606968	0,777507	0,491112	0,541364	40,81611
UCLU	48,9256	234,4584	0,498413	0,630212	0,76201	0,354449	0,422447	0,490445	0	0,6126	0	0	0,6109	0	0,557386	0,639627	0,721868	0,494069	0,462349	42,60873
ULAB	47,8651	107,0523	0	0,6344	0	0	0,6182	0	0	0,6126	0	0	0,6109	0	0	0,6109	0	0,514436	0,519829	17,15826
USUD	36,1331	138,362	0,571515	0,630483	0,689451	0,537215	0,599592	0,661969	0,50589	0,576902	0,647914	0	0,6109	0	0,511446	0,636135	0,760824	0,478251	0,447029	2,543895
VGMO	-39,4074	175,7543	0,55044	0,659455	0,768471	0,487826	0,568419	0,649013	0,491796	0,569478	0,647161	0,402334	0,465649	0,528964	0,439934	0,609216	0,778498	0,468069	0,458429	-59,4065
VGMT	-39,3846	175,4705	0	0,6344	0	0,488891	0,576658	0,664424	0,487771	0,563444	0,639117	0,402028	0,473292	0,544556	0,39975	0,569081	0,738411	0,460857	0,448644	-59,54
VGOB	-39,1998	175,5422	0	0,6344	0	0,489352	0,567171	0,644991	0,444413	0,531563	0,618713	0,355659	0,419475	0,483291	0,318464	0,530667	0,74287	0,429546	0,425329	-59,367
VILL	40,4436	356,048	0	0,6344	0	0	0,6182	0	0,507277	0,561423	0,615568	0,458538	0,494148	0,529759	0	0,6109	0	0,468635	0,501208	59,99697
VNDP	34,5563	239,3836	0,588118	0,633062	0,678006	0,49799	0,583446	0,668901	0,351944	0,407427	0,462911	0,430403	0,477863	0,525324	0,702376	0,775216	0,848055	0,473192	0,447427	34,92578
WGTM	-41,3235	174,8059	0,494392	0,544962	0,595532	0,489323	0,571762	0,654201	0,48743	0,556421	0,625412	0,392084	0,454157	0,516229	0,498048	0,624599	0,75115	0,458744	0,437855	-61,2831
WHIT	60,7505	224,7779	0	0,6344	0	0,504328	0,579036	0,653743	0	0,6126	0	0,396138	0,451757	0,507375	0,663777	0,742974	0,82217	0,514978	0,557926	45,8612
WPUK	-40,0642	176,4406	0	0,6344	0	0,492795	0,558374	0,623953	0	0,6126	0	0,420967	0,466159	0,51135	0	0,6109	0	0,463501	0,464986	-59,5163
WTZR	49,1442	12,8789	0	0,6344	0	0,499098	0,562891	0,626684	0	0,6126	0	0,462312	0,487544	0,512776	0,480149	0,614408	0,748667	0,49571	0,516056	56,25103
WTZZ	49,1442	12,8789	0	0,6344	0	0,478301	0,540036	0,601771	0,452282	0,516284	0,580285	0,368424	0,424379	0,480335	0,410198	0,560828	0,711458	0,506351	0,52548	56,25104
WUHN	30,5317	114,3573	0,555897	0,631036	0,706175	0	0,6182	0	0	0,6126	0	0	0,6109	0	0,368696	0,550943	0,73319	0,478422	0,364814	-1,01662
XMIS	-10,45	105,6885	0	0,6344	0	0,479515	0,556264	0,633013	0,471969	0,533647	0,595324	0,40158	0,452459	0,503339	0,349457	0,479244	0,609032	0,481624	0,39219	-38,1336
ZECK	43,7884	41,5651	0	0,6344	0	0,473888	0,542976	0,612064	0,470912	0,531036	0,59116	0,374488	0,43407	0,493651	0,444039	0,585018	0,725997	0,436591	0,491861	37,74398
ZIM2	46,8771	7,465	0	0,6344	0	0,471691	0,541742	0,611793	0,482191	0,543929	0,605667	0,371939	0,407507	0,443074	0,516395	0,615611	0,714827	0,516893	0,481719	57,90871
ZIMM	46,8771	7,4653	0	0,6344	0	0	0,6182	0	0,488069	0,542839	0,597609	0,419655	0,451046	0,482437	0	0,6109	0	0,493961	0,509952	57,90857

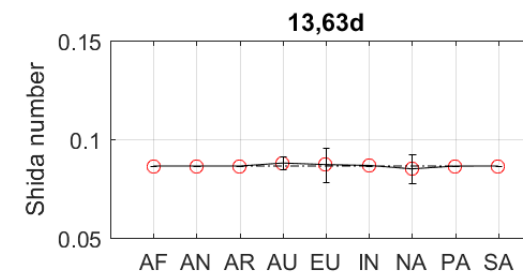
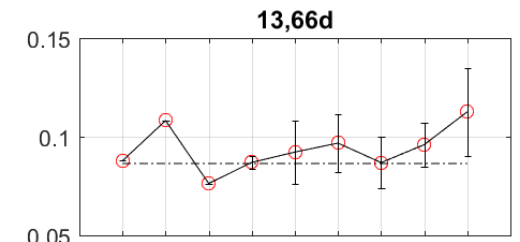
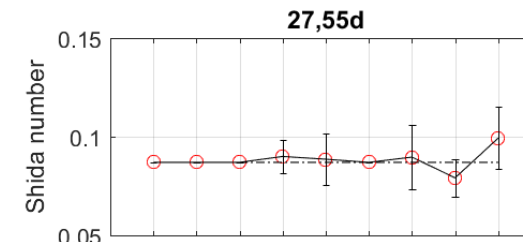
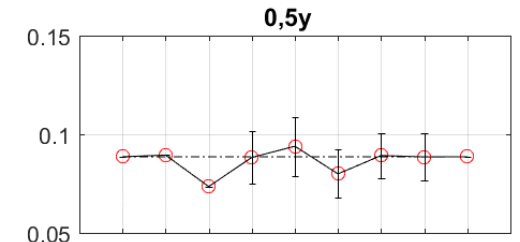
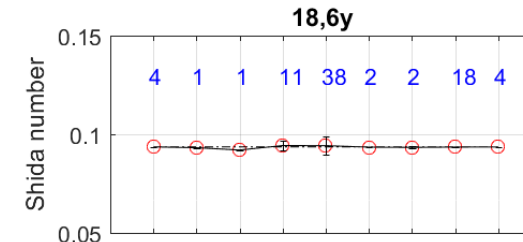


Global Stations against Tectonic Equator



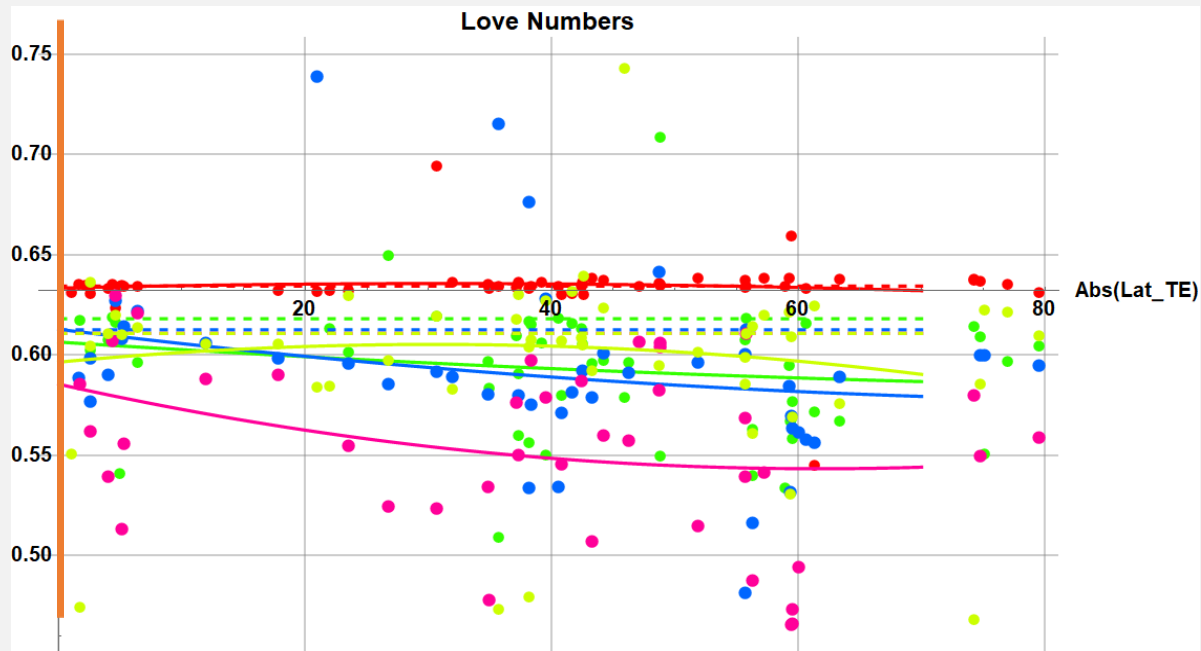


AF = Africa
 AN = Antartica
 AR = Arabia
 AU = Australian
 EU = Eurasia
 IN = Indi
 NA = North America
 PA = Pacifico
 SA = South Ameica

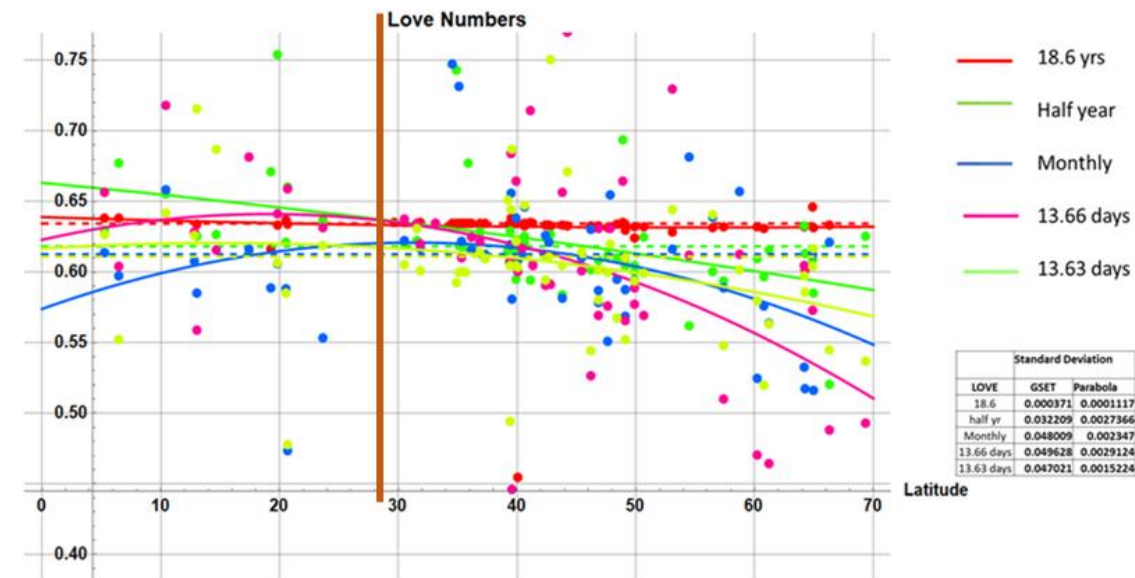


AF = Africa
 AN = Antartica
 AR = Arabia
 AU = Australian
 EU = Eurasia
 IN = Indi
 NA = North America
 PA = Pacifico
 SA = South Ameica

New Solution



Old Solution

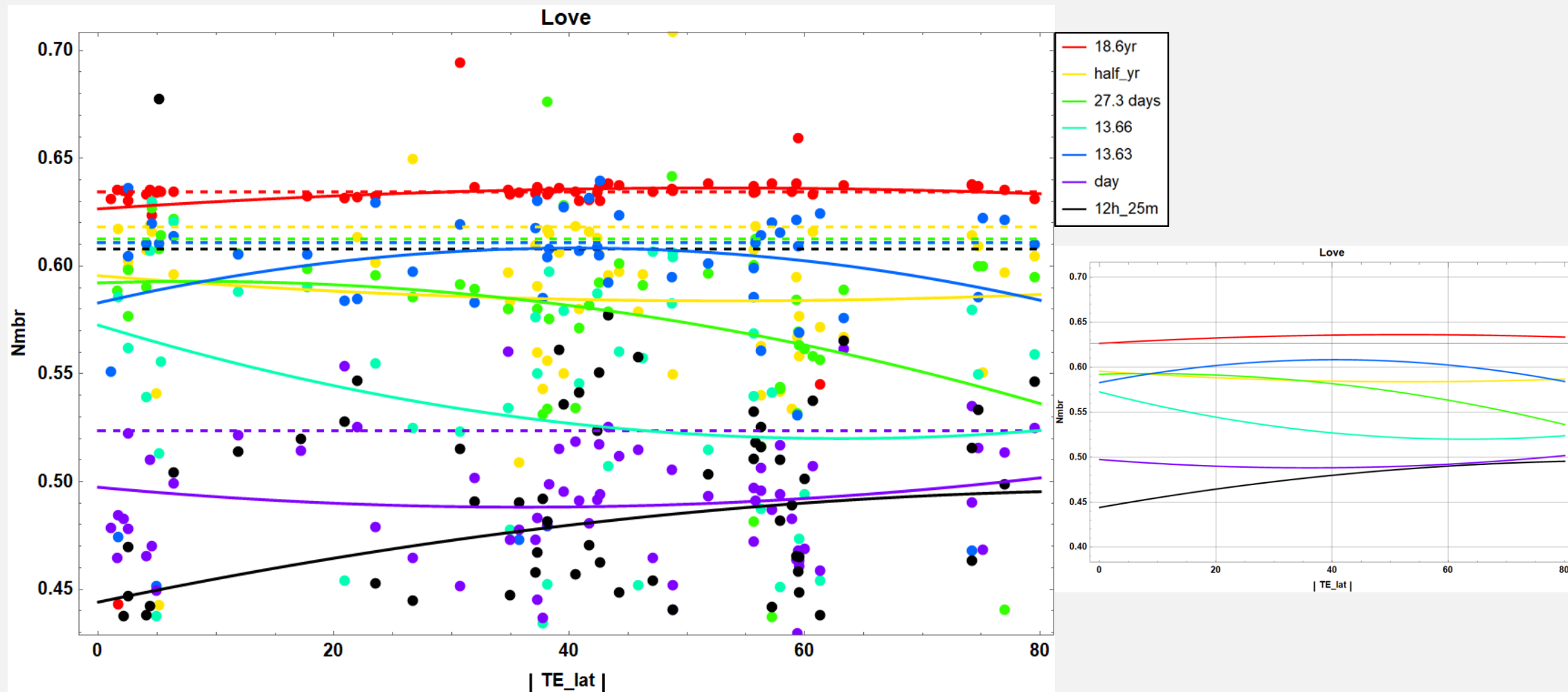


Pole of Tectonic Equator:

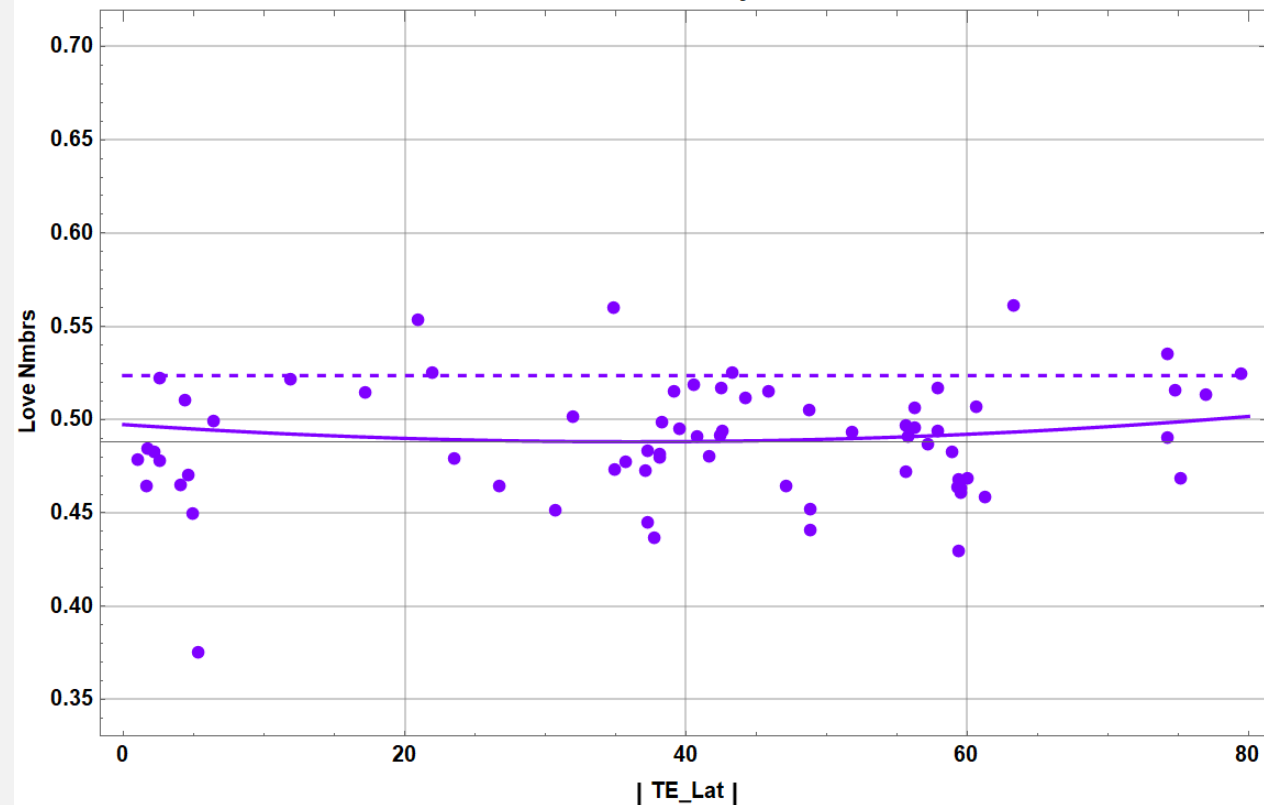
Lat=-56°.34

Lon=136.7 E

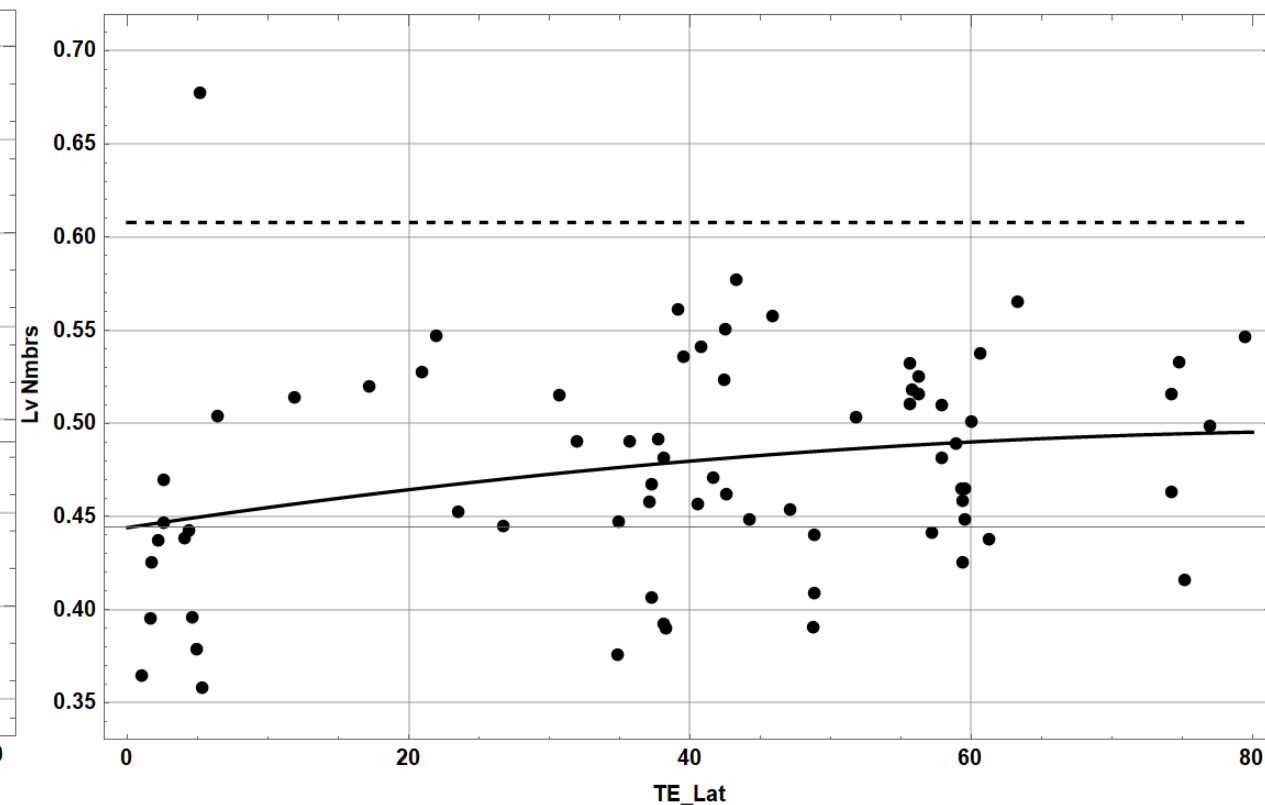
The Plots were estimated with the new DI solution provided by RIGTC



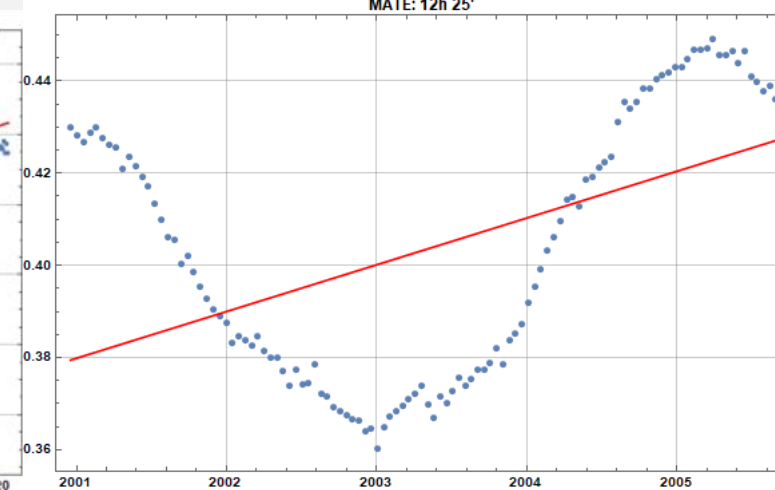
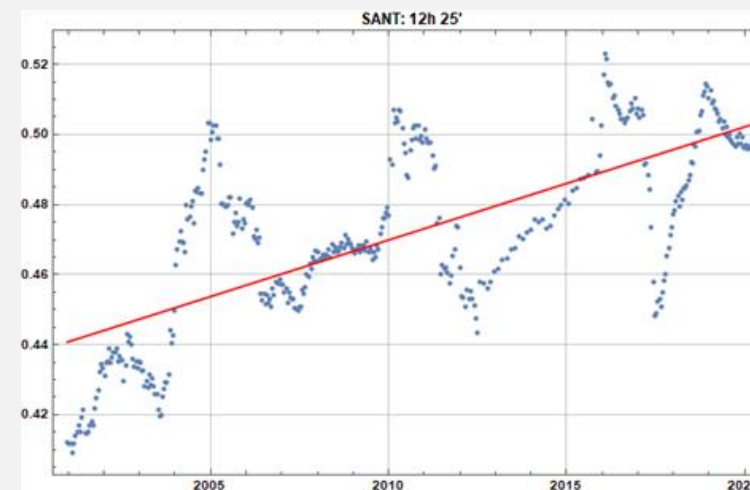
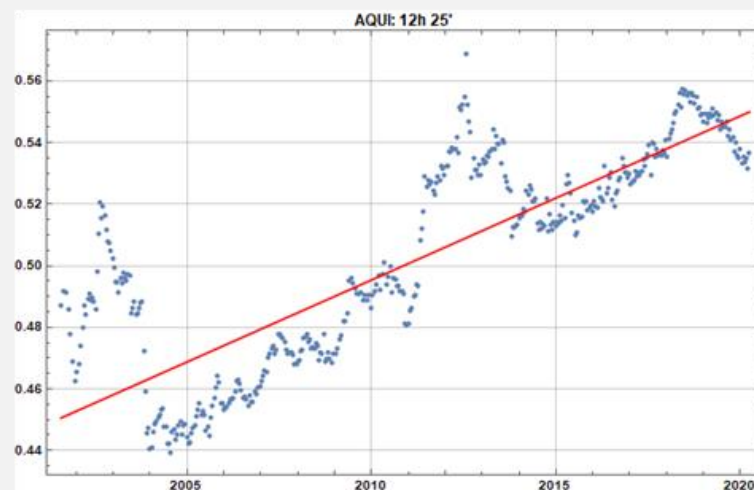
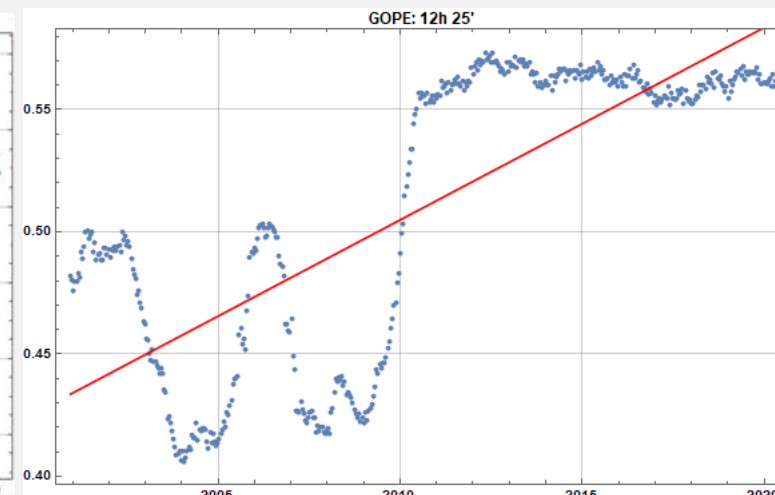
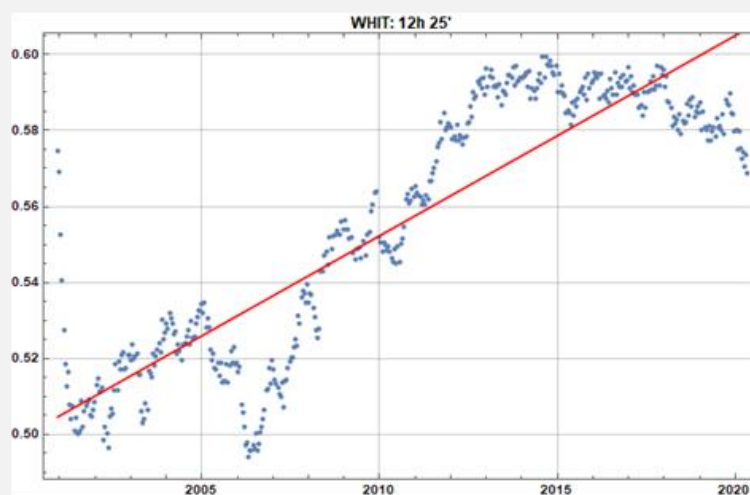
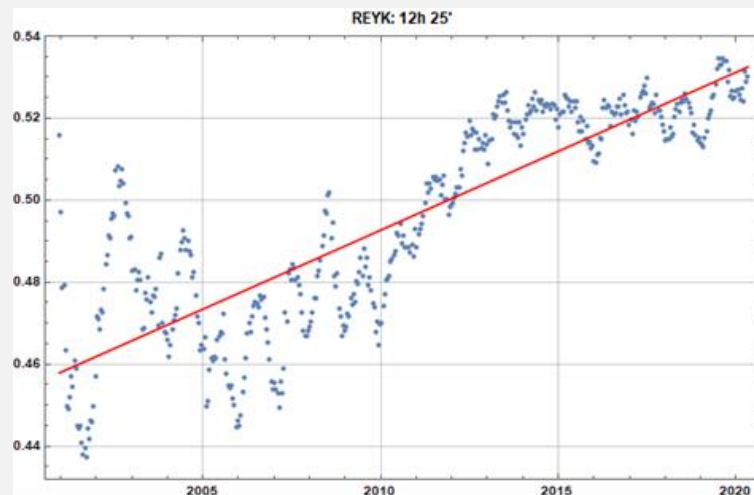
K1 tide day



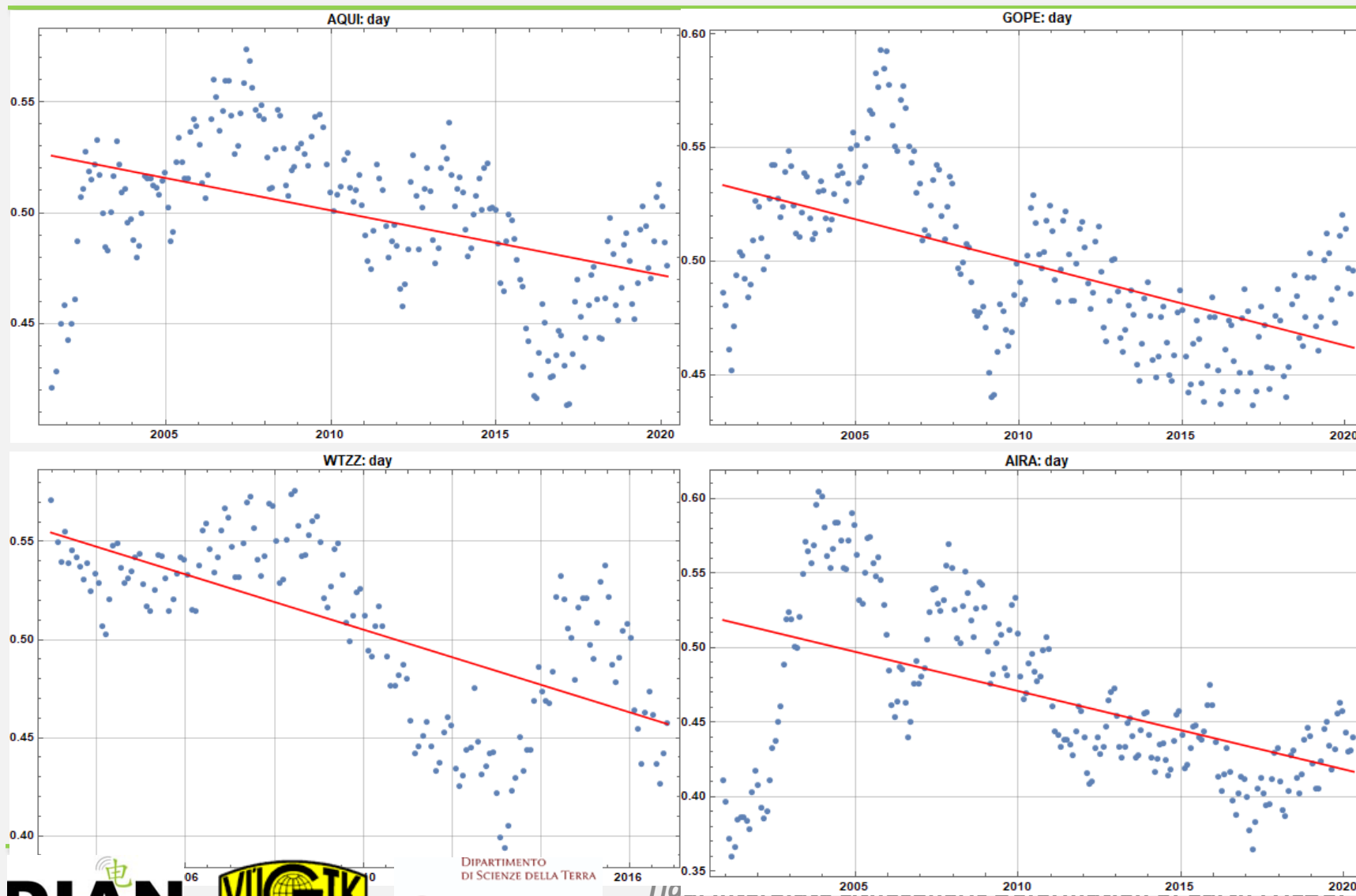
M2 Tide (12 h 25')



The anomaly of M2 Tide ($12^h 25'$)



The K1 Tide (1 day)



1. The values of M2 are meaningfully lower than nominal one (up to 15% less than 0.6078)
2. They increase with time
3. The values of K1 are very close to the nominal one (0.52)
4. They slightly decrease in time

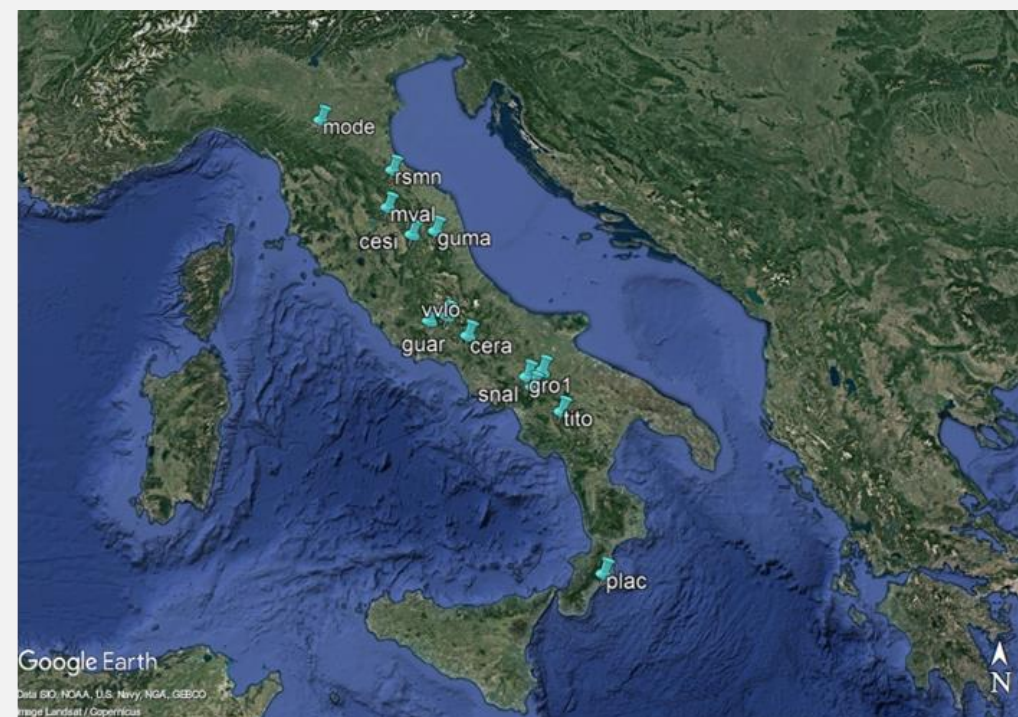
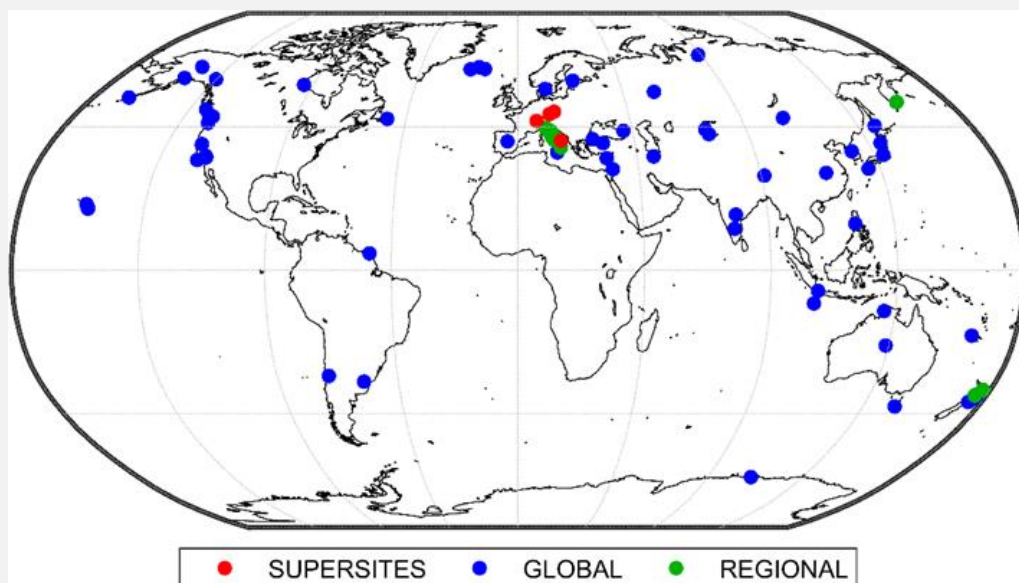
WP 3200 (SAPIENZA). Title: Geological and geophysical data analysis and modelling for earthquake risk

Analysis will be focused on the following aspects:

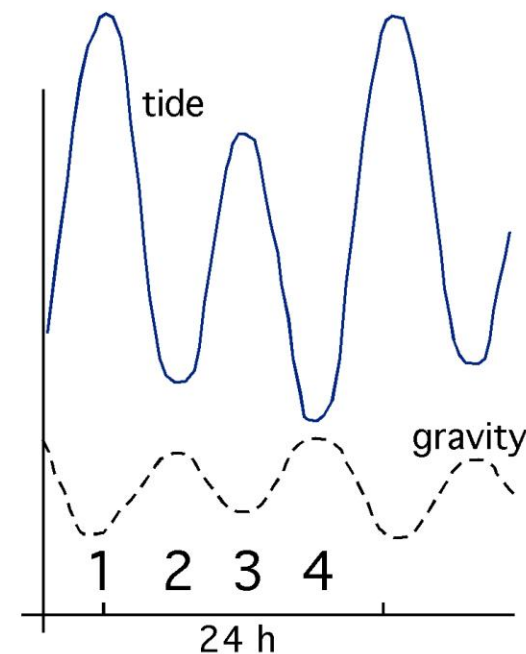
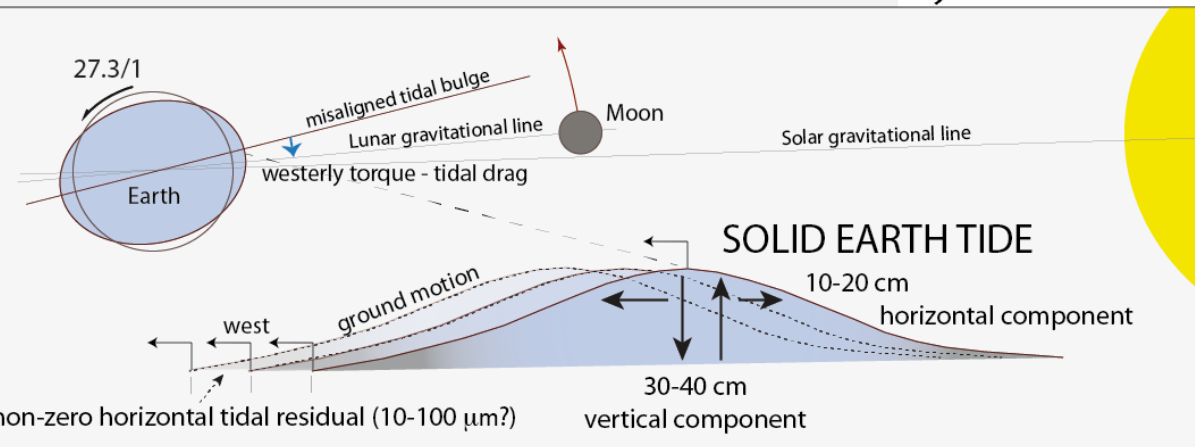
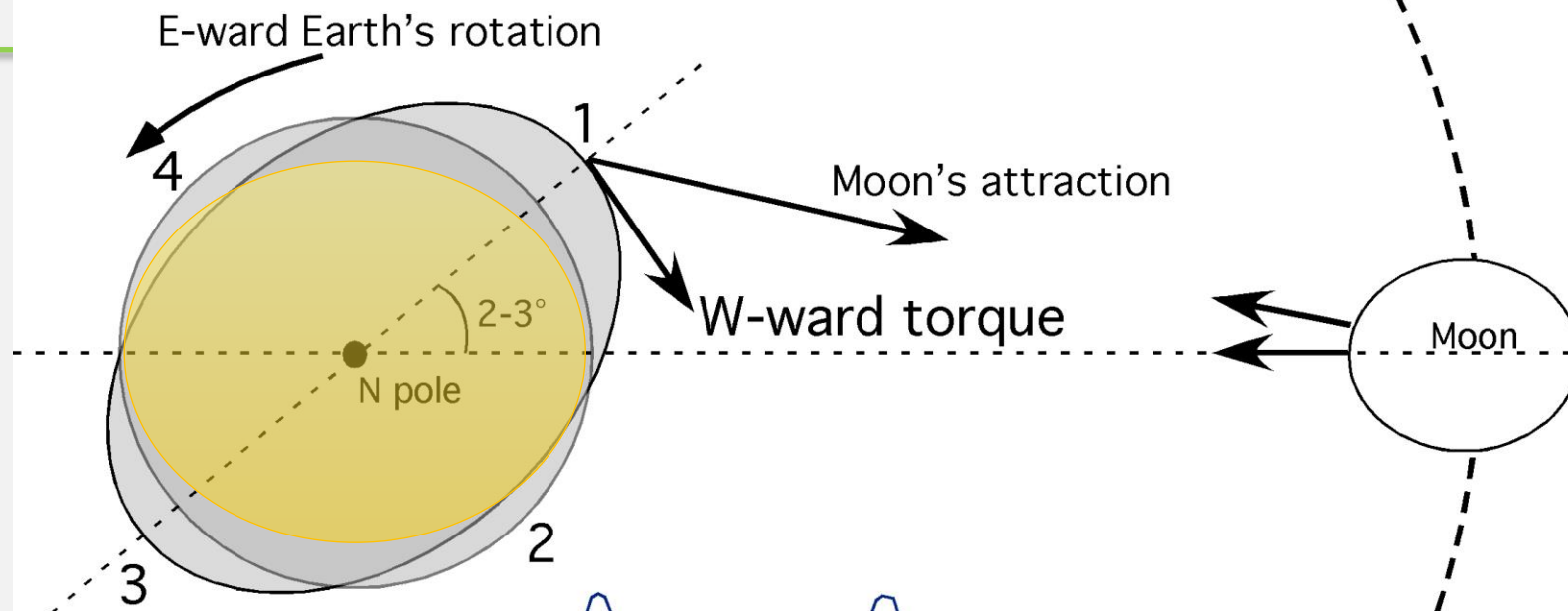
- Analysis of LSET data collected during the project;
- Correlation analysis between LSET and measured crustal deformations;

Outputs:

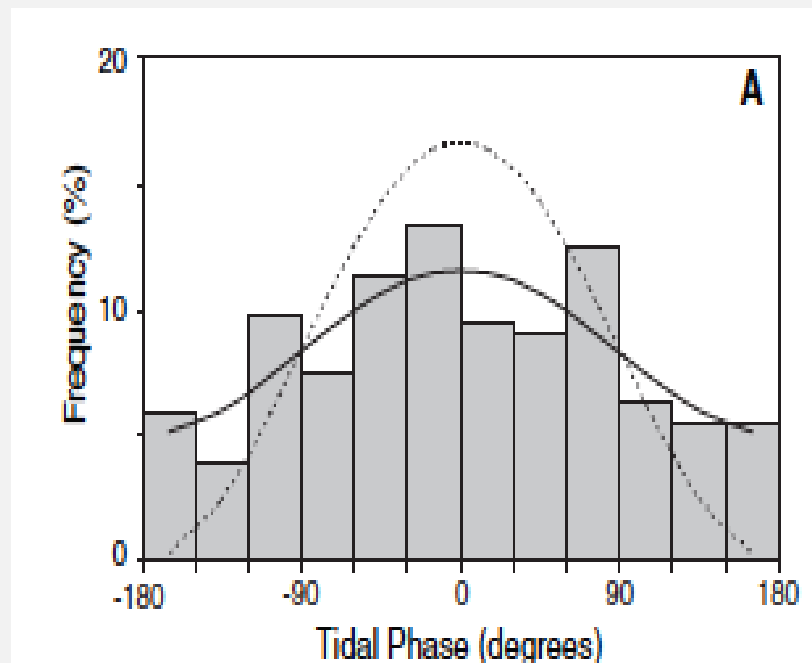
- [DL3] “Geological Analysis Report” including:
- Input Data Description (origin, availability, selection criteria, etc.);
- LTSE measurements and models produced with GNSS observations from different GNSS data networks (IGS, EUREF, UNAVCO, etc.) and GNSS receivers provided and deployed or accessible by the Contractor near or in areas with significant geological risk;
- Geophysical data from IERS, EGD1 or USGS, etc. for those GNSS stations;
- Correlation analysis and results;
- Preliminary conclusions about the possible use for risk assessment of LSET measured or predicted variables correlated with identified geological events.





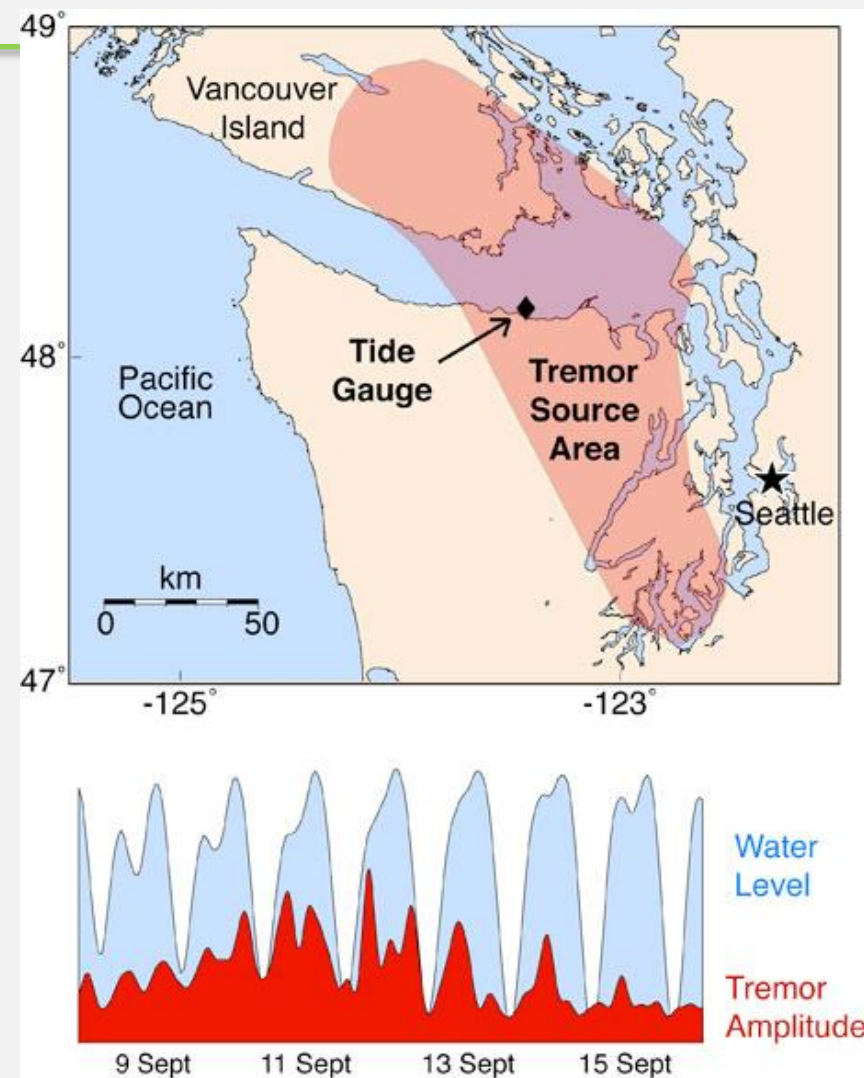


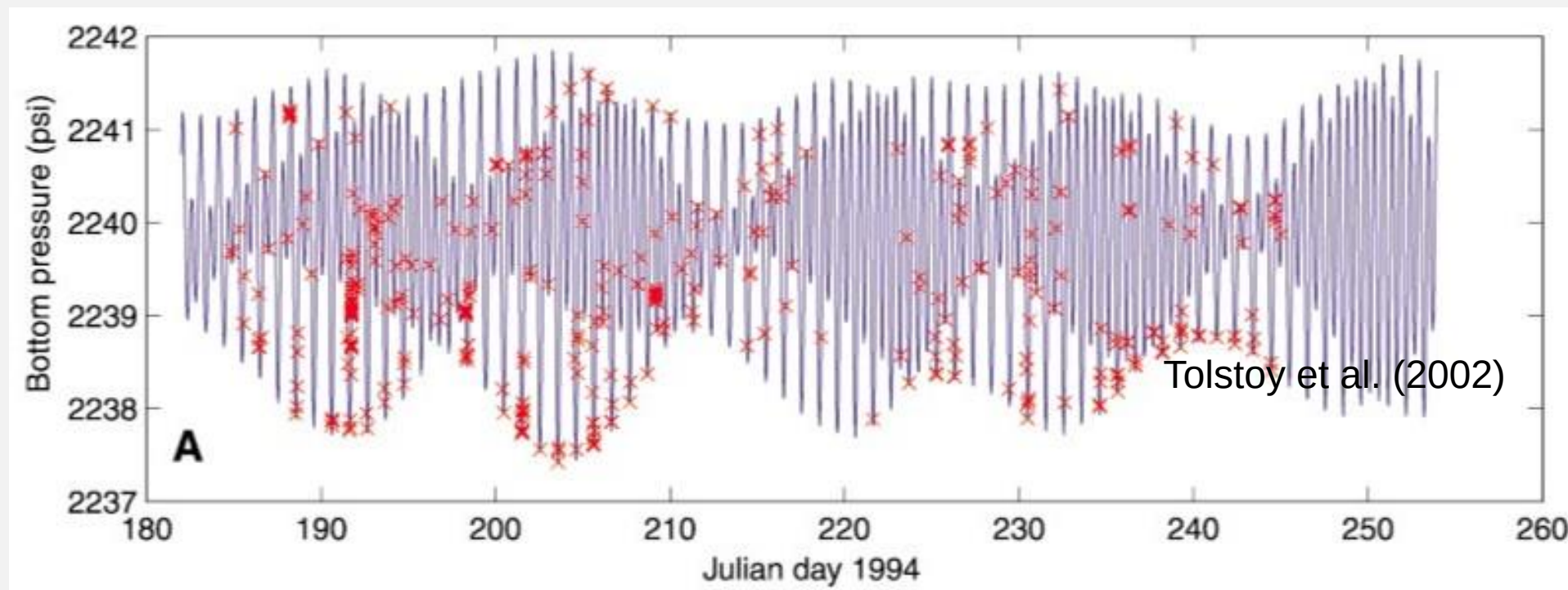
Cochran et al. 2004 Science



Earthquakes >40 km

Rubinstein et al. 2009 Science

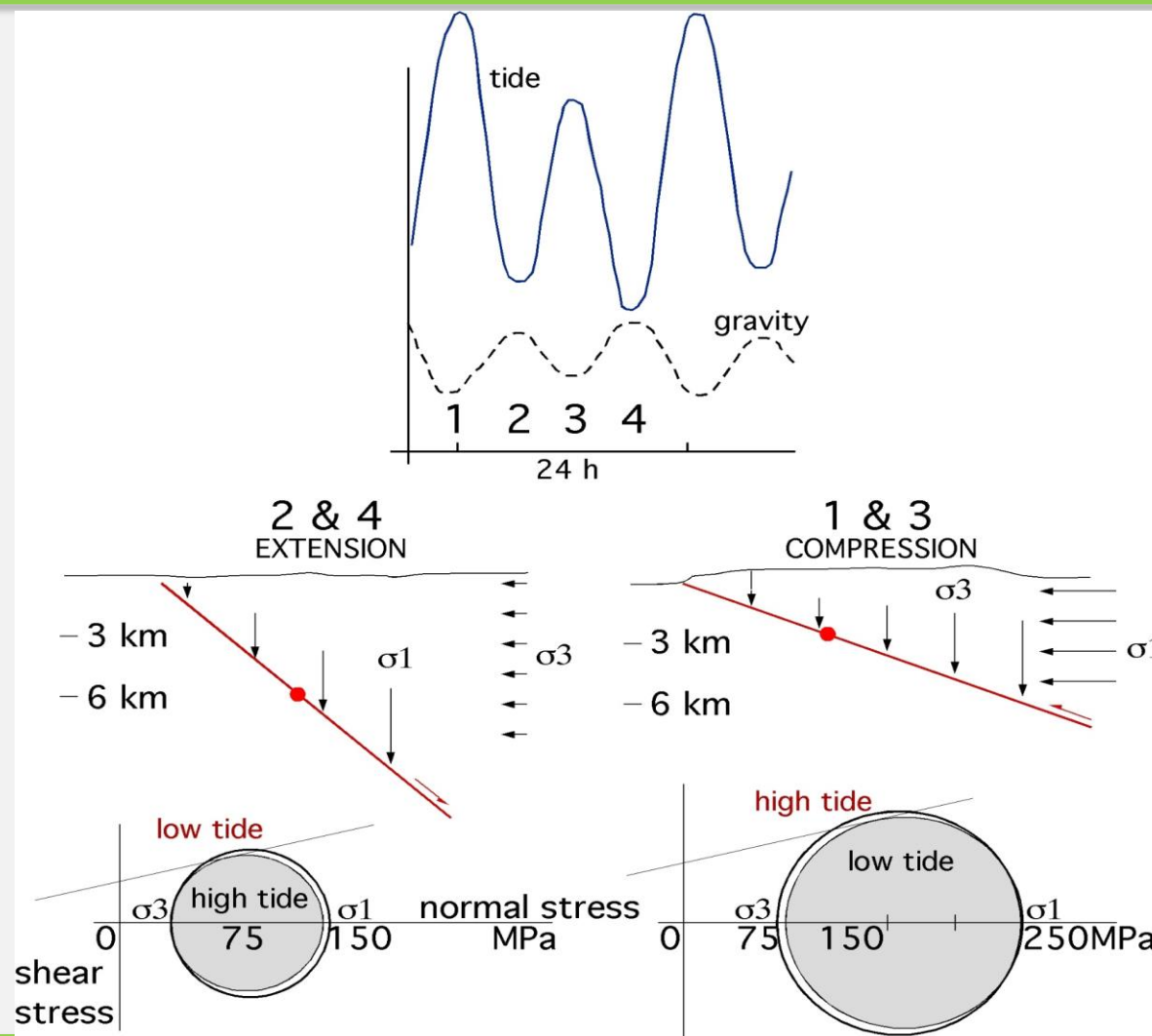




Normal fault earthquakes more frequent during low tide

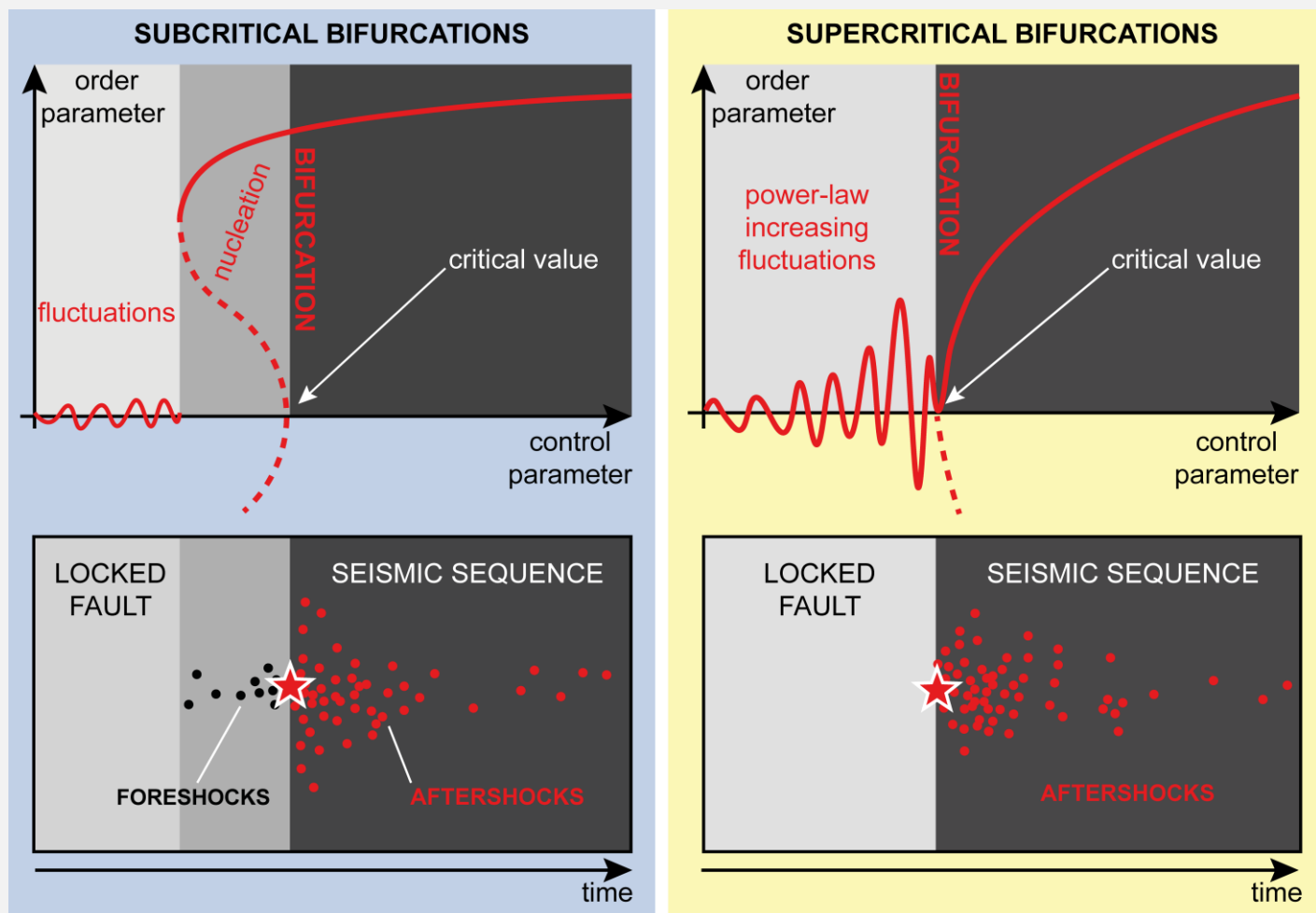
Thrust fault earthquakes more frequent during high tide

vertical stress = lithostatic load = density x gravity x depth

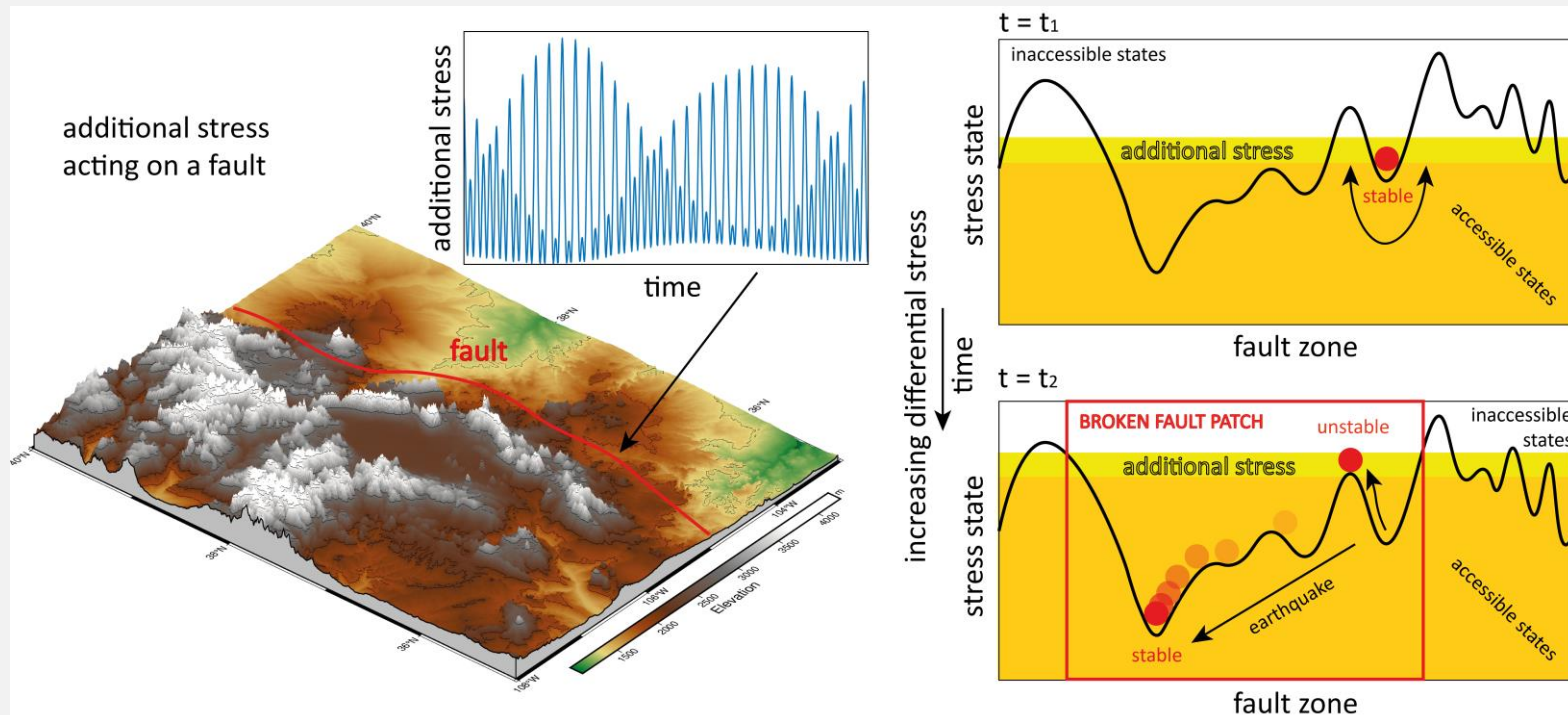


The horizontal component of the body tide (e.g., 102 N/m^2) multiplied for 365 days (times 2?), multiplied, as an example, for 300 years (in order to pump the stress gradient along a fault), would give 27 N/m^2 , which is consistent with the stress drop of a major earthquake

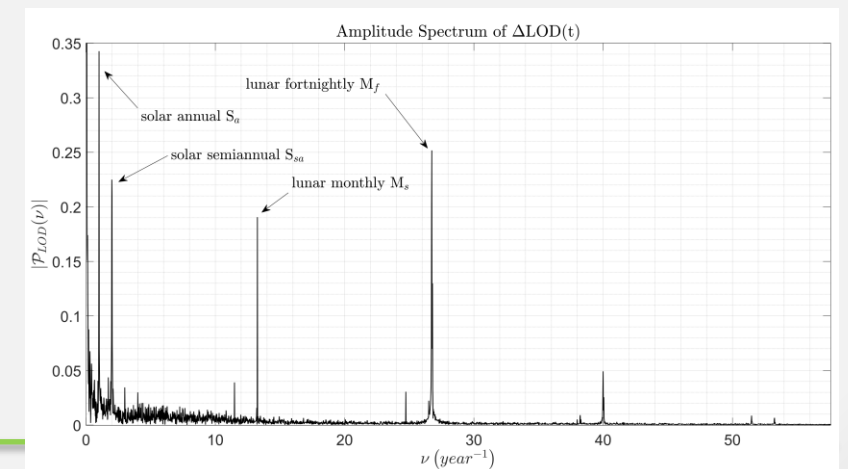
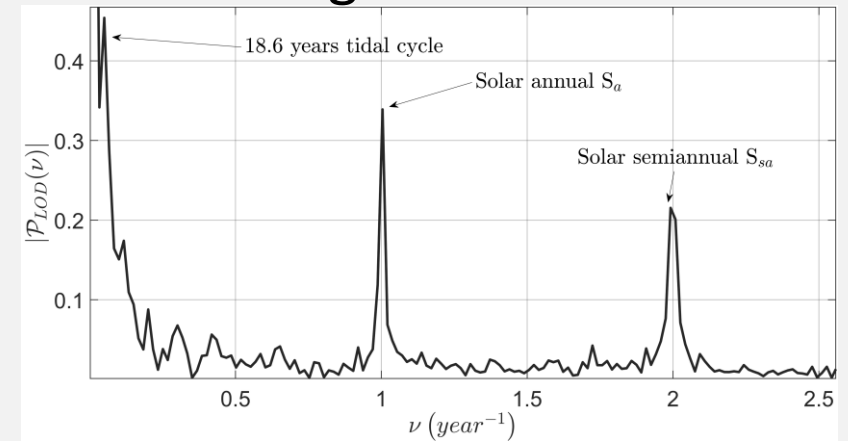
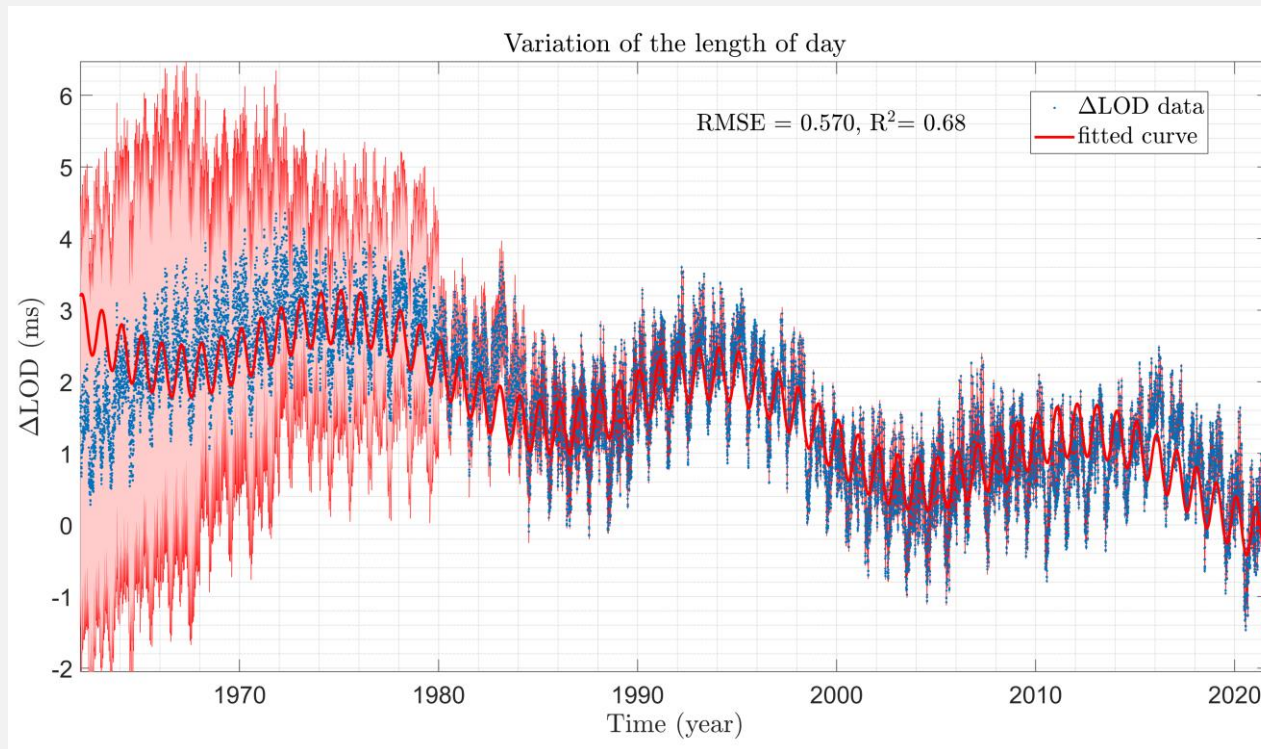
How do large-scale catastrophic patterns arise from progressive cooperative processes?

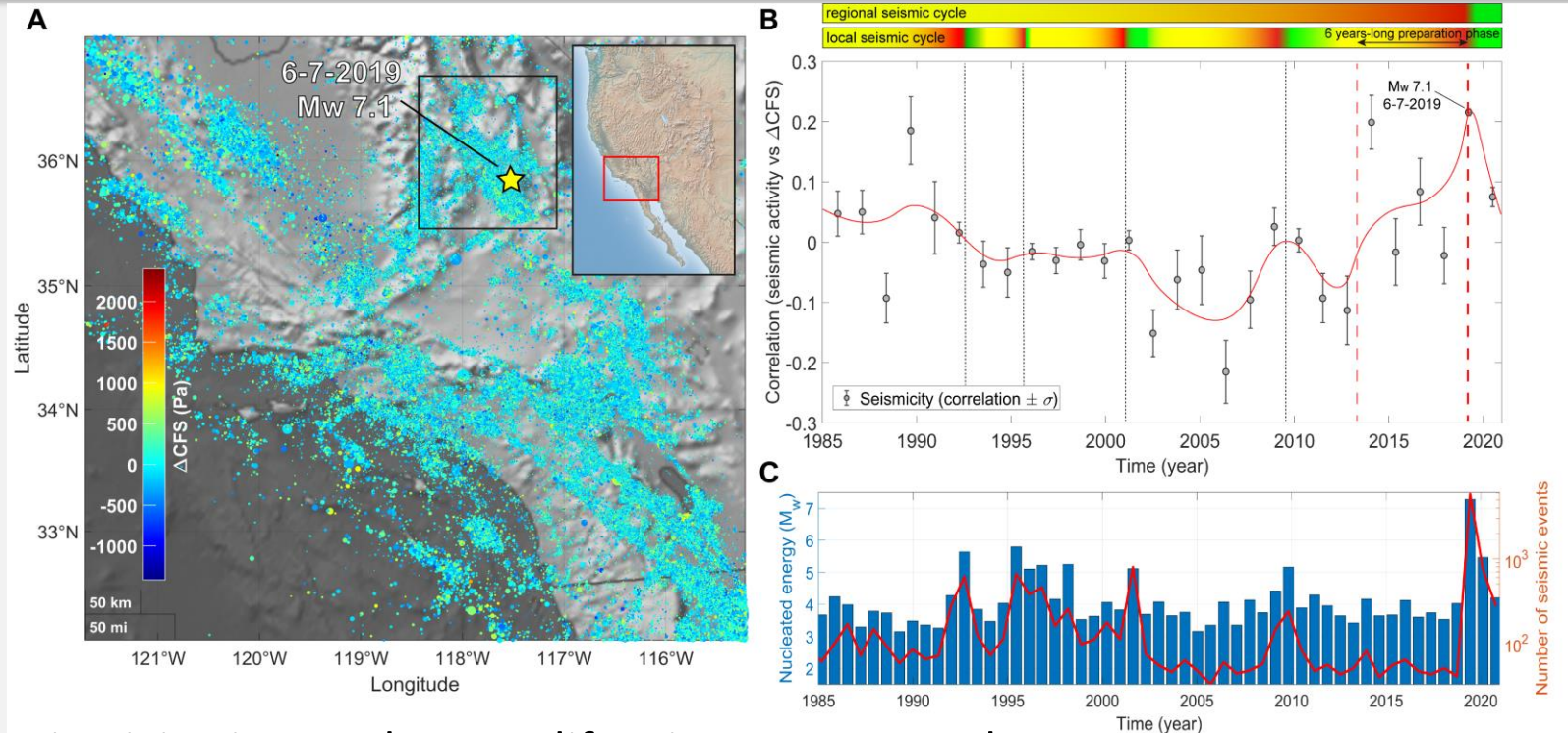


- Assessing the stability state of faults is a crucial task not only for seismic hazard, but also for understanding how the earthquake machine works.
- A possible approach consists in perturbing faults and studying how seismicity changes as additional stress is applied: if the initial energy state is stable, the system will oscillate around it; otherwise, the background seismic rate will be modified.

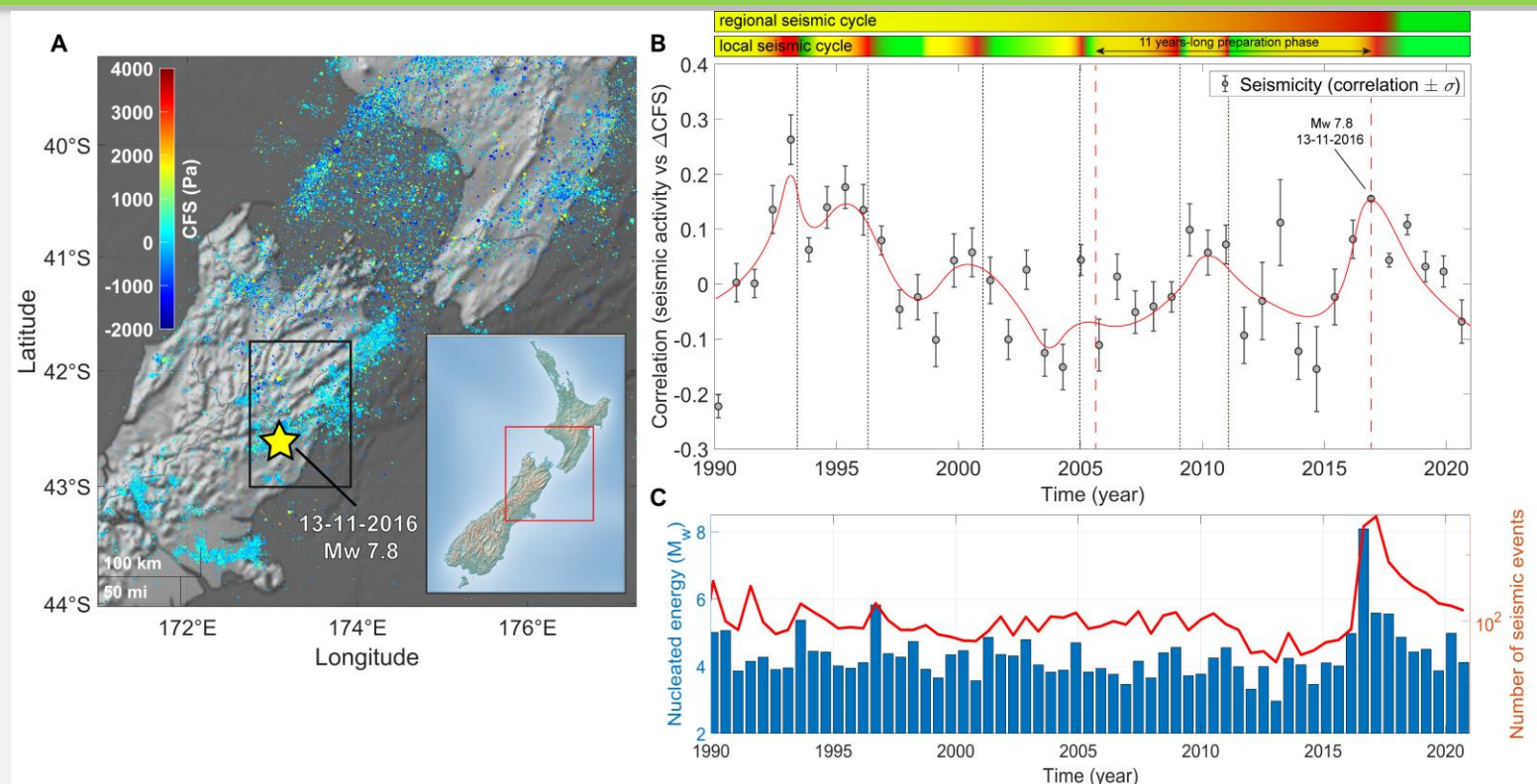


Tides provide natural stress sources featured by wide ranges of frequencies and amplitudes, which make them a suitable candidate for our investigation.



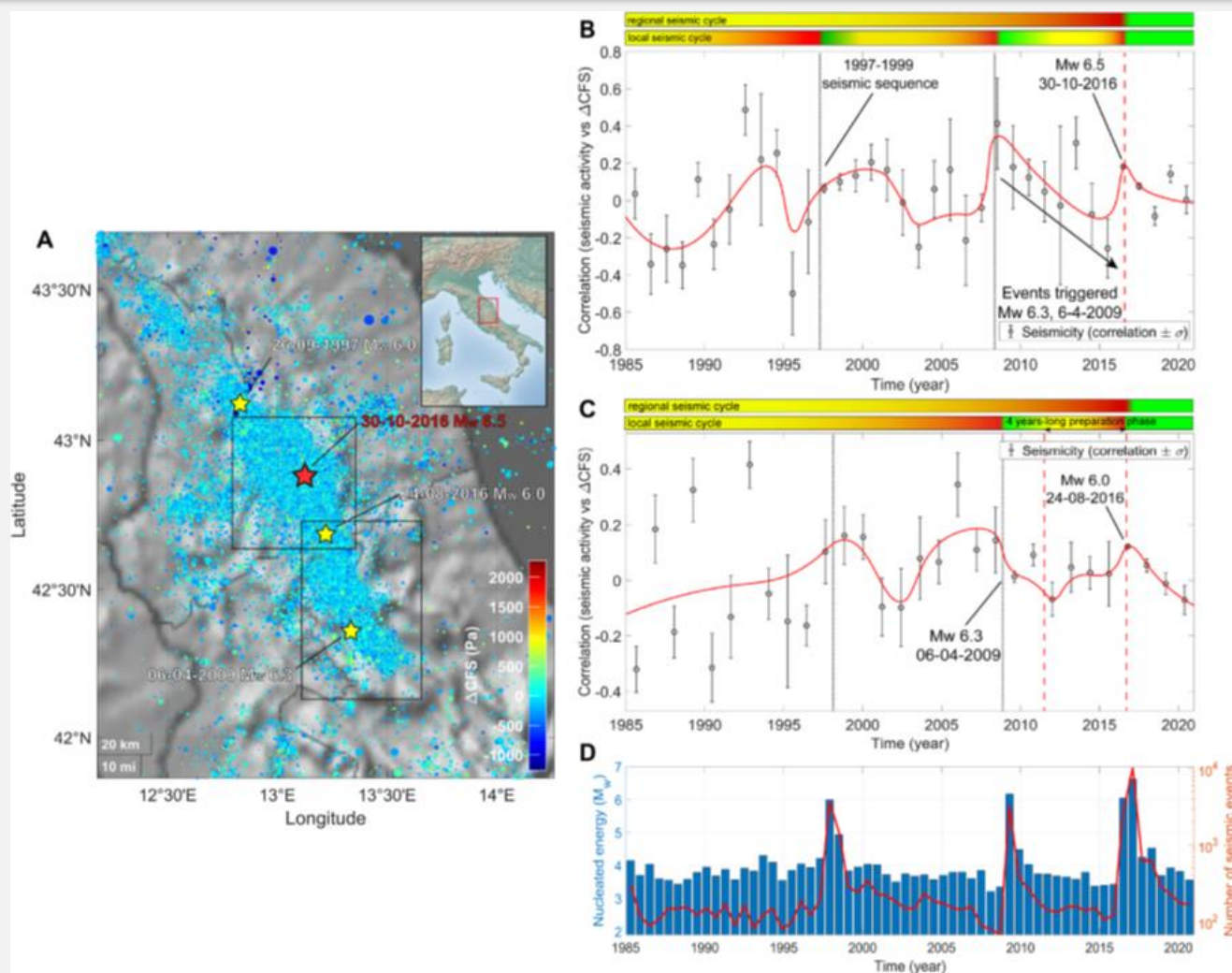


A: ΔCFS map for seismicity in Southern California, SCEDC Catalogue, 1985–2021, $M_L \geq 1.0$. Seismicity occurs, on average, at slightly positive ΔCFS values. B: Correlation ρ between ΔCFS and seismicity in the Ridgecrest District, California. The scatter plot is realized by taking into account earthquakes happened in the black contour square at depth of -2–20 km. C: Histogram of cumulative energy (M_w) nucleated by earthquakes (blue bars) and plot of the number of recorded seismic events (red line)



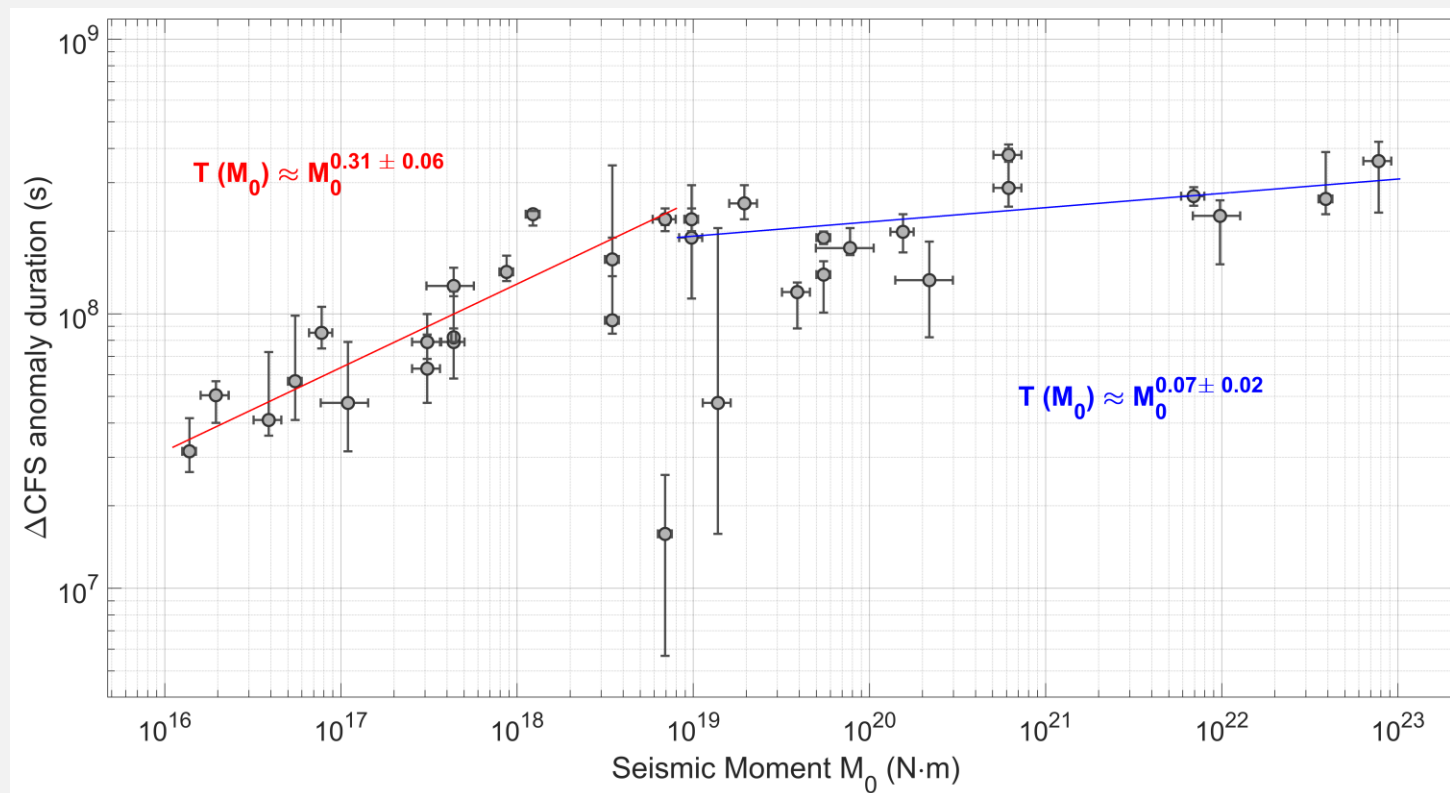
(A) CFS map for seismicity in the Christchurch region, South Island, New Zealand, GeoNet Catalog, 1990–2021, $M_L \geq 2.5$. (B) Correlation ρ between CFS and seismicity in the Kaikoura District, South Island, New Zealand (C) Histogram of energy nucleated by earthquakes with $M_L \geq 2.5$ (blue bars) and plot of the number of recorded seismic events (red line)

(A) CFS map for seismicity in Central Italy, INGV Catalog, 1985–2021, $M_L \geq 2.0$. (B) Correlation ρ between CFS and seismicity in the Valnerina area between 1985 and 2021. The plot is realized by considering earthquakes happened at latitude 42.7° – 43.1° N and longitude 12.9° – 13.3° E. Only 5–15 km deep seismic events are considered, $M_L \geq 2.0$. (C) Correlation ρ between CFS and seismicity in Central Italy, Monti della Laga and North L'Aquila province, between 1985 and 2021. (D) Histogram of energy nucleated by earthquakes with $M_L \geq 2.0$ (blue bars) and plot of the number of recorded seismic events (red line).



Comments

1. In mean-field regime, the critical dynamics of the order parameter is $m \sim H^{(1/\delta)}$, $\delta = 3$, where H is the intensity of the perturbing field $\rightarrow T \sim M^{(1/\delta)}$.
2. $\delta \sim 3$ also characterizes seismic nucleation scaling of single earthquakes $\Rightarrow$ Are observed trends related to coalescent nucleation phases in the crust?
3. The latter exponent, $\delta \sim 0.1$, may stem from cascade triggering.

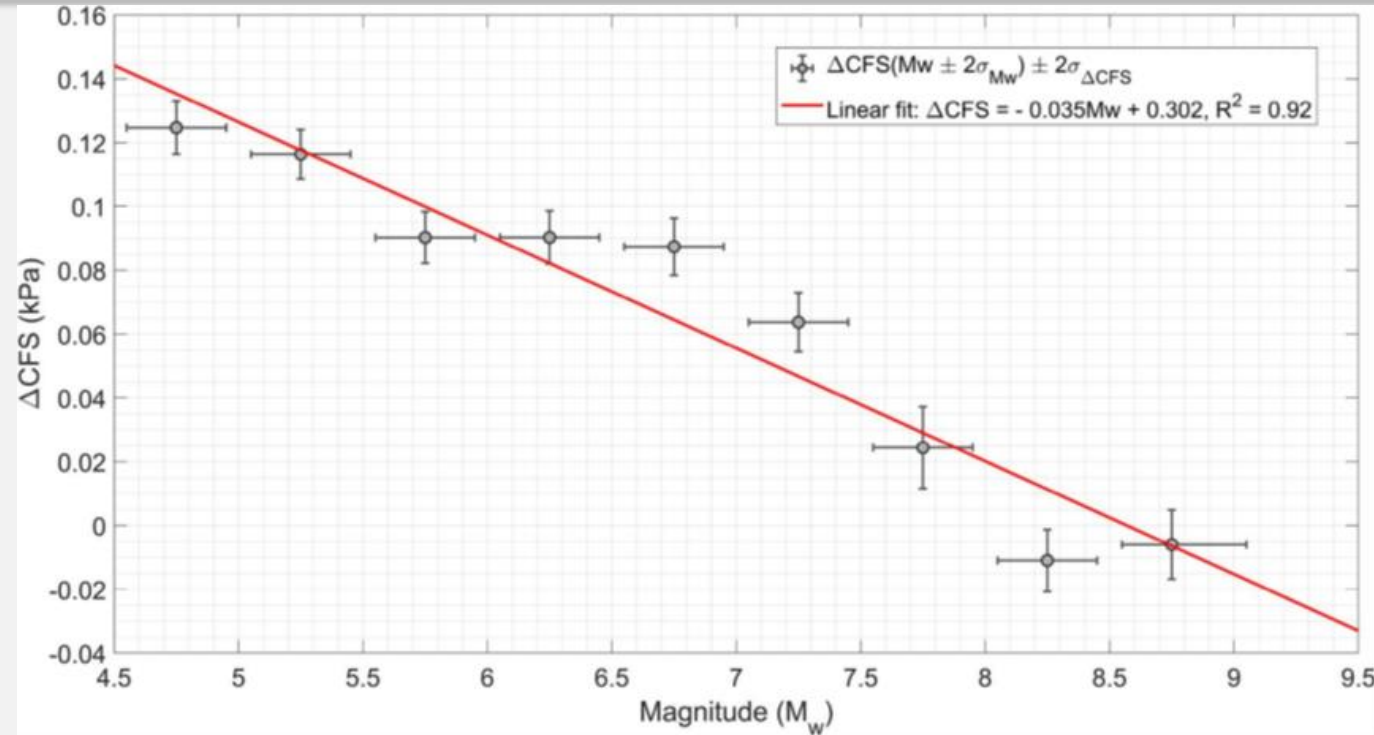


Correlations between tidal stress and nucleated seismic energy

Table 1. Correlation values between tidal CFS and nucleated energy concerning sixteen full-catalog and declustered one-years-long seismic time series in correspondence of moderate and large seismic sequences. The time series starts six months before the mainshock and stops six months later. Only shallow (depth ≤ 50 km) events occurring within the future epicentral area (rectangular regions hit by increased seismic activity during the impending seismic sequence) above the completeness magnitude are considered in this analysis. The fourth column shows our results for full seismic catalogs ($\rho_{0.5d}$), while in the fifth one, correlations are calculated for simulated tidal stress in which semi-diurnal and diurnal harmonics are removed (ρ_{14d}). The last column contains the outputs for Uhrhammer-declustered catalogs ($\rho_{0.5d}^{(DECL)}$). Declustered time series do not provide useful information about tidal triggering of earthquakes, since the correlation values are always compatible with zero. These results strongly suggest that the statistical properties of clustering change as a function of the stability state of crustal volumes. This is obvious after large earthquakes occur, as aftershocks prove, but how earthquake clusters are affected by local spatial and temporal stress patterns is still a puzzle. For the sake of readability, except for this table, only results for $\rho_{0.5d} = \rho$ time series are shown.

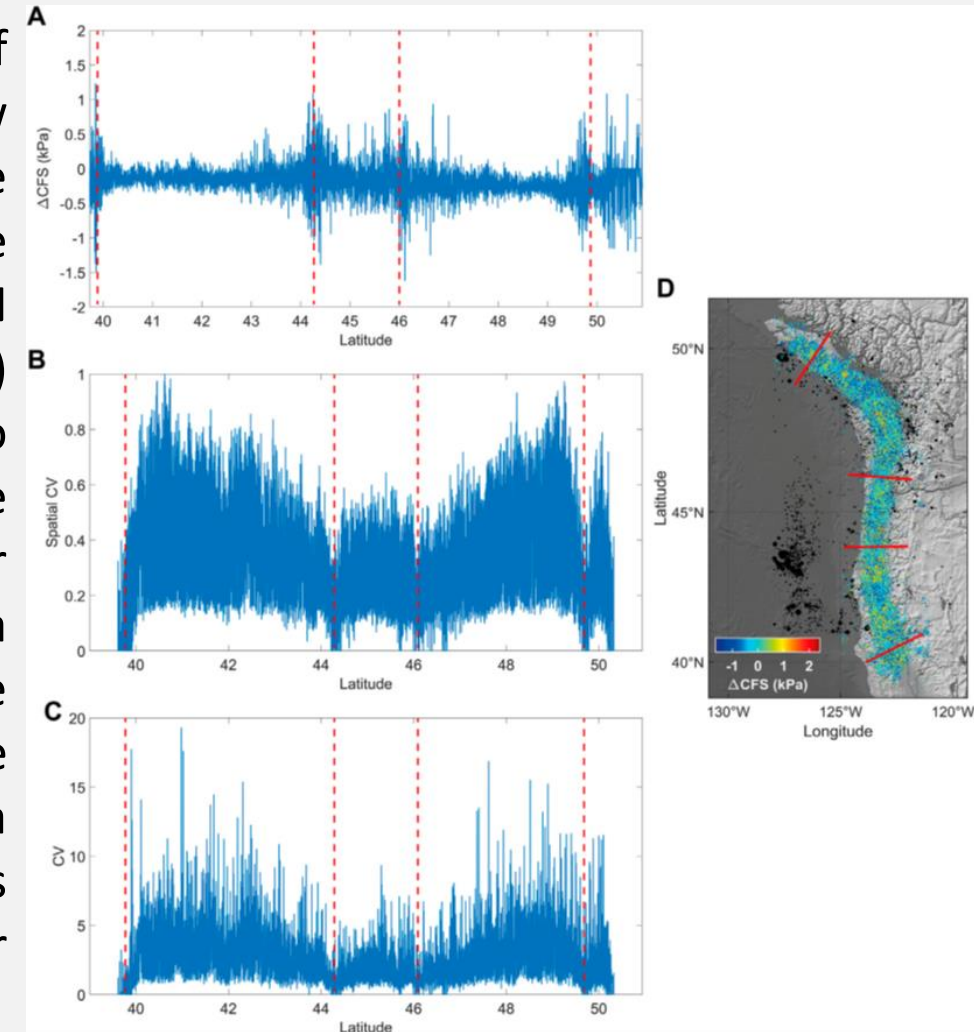
Place	Earthquake	M_w	$\rho_{0.5d}(\sigma_p)$	$\rho_{14d}(\sigma_p)$	$\rho_{0.5d}^{(DECL)}(\sigma_p)$
Ormond	10/06/1993	6.7	0.12 (0.02)	0.18 (0.03)	- 0.02 (0.10)
Colfiorito	26/07/1997	5.6	0.07 (0.01)	0.09 (0.01)	0.00 (0.04)
Lithakia	18/11/1997	6.6	0.08 (0.03)	0.05 (0.02)	- 0.01 (0.02)
South Iceland	29/05/2000	6.5	0.10 (0.01)	0.00 (0.01)	0.00 (0.08)
Molise	31/10/2002	5.7	0.06 (0.01)	0.15 (0.03)	0.04 (0.12)
L'Aquila	06/04/2009	6.3	0.09 (0.01)	0.42 (0.08)	0.03 (0.08)
Fiordland	15/07/2009	7.8	0.07 (0.01)	0.39 (0.02)	0.03 (0.07)
Tohoku	11/03/2011	9.0	0.19 (0.03)	0.13 (0.05)	0.04 (0.10)
Emilia	20/05/2012	5.9	0.05 (0.01)	0.07 (0.01)	- 0.03 (0.12)
Lefkada	26/01/2014	6.1	0.13 (0.02)	0.14 (0.03)	0.01 (0.10)
Amatrice	24/08/2016	6.0	0.06 (0.01)	0.19 (0.02)	- 0.02 (0.06)
Kaikoura	13/11/2016	7.8	0.16 (0.01)	0.37 (0.02)	0.02 (0.08)
Molise	16/08/2018	5.1	0.21 (0.02)	0.21 (0.02)	- 0.02 (0.17)
Lithakia	25/10/2018	6.8	0.14 (0.02)	0.08 (0.02)	0.01 (0.06)
Ridgecrest	04/07/2019	6.4	0.24 (0.01)	0.12 (0.04)	0.07 (0.08)
Thessaly	03/03/2021	6.3	0.29 (0.02)	0.26 (0.01)	0.05 (0.06)

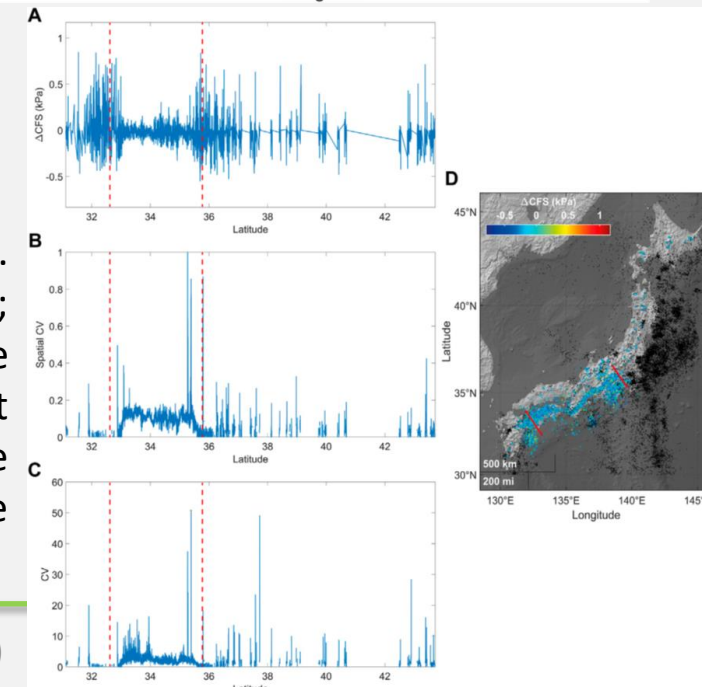
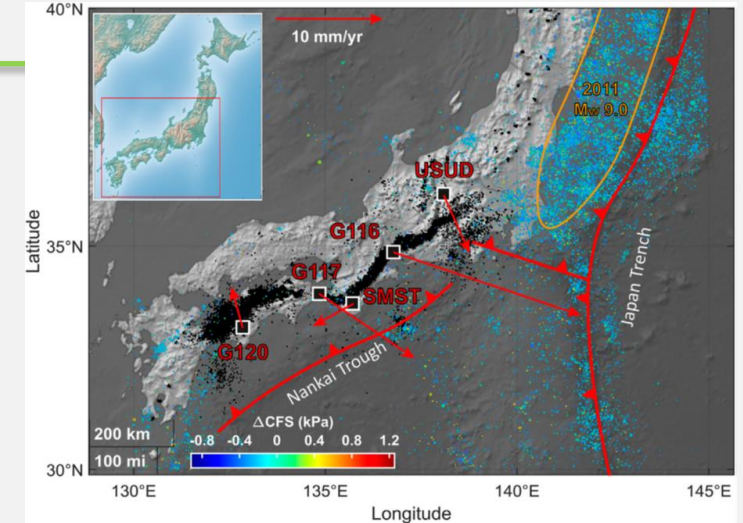
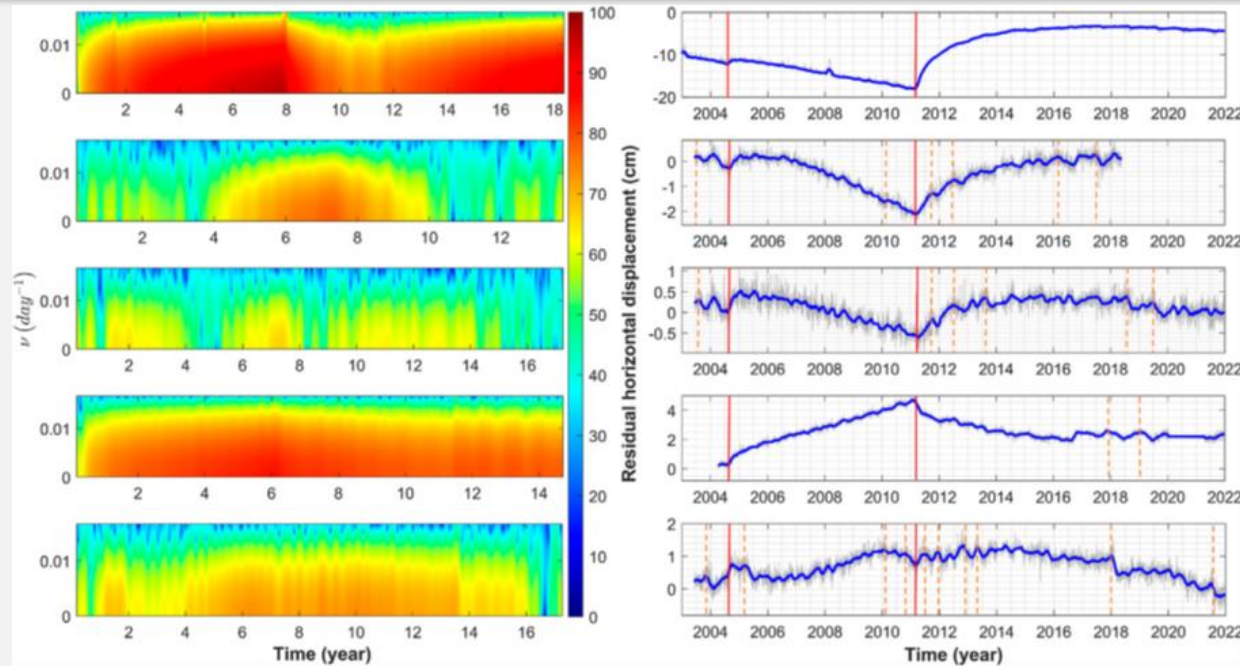
Why are smaller earthquakes more likely triggered by tides?



Moderate seismicity is more strongly triggered by solid Earth tides than larger earthquakes. Stress perturbations directly affect small unstable faults more likely than larger ones, while fracture propagation over large patches is almost completely controlled by their internal state of stress. The plot is obtained by averaging the tidal Coulomb Failure stress values over groups of earthquakes with different moment magnitudes. The figure is realized by analysing worldwide seismic events listed in the USGS catalogue between 2001 and 2021, $M_w \geq 4.5$.

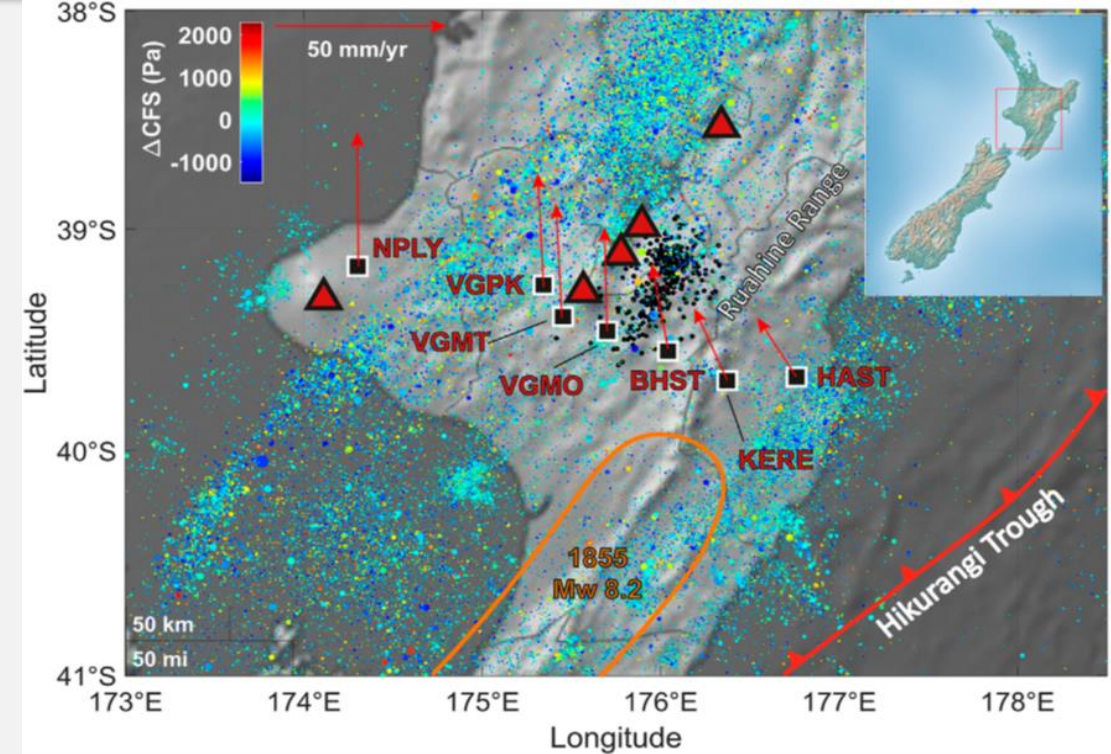
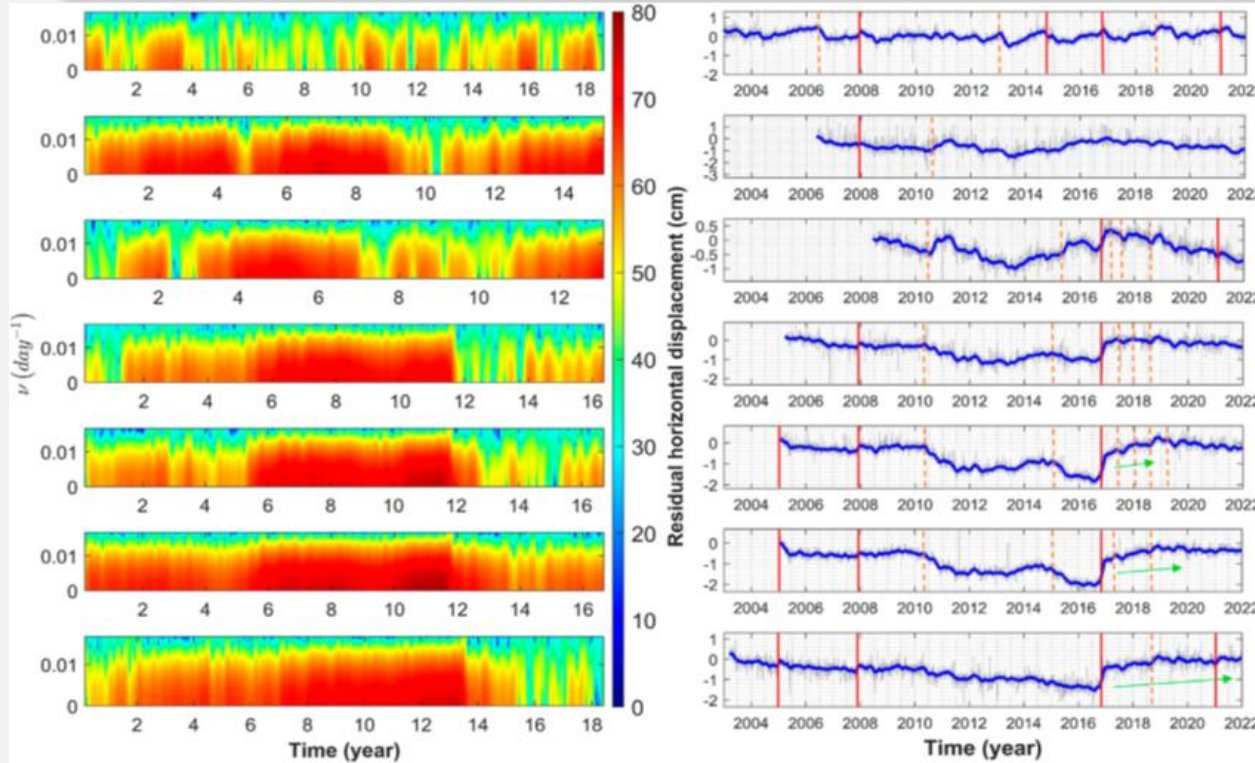
Δ CFS for tremors along the Cascadia subduction zone as a function of epicentral latitude. We highlight four fault segments that show elevated mean tidal stress values for the occurrence of tremors: the Northernmost and Southernmost patches of the subduction zone and two intermediate areas approximately located at 44.5° and 46° N (red lines in the map and dashed red lines in panels a, b and c). (B) Spatial coefficient of variation for tremors along the ETS zone. Two minima are observed in correspondence with the maxima of the average Δ CFS plotted in (A). (C) Coefficient of variation of tremor time series between 2009 and 2021 as a function of latitude (data from PNSN and EPS Catalogues, 2009 – 2021, respectively available at <http://pnsn.org>). Two minima are observed in correspondence with the maxima of the average Δ CFS plotted in (A) and the minima points of the spatial coefficient of variation. (D) Map of tremors along the Cascadia ETS zone. Black points represent regular earthquakes, their size is proportional to the magnitude.



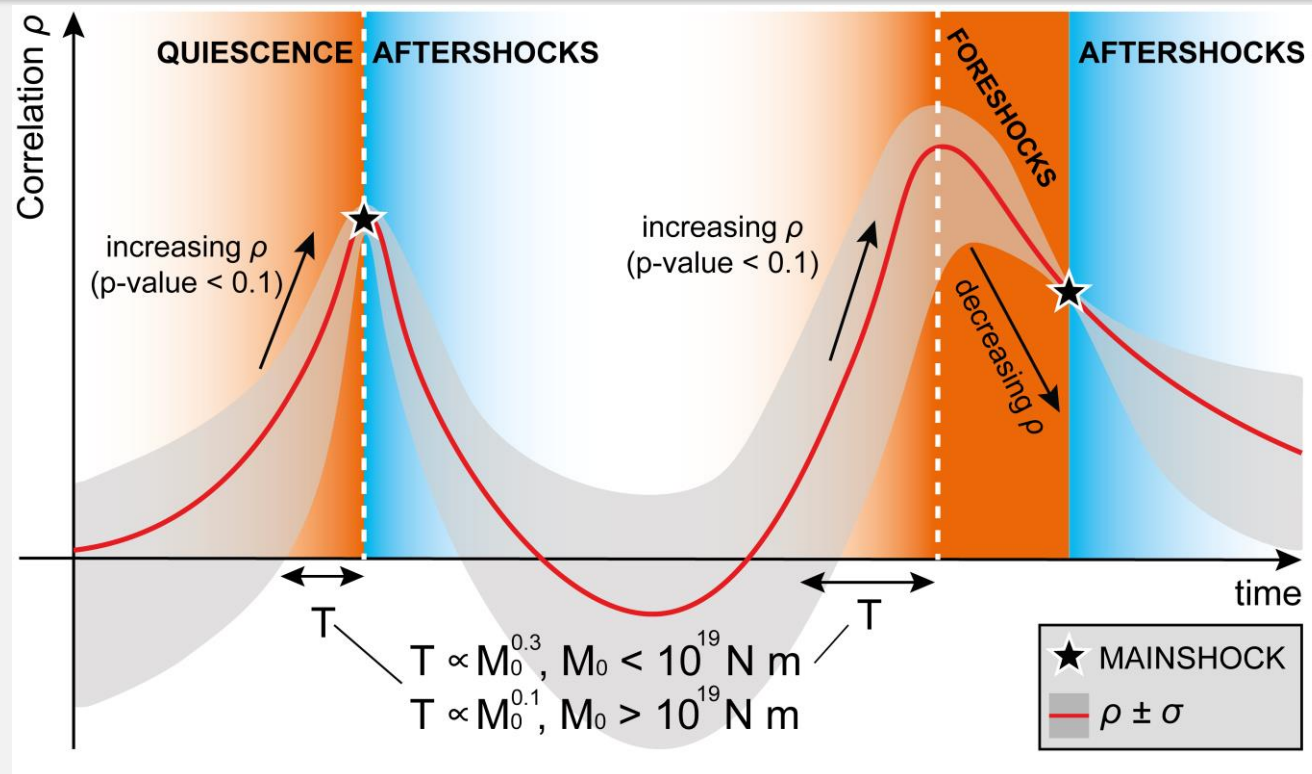


Spectrograms and detrended horizontal geodetic time series of five GNSS stations in the Nankai region. From top to bottom: USUD, G116, G117, SMST, and G120. SSEs are observed (2004, 2010, and 2019); moreover, the spectral amplitudes are noticed to increase before the Giant Tohoku-Oki Earthquake (11/03/2011, Mw 9.0) in the recordings of stations to the north and nearer to the trench with respect to others. The red lines stand for large earthquakes which caused a measurable displacement of the GNSS stations, while the orange dashed lines represent slow slip events. The gaps produced by the Tohoku-Oki earthquake are removed for improving readability.

Connection between tidal triggering of earthquakes, slow slip events, GNSS time series and large seismic events NEW ZEALAND

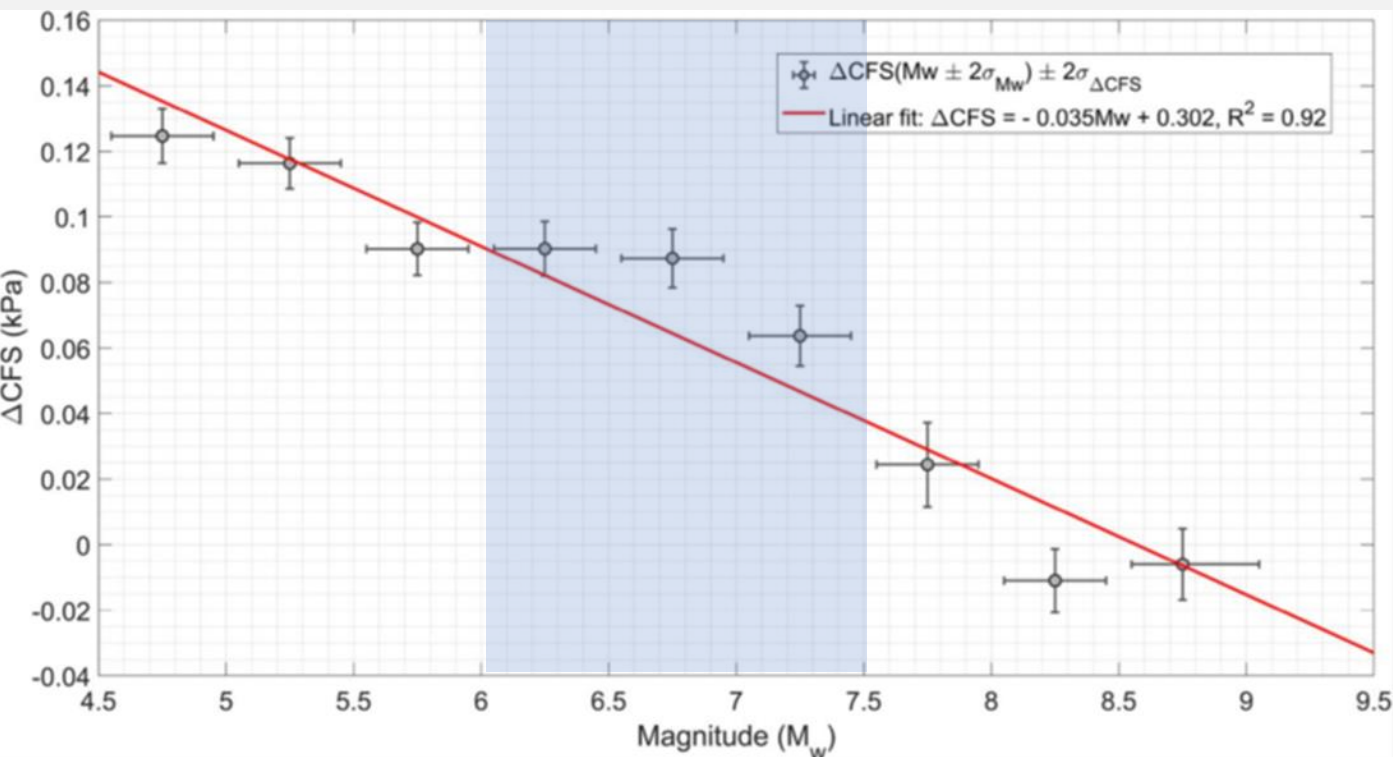


Spectrograms and residual horizontal geodetic time series of seven GNSS stations in Manawatu. From top to bottom: HAST, KERE, BSHT, VGMO, VGMT, VGPK, and NYPT. SSEs are observed, moreover, the spectral amplitudes are noticed to increase before the Kaikoura Earthquake (13/11/2016, Mw 7.8) downline of the Manawatu ETS zone in the recordings of NYPT, VGPK, and VGMT. The red lines stand for large earthquakes which caused a measurable displacement of the GNSS stations, while the orange dashed lines represent slow slip events. The green arrows highlight afterslip. Modified from Zaccagnino and Doglioni (2022).

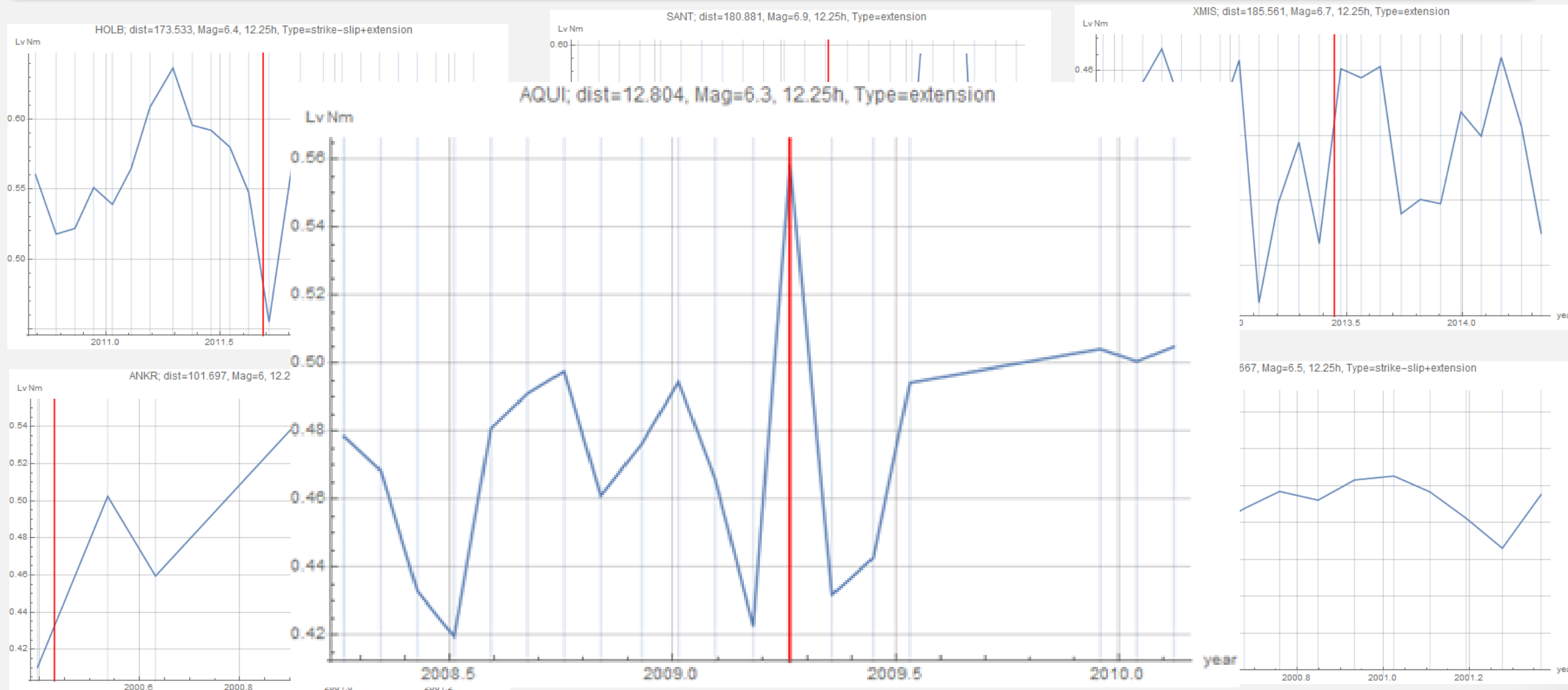


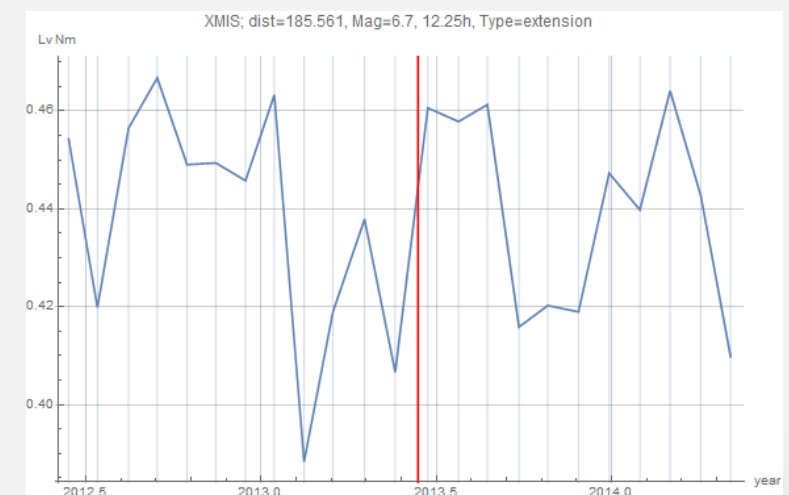
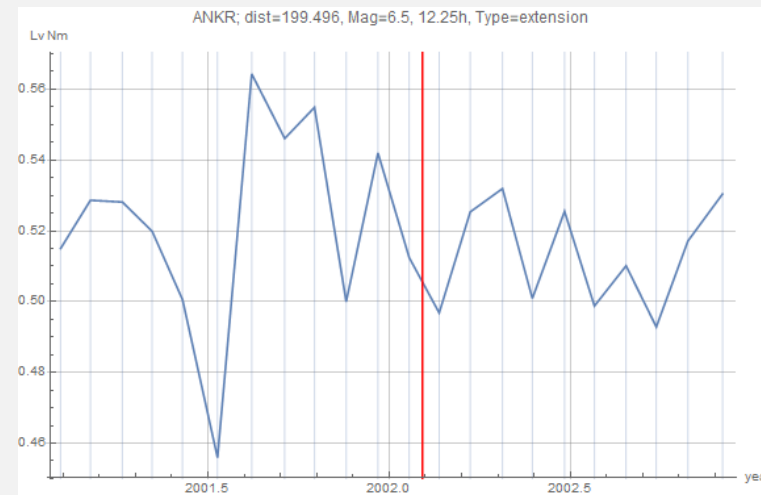
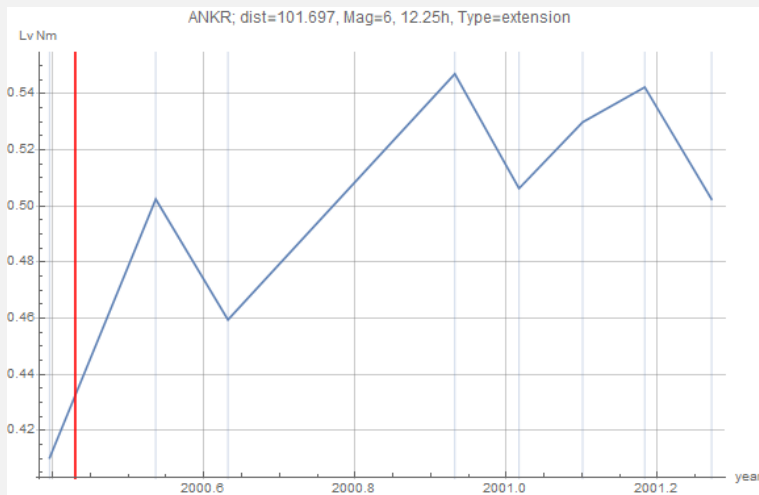
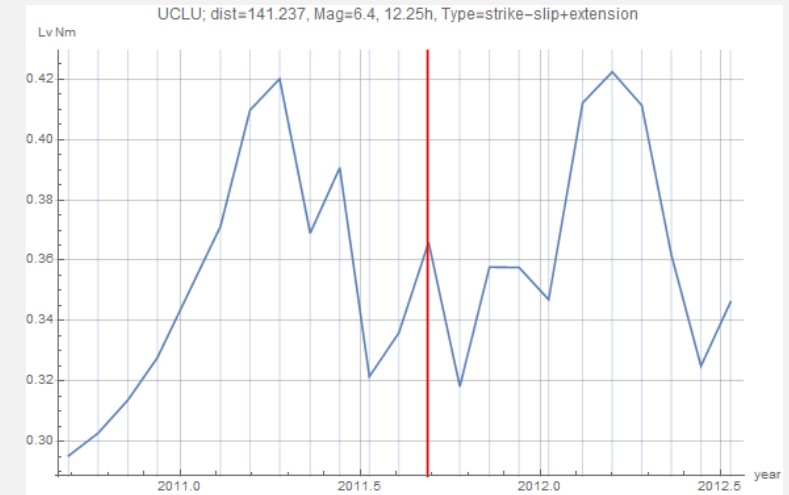
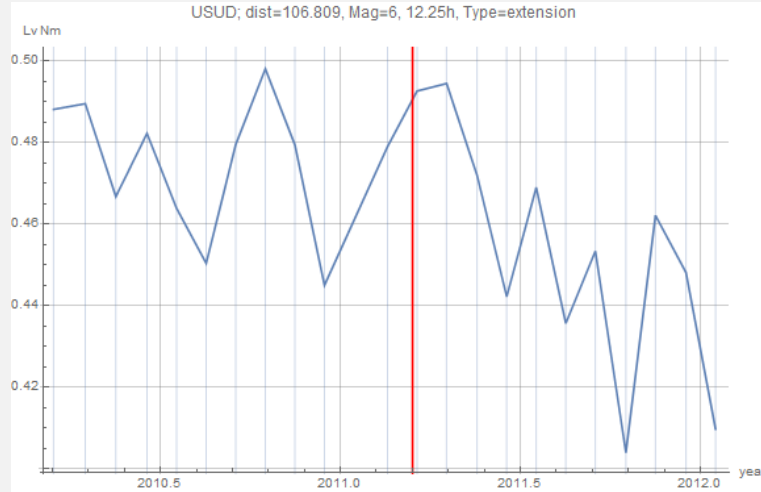
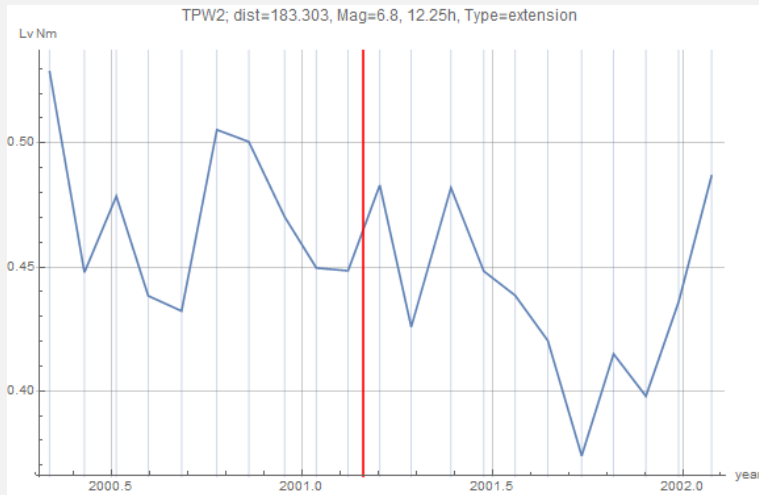
1. Stress perturbation analysis may highlight mounting instability in the brittle lithosphere
2. Even though it is unlikely that our results may ever be of practical use for seismic hazard, analogous procedures could illuminate slow hidden processes of destabilization taking place in the upper crust.
3. Different types of seismic events share the same response to tidal stress perturbations.

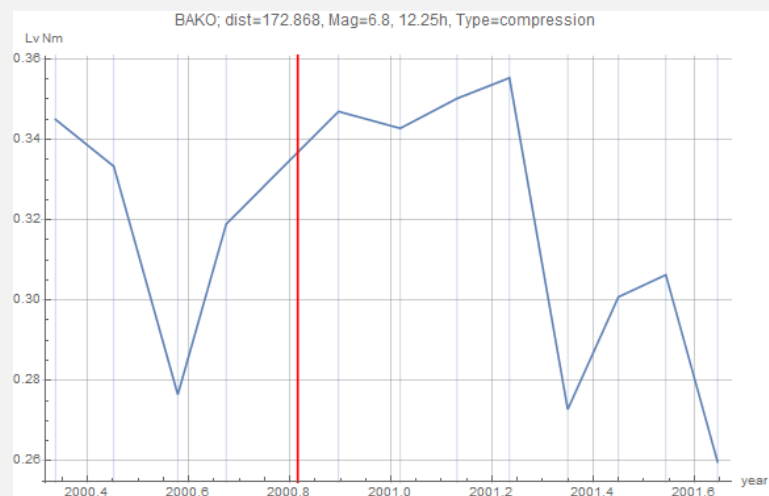
The EQ events studied
with global stations at a
distance <200 km from the epicenter



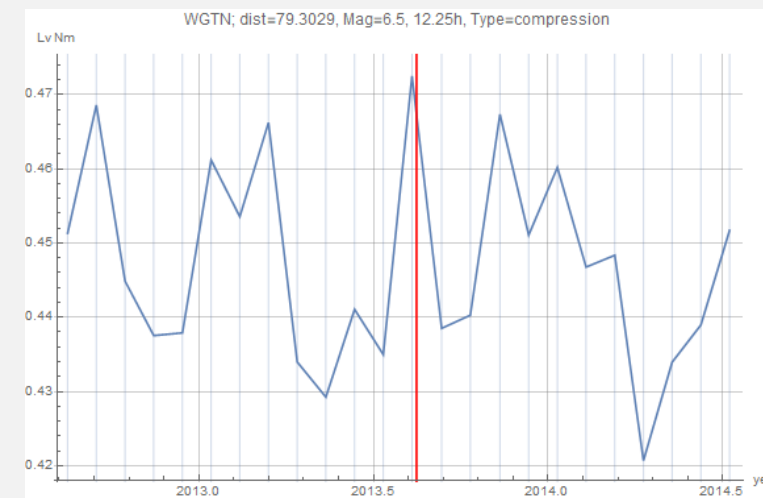
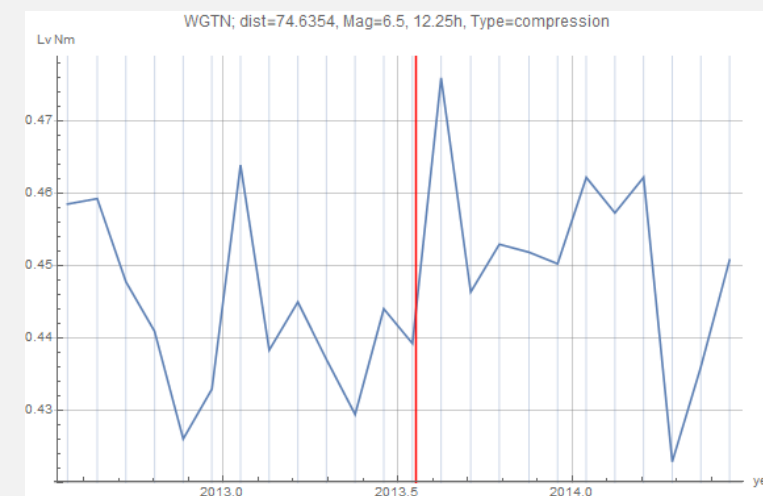
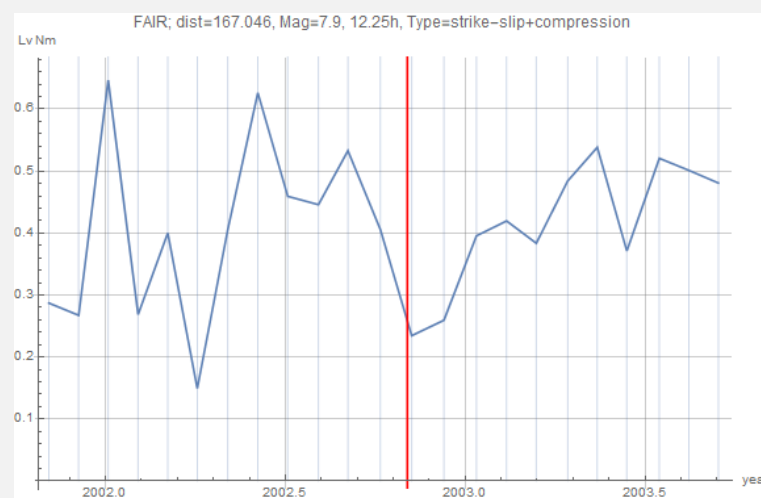
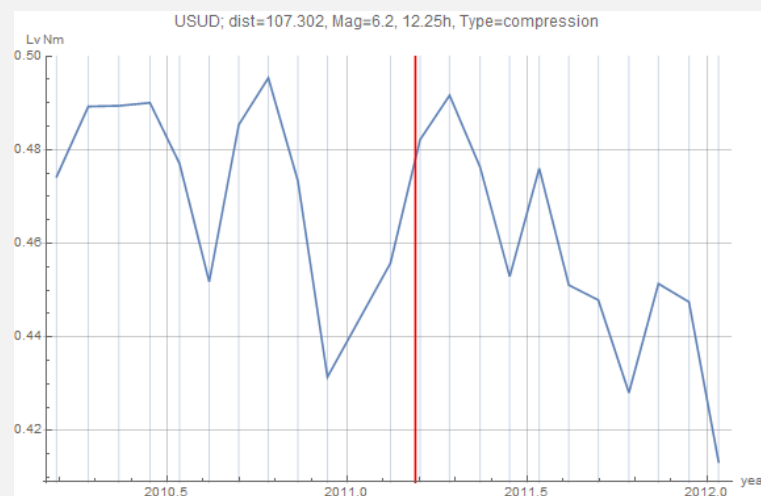
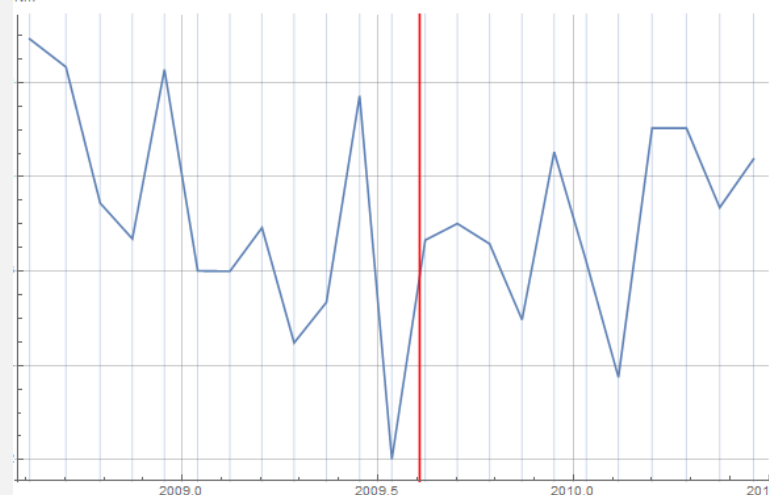
DD-MM-YYYY	hh-mm-ss	Lat(EQ)	Lon(EQ)	Depth(km)	Magnitude	GNSS	Lat(GNSS)	Lon(GNSS)	H(GNSS)	Dist(km)	EQ_type	components
06-Jun-2000	02:41:49	40.69	32.99	10	6	ANKR	32.759	39.888	975.217	101.6968	extension	
17-Jun-2000	15:40:41	63.96	-20.48	10	6.5	FJOC	-18.006	64.875	1035.436	166.2493	strike-slip+extension	
17-Jun-2000	15:40:41	63.96	-20.48	10	6.5	REYK	-21.955	64.139	93.496	83.98976	strike-slip+extension	
21-Jun-2000	00:51:46	63.98	-20.75	10	6.5	FJOC	-18.006	64.875	1035.436	175.4133	strike-slip+extension	
21-Jun-2000	00:51:46	63.98	-20.75	10	6.5	REYK	-21.955	64.139	93.496	70.86671	strike-slip+extension	
25-Jun-2000	06:34:42	31.18	131.2	10	6	AIRA	130.6	31.824	315.046	101.5769	compression	
25-Oct-2000	09:32:23	-6.54	105.63	38	6.8	BAKO	106.849	-6.491	158.595	172.8675	compression	
28-Feb-2001	18:54:32	47.14	-122.72	51.8	6.8	TPW2	-123.768	46.207	-14.554	183.3027	extension	
15-Mar-2001	13:02:42	-32.32	-71.49	37	6	SANT	-70.669	-33.15	723.526	157.1333	compression	
08-Oct-2001	18:14:26	52.59	160.32	48.5	6.5	PETP	158.607	53.067	210.697	175.4538	compression	
08-Oct-2001	18:14:26	52.59	160.32	48.5	6.5	PETS	158.65	53.023	102.596	170.8821	compression	
08-Oct-2001	18:20:38	52.63	160.21	33	6.4	PETP	158.607	53.067	210.697	151.3386	compression	
08-Oct-2001	18:20:38	52.63	160.21	33	6.4	PETS	158.65	53.023	102.596	146.7951	compression	
15-Jan-2002	07:12:58	-6.31	105.2	10	6.1	BAKO	106.849	-6.491	158.595	192.7858	extension	
03-Feb-2002	07:11:28	38.57	31.27	5	6.5	ANKR	32.759	39.888	975.217	199.496	extension	
23-Oct-2002	11:27:19	63.51	-147.91	4.2	6.6	FAIR	-147.499	64.978	319.557	168.213	strike-slip	
03-Nov-2002	22:12:41	63.51	-147.45	4.2	7.9	FAIR	-147.499	64.978	319.557	167.0457	strike-slip+compression	
06-Jan-2003	23:43:50	15.65	119.65	10	6	PIMO	121.078	14.636	95.994	199.711	compression	
15-Feb-2003	03:32:36	53.64	-164.64	19	6.6	AV27	-164.723	54.492	978.475	113.3569	compression	
15-Mar-2003	19:41:28	52.24	160.38	30.2	6.1	PETP	158.607	53.067	210.697	180.8626	compression	
15-Mar-2003	19:41:28	52.24	160.38	30.2	6.1	PETS	158.65	53.023	102.596	175.6588	compression	
09-Oct-2003	22:19:13	13.75	119.93	33	6.2	PIMO	121.078	14.636	95.994	190.1241	compression	
22-Dec-2003	19:15:56	35.7	-121.1	8.4	6.5	VNDP	-120.616	34.556	-11.089	143.117	compression	
06-Apr-2009	01:32:39	42.33	13.33	8.8	6.3	AQUI	13.35	42.368	713.399	12.80402	extension	
10-Aug-2009	20:07:09	34.74	138.26	40.4	6.2	USUD	138.362	36.133	1509.063	195.2654	compression	
02-Sep-2009	07:55:01	-7.78	107.29	46	7	BAKO	106.849	-6.491	158.595	197.8727	compression	
27-Feb-2010	07:12:28	-33.87	-71.94	35	6	SANT	-70.669	-33.15	723.526	178.2329	compression	
27-Feb-2010	10:30:36	-33.28	-71.95	35	6	SANT	-70.669	-33.15	723.526	155.5547	compression	
27-Feb-2010	19:00:06	-33.42	-71.82	31.1	6.2	SANT	-70.669	-33.15	723.526	143.0321	compression	
04-Mar-2010	01:59:48	-33.21	-72.12	24.2	6	SANT	-70.669	-33.15	723.526	159.9393	compression	
11-Mar-2010	14:39:43	-34.29	-71.89	11	6.9	SANT	-70.669	-33.15	723.526	180.8809	extension	
11-Mar-2010	14:55:27	-34.32	-71.79	18	7	SANT	-70.669	-33.15	723.526	185.435	extension	
25-Mar-2010	05:29:24	13.82	120.07	16	6	PIMO	121.078	14.636	95.994	157.0141	compression	
30-Jul-2010	03:56:13	52.49	159.84	23	6.3	PETP	158.607	53.067	210.697	127.4977	compression	
30-Jul-2010	03:56:13	52.49	159.84	23	6.3	PETS	158.65	53.023	102.596	122.2879	compression	
11-Mar-2011	18:59:16	37.01	138.37	9.3	6.2	USUD	138.362	36.133	1509.063	107.3022	compression	
11-Mar-2011	19:46:50	40.48	139.05	10	6.2	P104	139.703	39.942	45.056	91.5518	strike-slip+extension	
15-Mar-2011	13:31:46	35.27	138.58	9	6	USUD	138.362	36.133	1509.063	106.8094	extension	
16-Jul-2011	00:26:12	-33.81	-71.83	20	6	SANT	-70.669	-33.15	723.526	151.0631	compression	
09-Sep-2011	19:41:34	49.53	-126.89	22	6.4	HOLB	-128.135	50.64	559.961	173.5326	strike-slip+extension	
09-Sep-2011	19:41:34	49.53	-126.89	22	6.4	UCLU	-125.542	48.926	10.452	141.2373	strike-slip+extension	
17-Apr-2012	03:50:15	-32.62	-71.36	29	6.7	SANT	-70.669	-33.15	723.526	116.3857	compression	
20-May-2012	02:03:52	44.89	11.23	6.3	6	GENO	8.921	44.419	153.901	196.3544	compression	
08-Nov-2012	02:01:50	49.23	-128.47	13.7	6.1	HOLB	-128.135	50.64	559.961	172.3245	strike-slip+extension	
19-May-2013	18:44:10	52.34	160.06	18	6.1	PETP	158.607	53.067	210.697	145.2577	compression	
19-May-2013	18:44:10	52.34	160.06	18	6.1	PETS	158.65	53.023	102.596	139.9635	compression	
21-May-2013	01:55:08	52.52	160.36	30	6	PETP	158.607	53.067	210.697	162.7941	compression	
21-May-2013	01:55:08	52.52	160.36	30	6	PETS	158.65	53.023	102.596	158.0698	compression	
21-May-2013	05:43:21	52.28	160.07	30	6.1	PETP	158.607	53.067	210.697	161.9278	compression	
21-May-2013	05:43:21	52.28	160.07	30	6.1	PETS	158.65	53.023	102.596	156.5618	compression	
13-Jun-2013	16:47:23	-10	107.23	9	6.7	XMIS	105.688	-10.45	262.026	185.5613	extension	
21-Jul-2013	05:09:31	-41.7	174.33	17	6.5	WGTN	174.806	-41.323	26.535	74.63544	compression	
16-Aug-2013	02:31:05	-41.73	174.15	8.2	6.5	WGTN	174.806	-41.323	26.535	79.3029	compression	
03-Sep-2013	20:19:06	51.24	-130.39	2.7	6.1	HOLB	-128.135	50.64	559.961	174.8818	compression	
04-Sep-2013	00:23:11	51.18	-130.22	9.9	6	HOLB	-128.135	50.64	559.961	168.4027	strike-slip+extension	
23-Apr-2017	02:36:07	-33.03	-72.02	21	6	SANT	-70.669	-33.15	723.526	148.4294	compression	
24-Apr-2017	21:38:30	-33.03	-72.06	28	6.9	SANT	-70.669	-33.15	723.526	158.3818	compression	
01-May-2017	12:31:55	59.82	-136.71	10	6.2	WHIT	-135.222	60.751	1427.846	142.0771	compression	
01-May-2017	14:18:15	59.82	-136.7	2.5	6.3	WHIT	-135.222	60.751	1427.846	133.5748	strike-slip+compression	

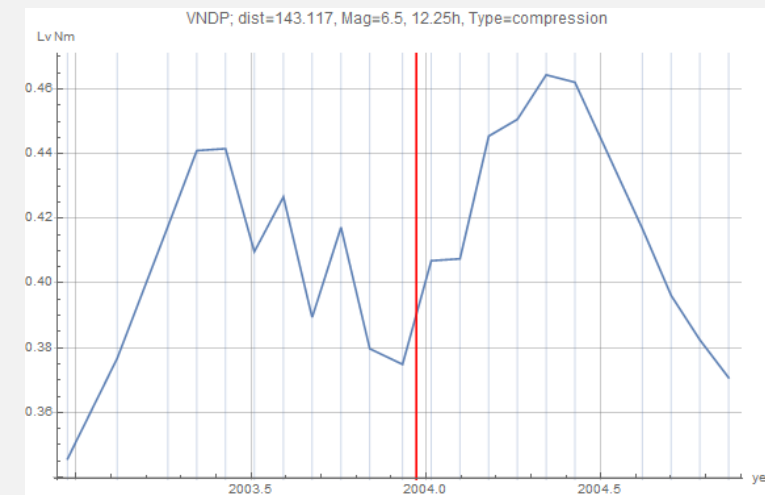
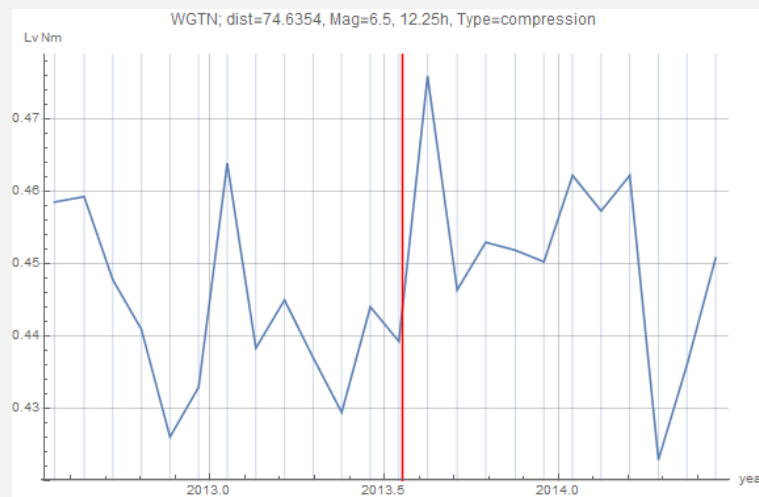
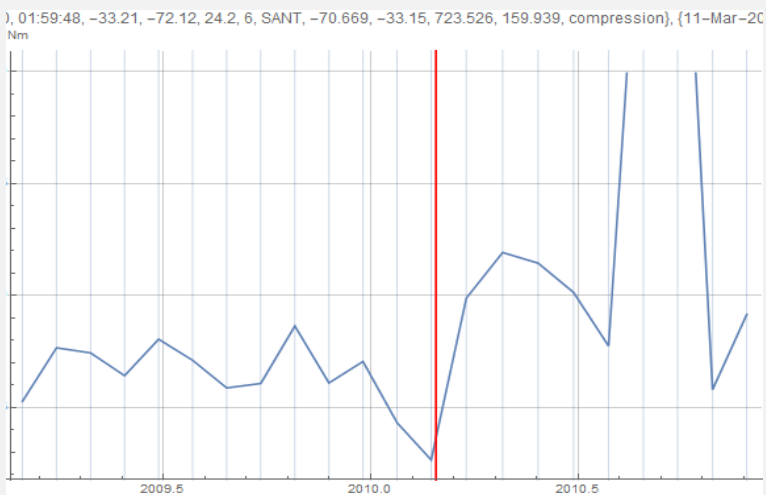
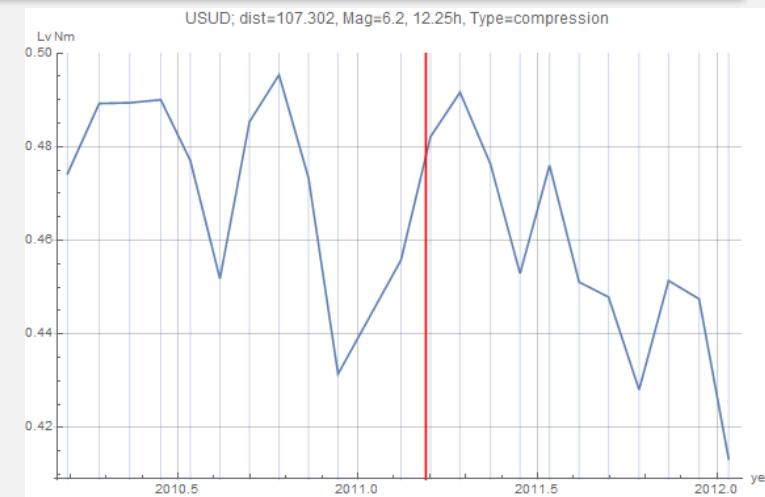
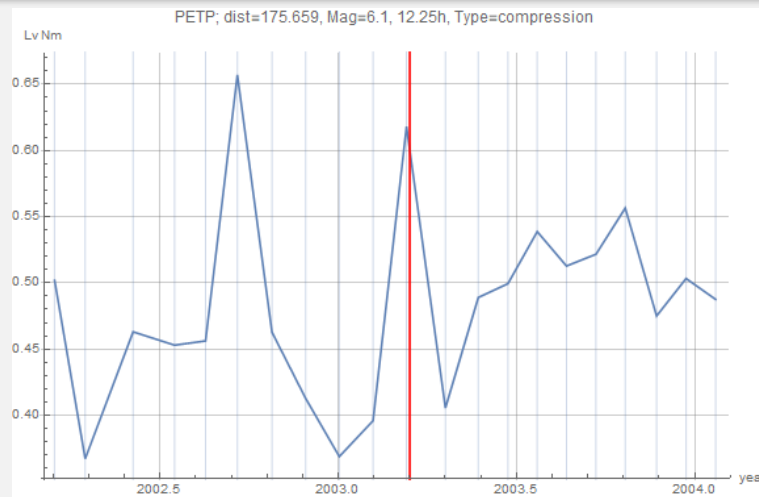
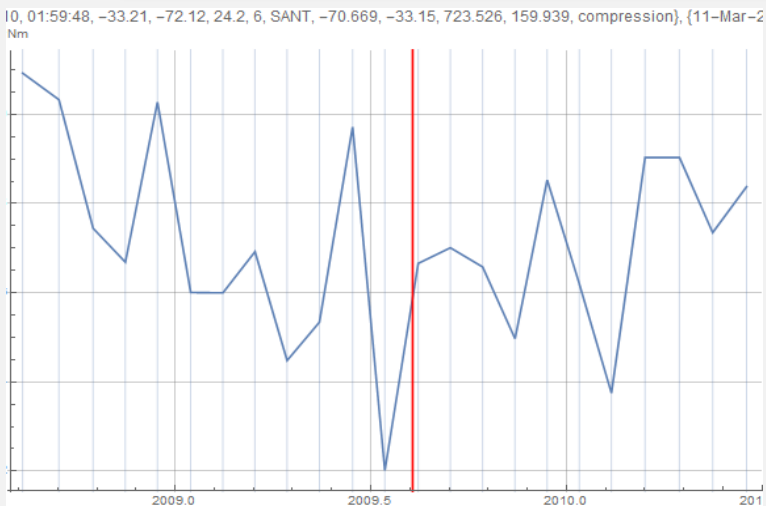


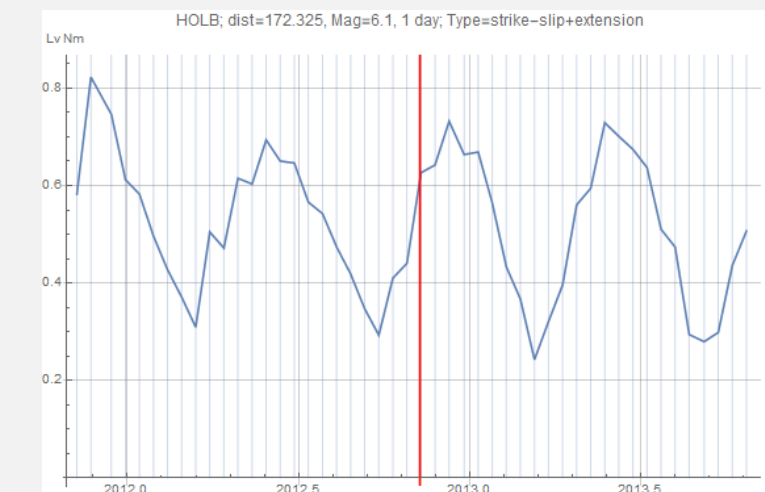
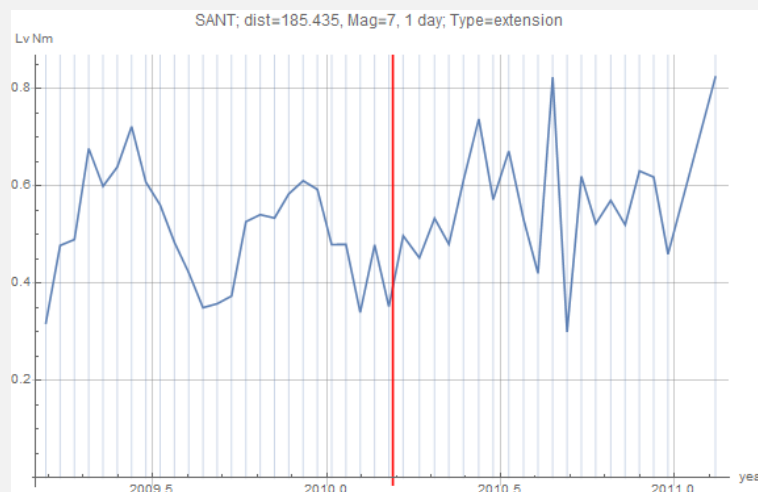
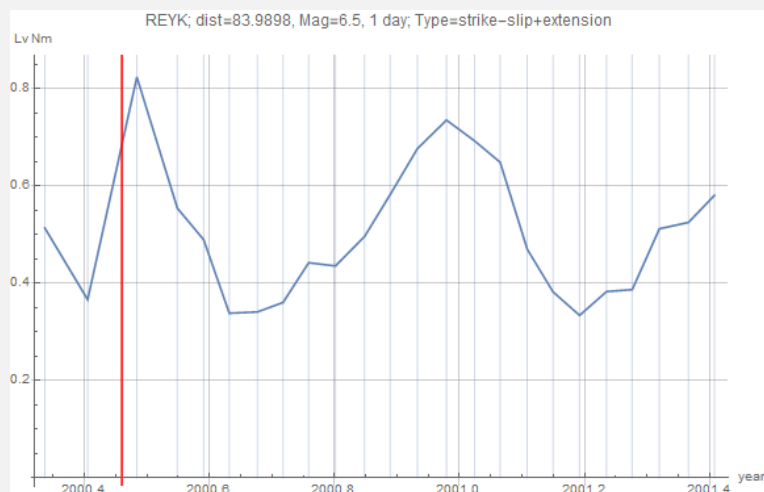
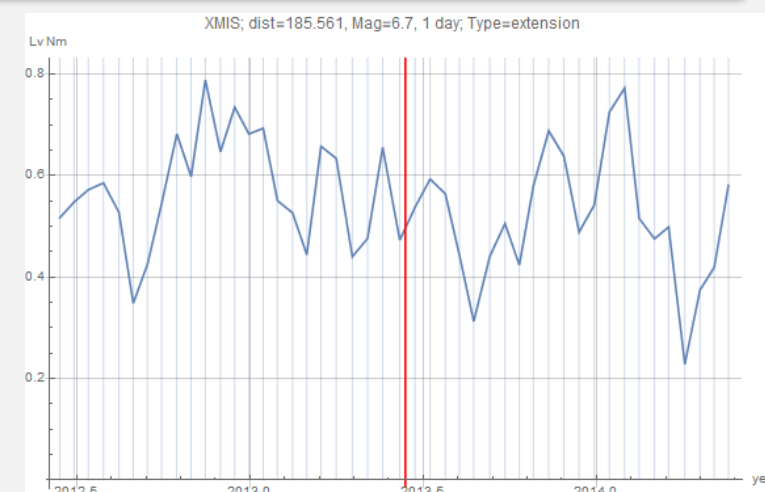
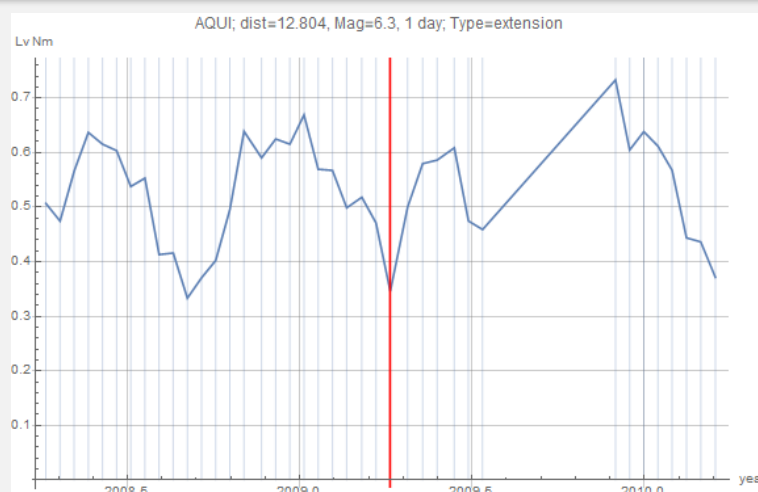
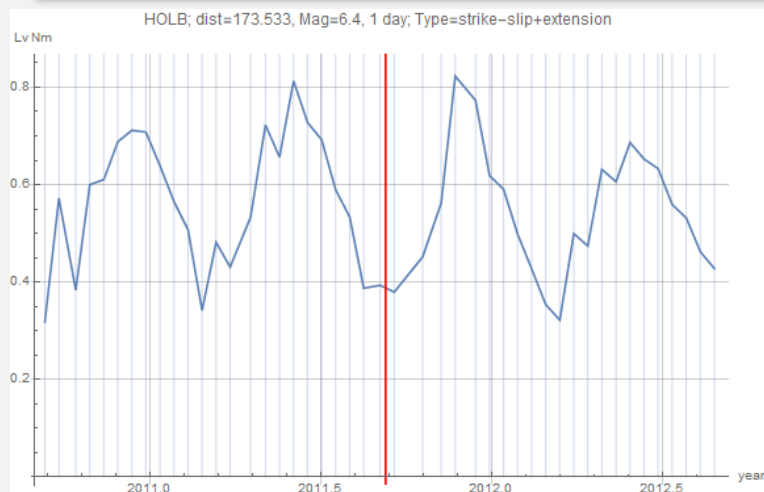


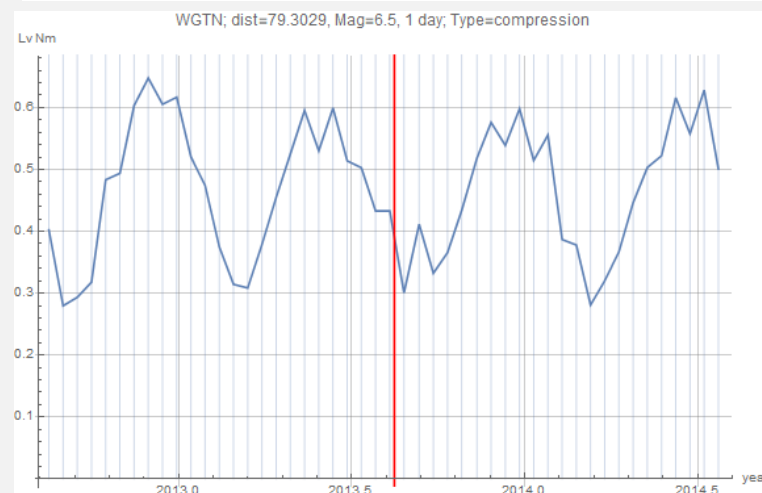
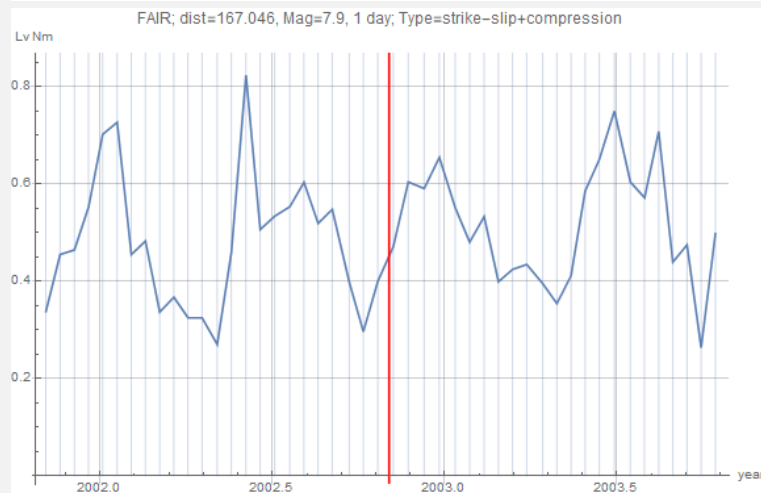
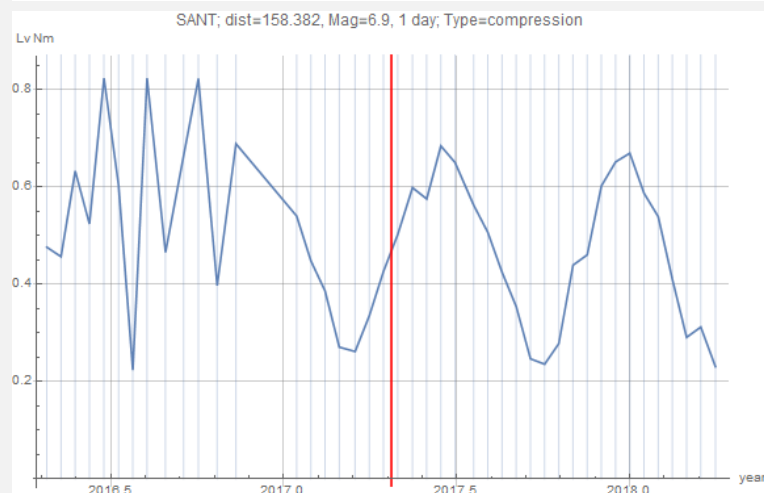
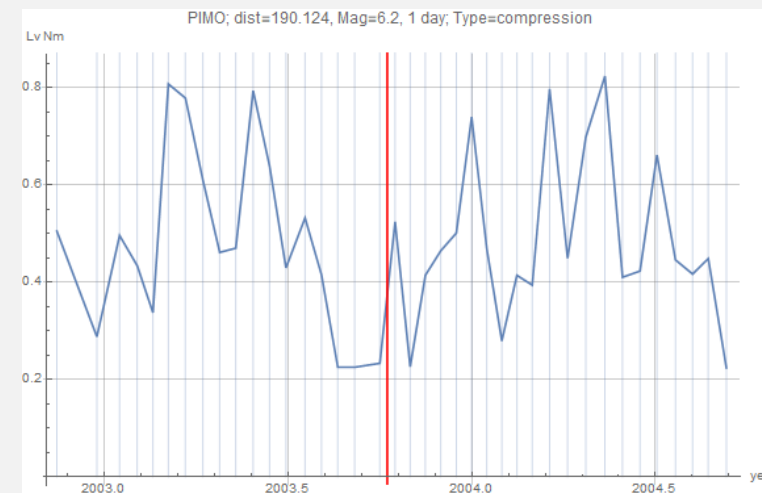
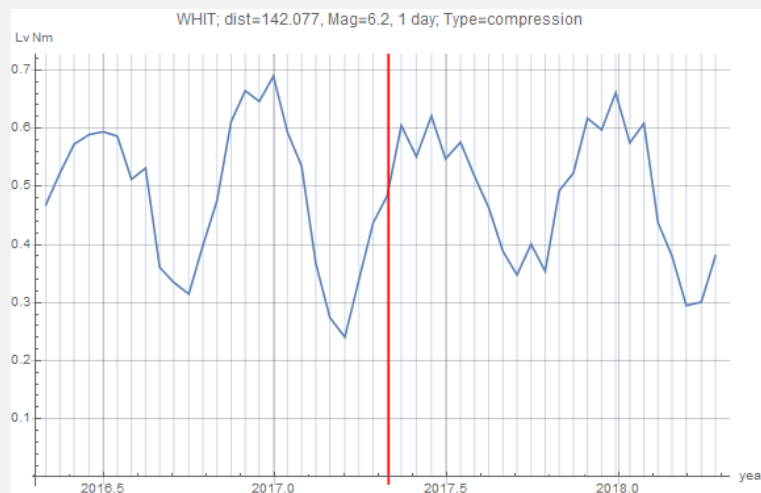
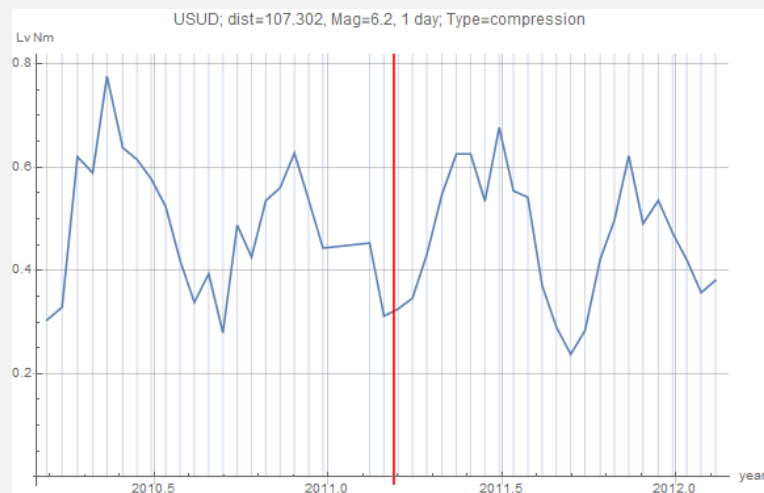


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WP 3300 (SAPIENZA). Title: Geological and geophysical data analysis and modelling for volcanic hazard risk

Analysis will be focused on the following aspects:

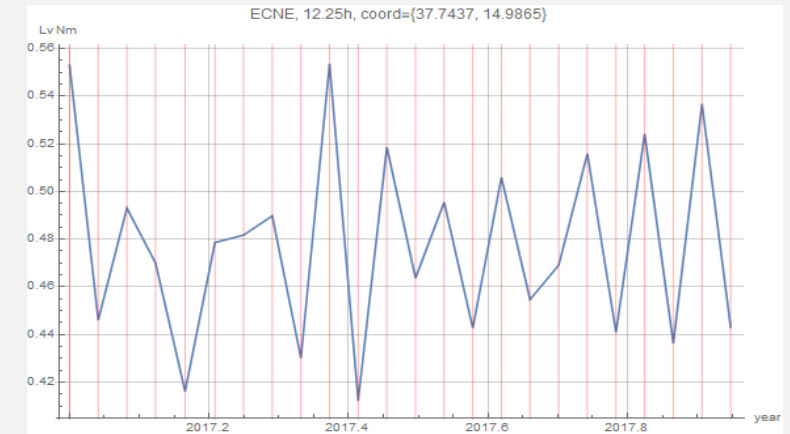
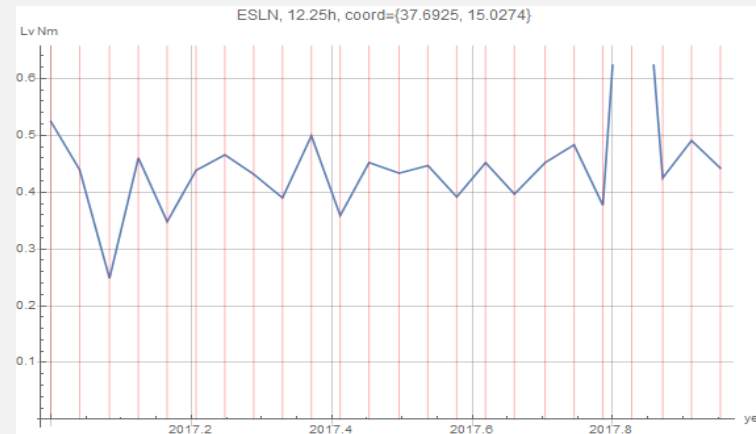
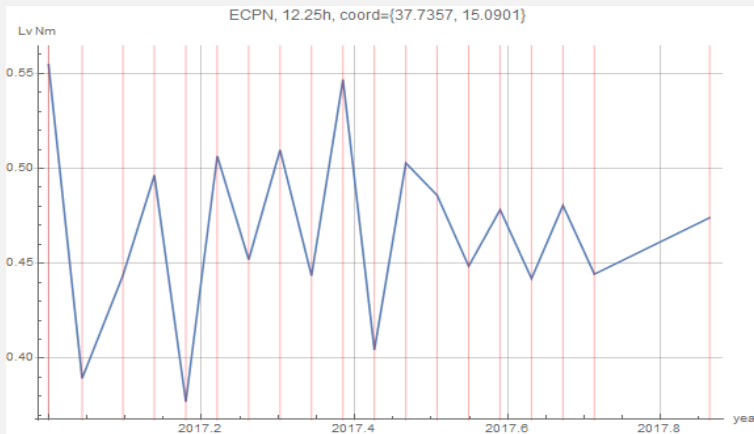
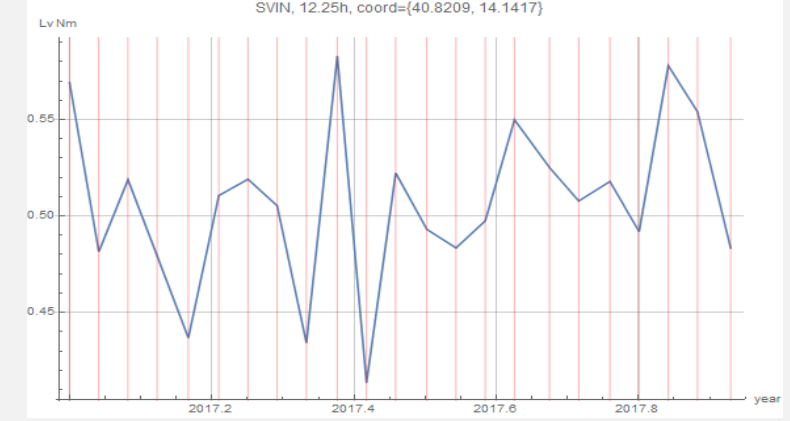
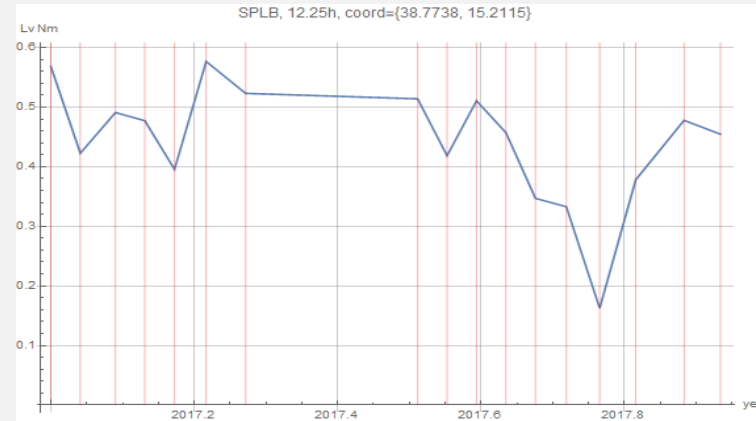
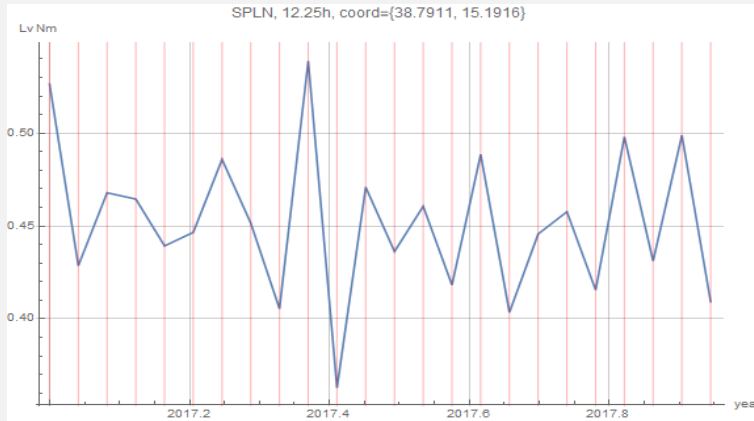
- Analysis of LSET data collected during the project;
- Correlation analysis between LSET and measured crustal deformations and volcanic signals including low- and high-frequency earthquakes, eruptive and degassing behaviour.
- The output of this sub-task will be included Geological Analysis Report and used to draw preliminary conclusions about the possible use for risk assessment related to identified crustal deformations.

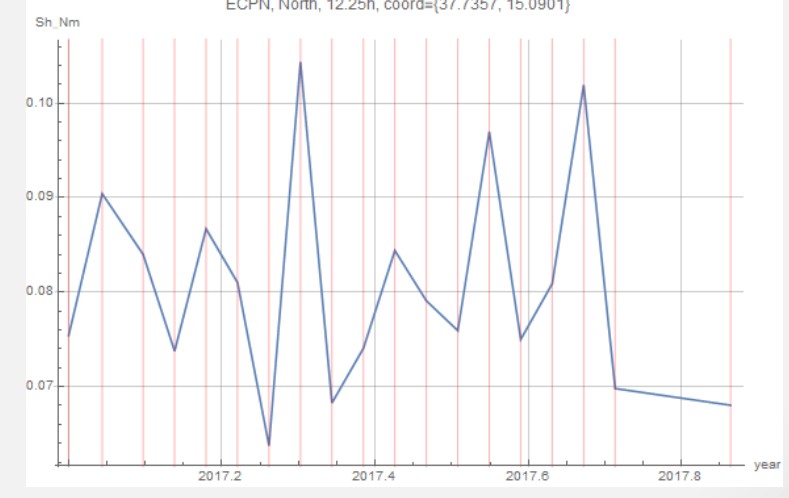
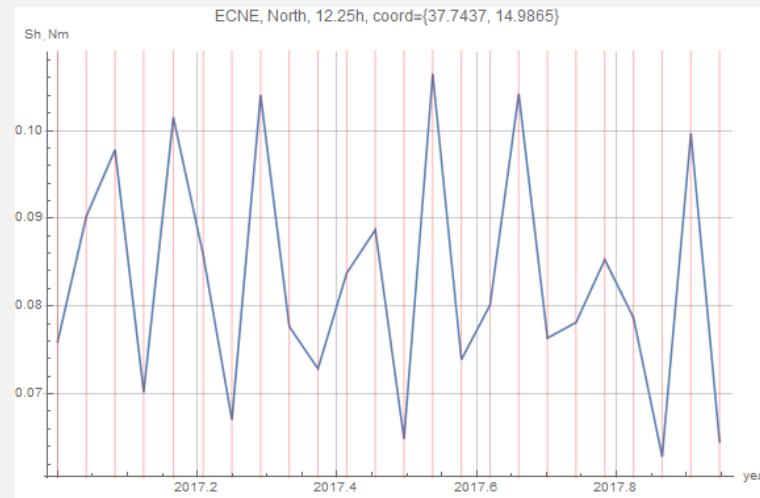
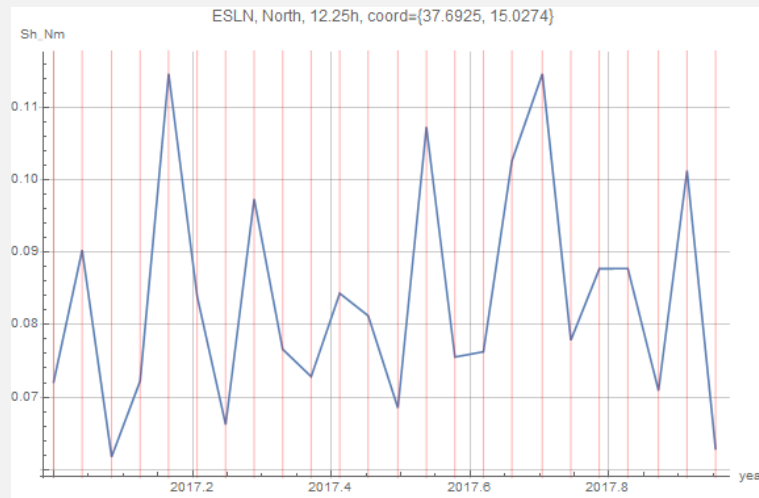
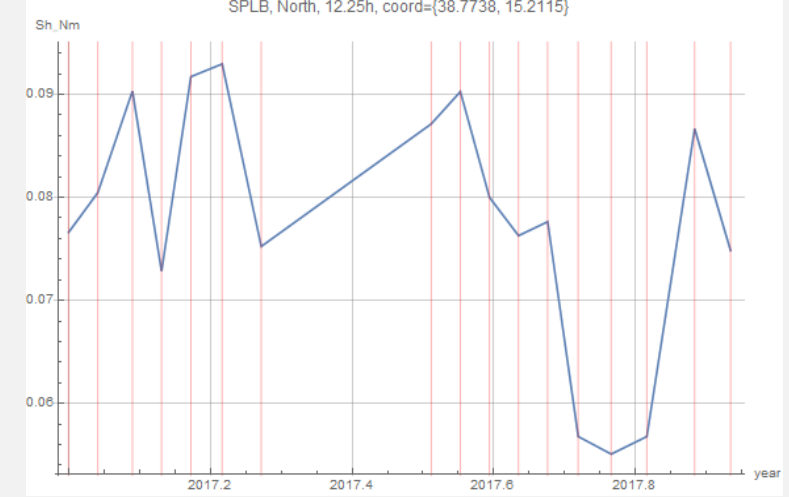
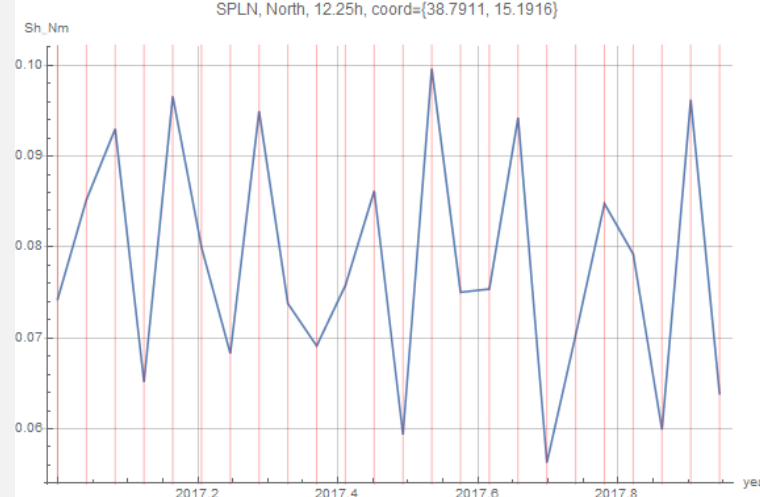
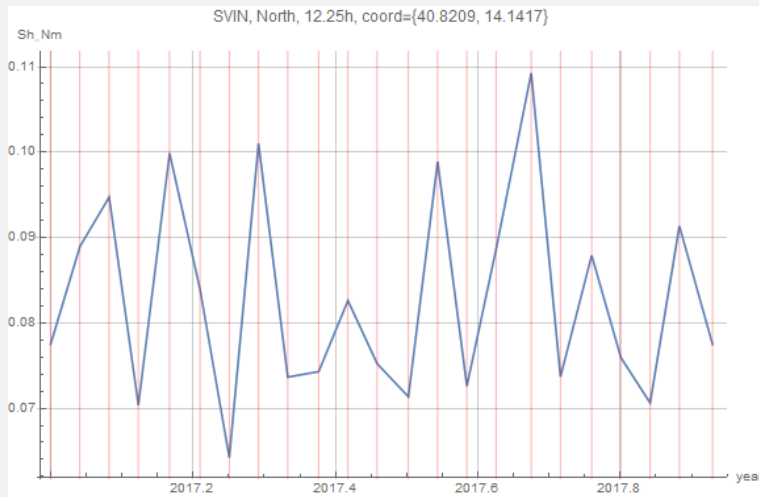
Outputs:

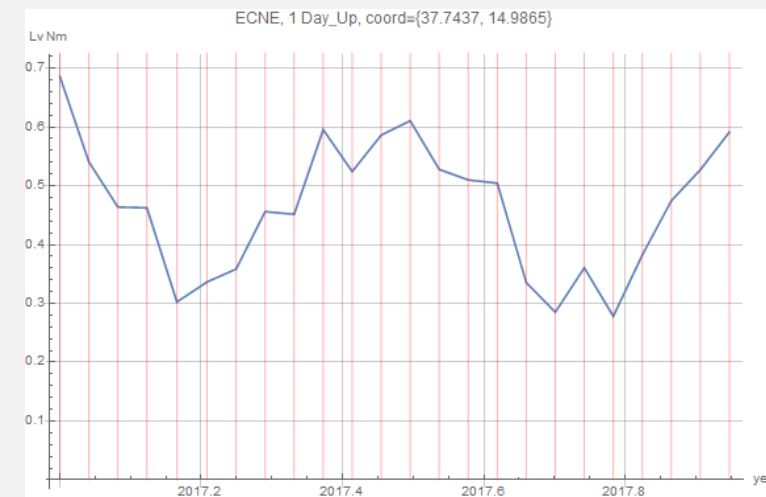
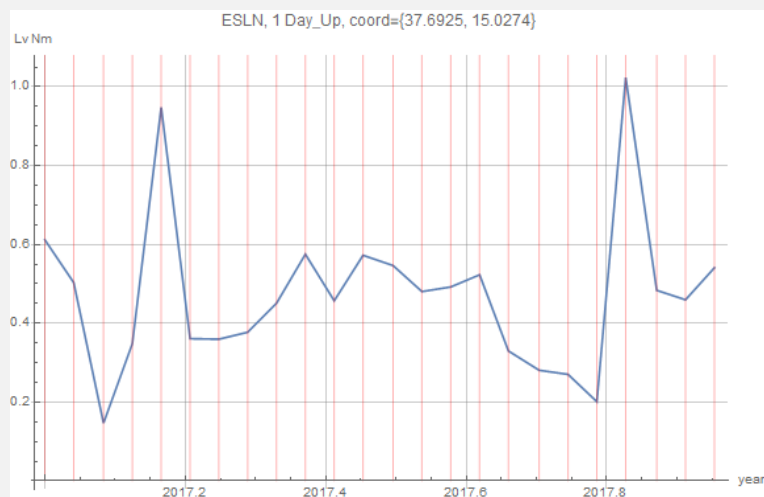
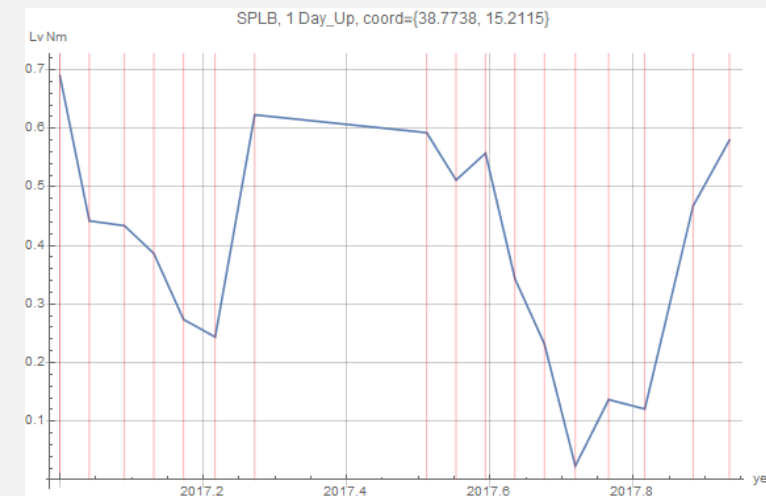
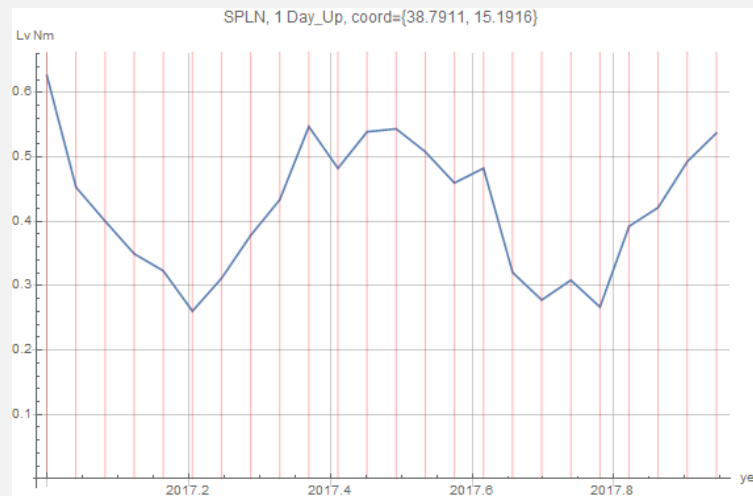
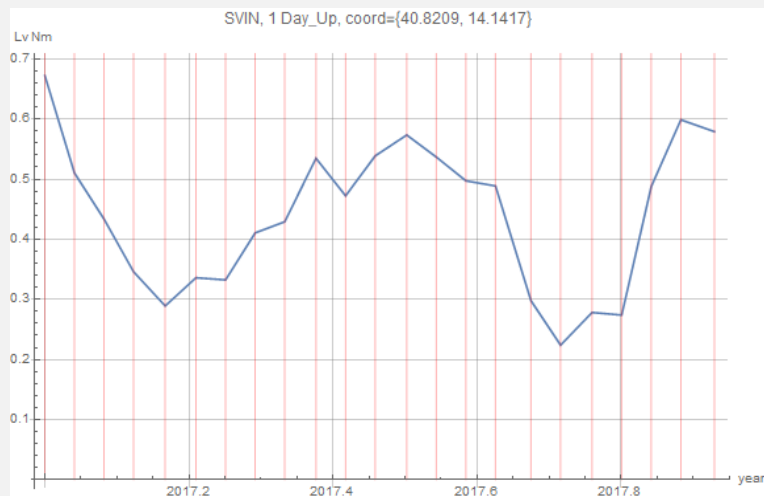
- [DL3] “Geological Analysis Report” including:
- Input Data Description (origin, availability, selection criteria, etc.):
- LSET measurements and models produced with GNSS observations from different GNSS data networks (IGS, EUREF, UNAVCO, etc.) and GNSS receivers provided and deployed or accessible by the Contractor near or in areas with significant geological risk;
- Geophysical data from IERS, EGD1 or USGS, etc. for those GNSS stations;
- Correlation analysis and results;
- Preliminary conclusions about the possible use for risk assessment of LSET measured or predicted variables correlated with identified geological events.

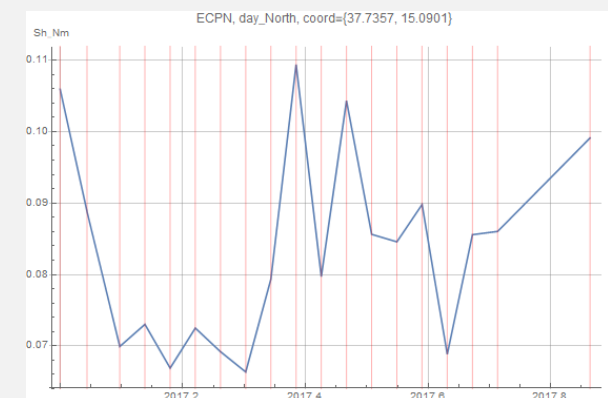
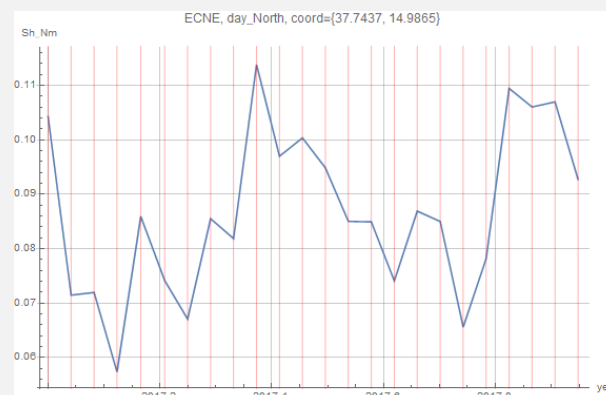
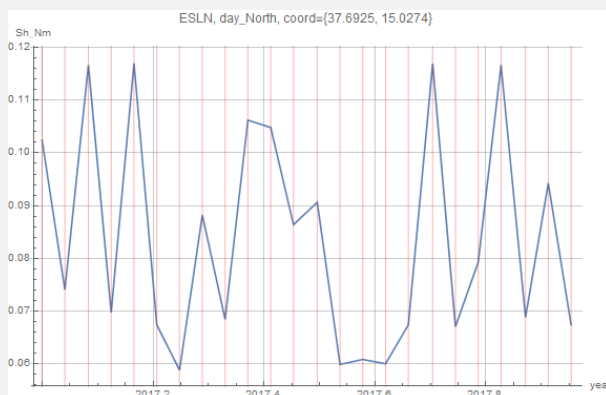
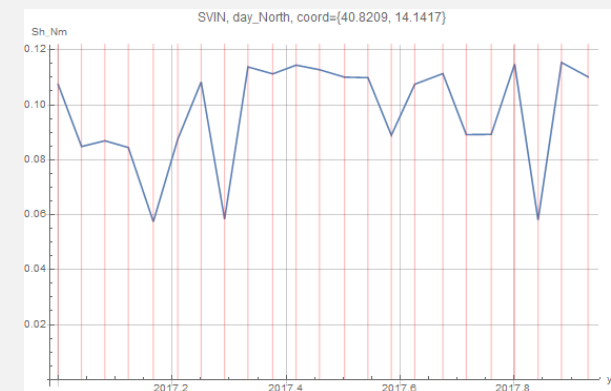
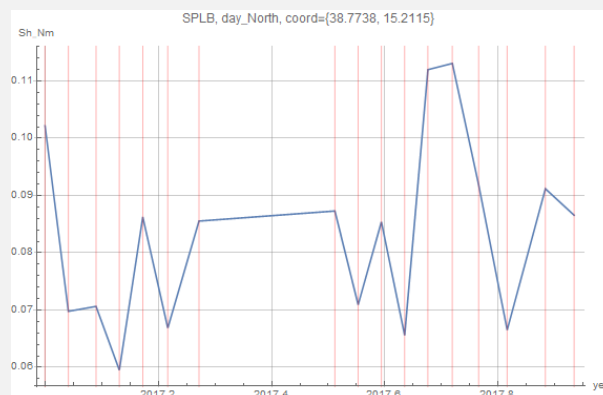
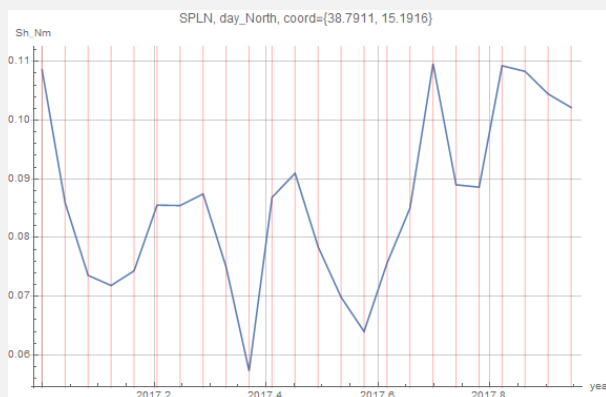
- For Tectonics & Earthquakes:
 - Global network with a sampling rate of 1 day with LPT switched off and SPT switched on (Should reduce the noise level)
 - Regional network with a sampling rate of 3H with all the Tides model Switched off
- For Volcanoes
 - Regional network with a sampling rate of 3H. Time span as long as possible (more than a couple of years at least). Tides model Switched Off

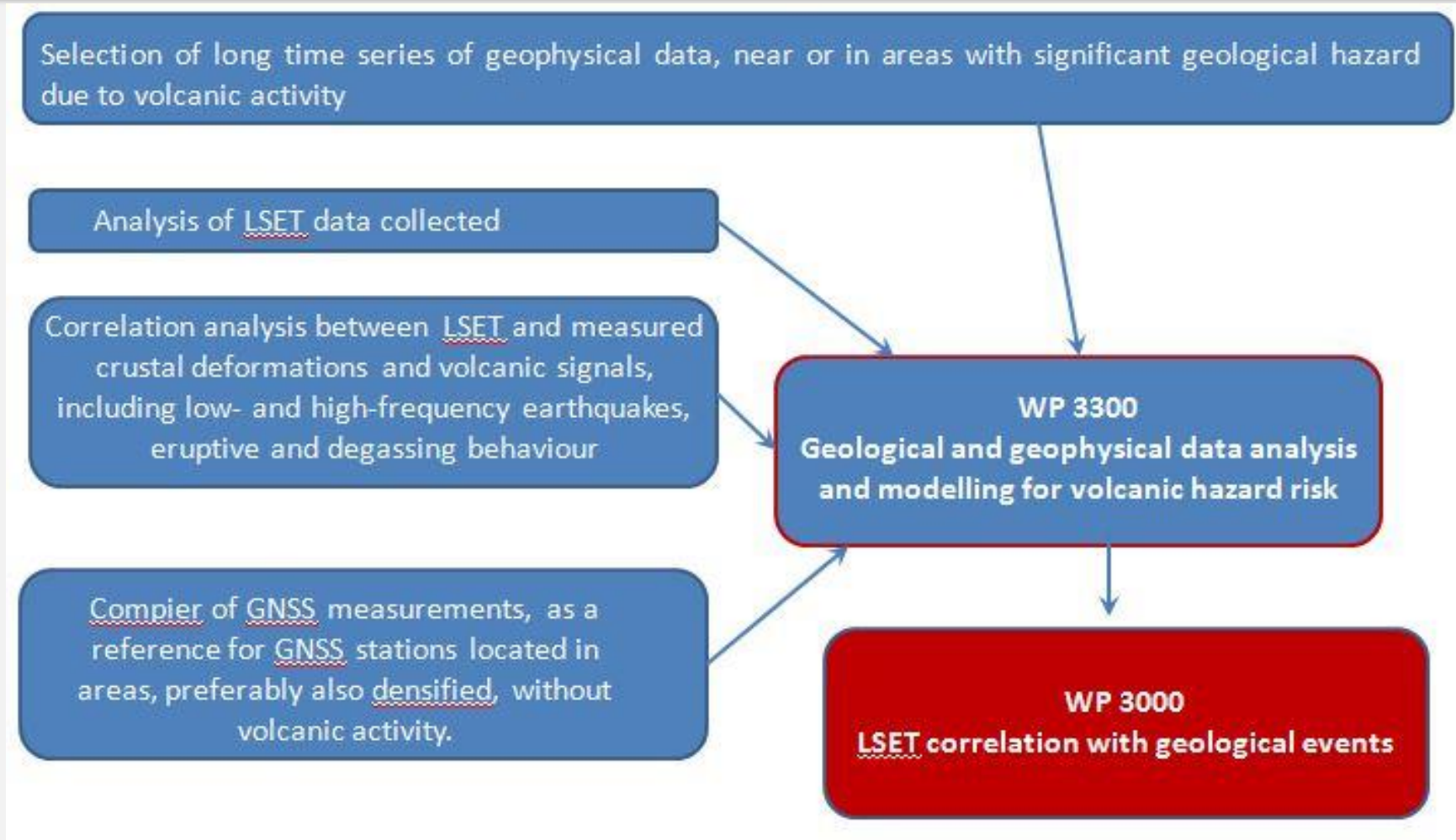
M2 Love Numbers of Etna & Stromboli Stations











Selection of long time series of geophysical data, near or in areas with significant geological hazard risk due to volcanic activity

Most of volcanoes influenced by tidal stresses share some common relevant features:

- The repeated refilling of a volatile-saturated magma in a **shallow reservoir**,
- The ongoing large-scale (Mm^3) **volcano flank deformations**,
- The **low-viscosity** (basalt) feeder magma (with a few notable exceptions),
- The tidal modulation of geophysical signals during **open vent activity** and/or frequent **unrest phases**.

Further criteria for the selection of case studies:

- Areas with significant volcanic hazard
- Complete and reliable data sets
- Volcanoes with recent and frequent volcanic activity

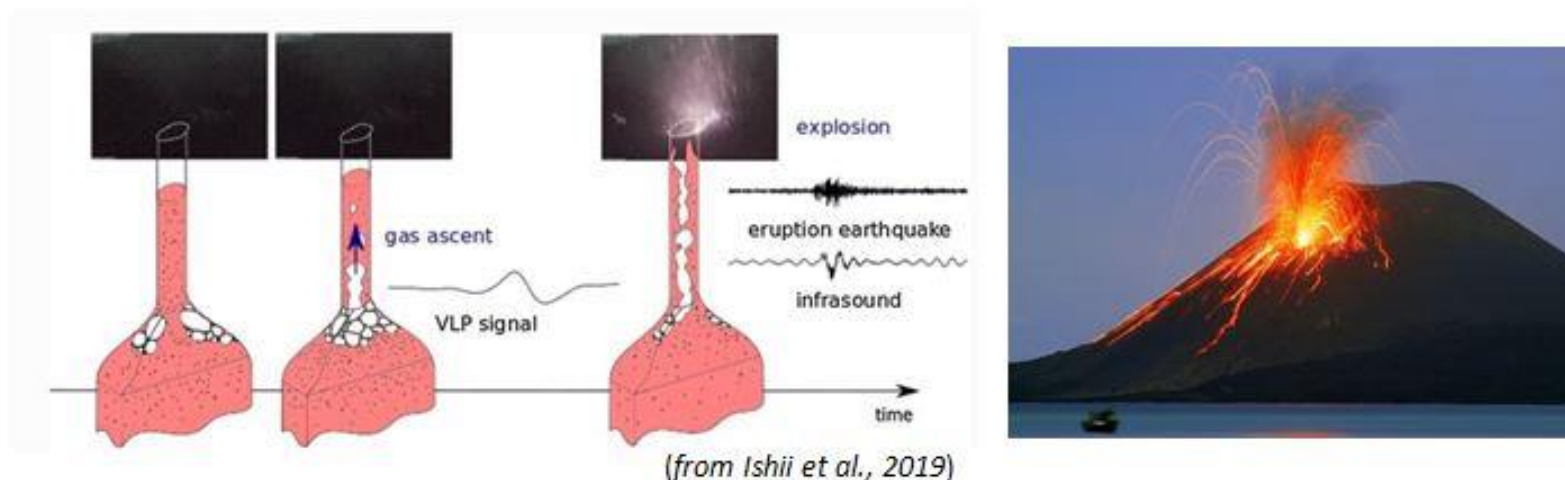


*images sources: personal archive, and INGV

Selection of long time series of geophysical data, near or in areas with significant geological hazard risk due to volcanic activity

The Stromboli study case:

Stromboli is an open conduit volcanic systems with persistent explosive activity (hundreds of weak explosions per day)



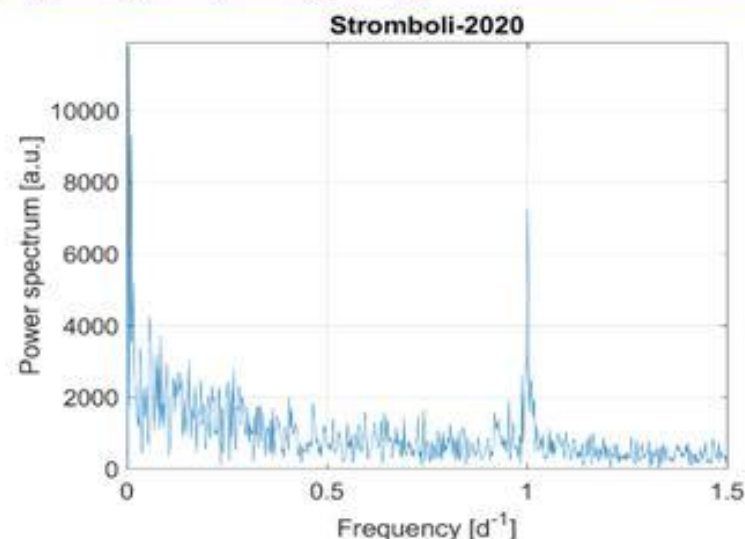
Very Long Period (VLP) are signals **related to explosive volcanic** activity mostly concentrated in the 0.05-0.5 Hz frequency band.

The position of the VLP seismic source indicates the elevation changes (depths) of the **magma free surface**. Stromboli volcano is affected by relevant phenomena of flank instabilities.

Correlation analysis between LSET and measured crustal deformations and volcanic signals, including low- and high-frequency earthquakes, eruptive and degassing behaviour

FREQUENCY- AND TIME-DOMAIN ANALYSIS

λ_1 λ_2 λ_3 λ_4 λ_5 (recurrence times among VLP signals)



VLP signals provide a **high temporal resolution** dataset from INGV Seismic Monitoring Network (EOLO) and represent a fundamental clue to investigate the effects of **short-period tidal stresses** (e.g. ter- semi- and quasi-diurnal components).

Correlation analysis between LSET and measured crustal deformations and volcanic signals, including low- and high-frequency earthquakes, eruptive and degassing behaviour

FREQUENCY- AND TIME-DOMAIN ANALYSIS

The effects of tidal stresses at Stromboli:

Fortnightly tidal modulation of VLP, with peaks of activity aligned with the synodic month (*Johnston and Mauk, 1972; Sottili and Palladino 2012*).

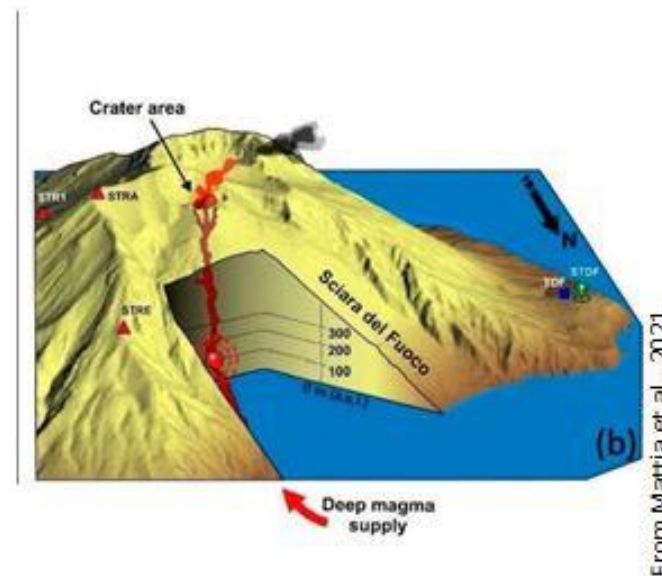
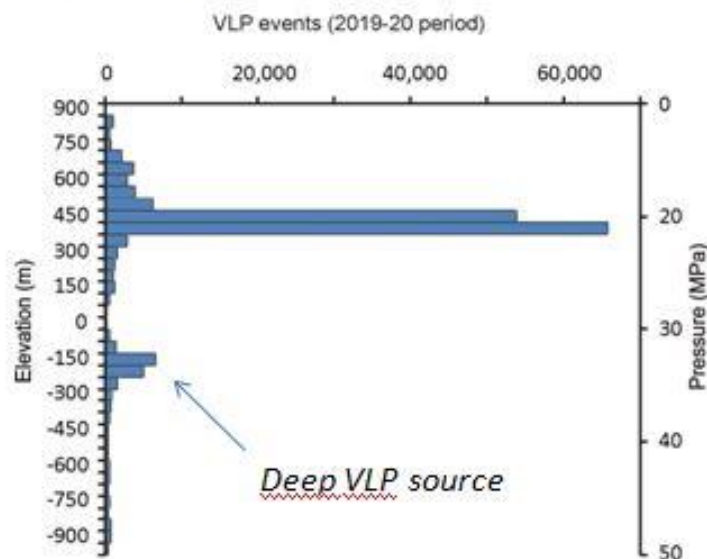
- Fortnightly periodicity for ^{222}Rn degassing rates (*Cirolini et al., 2009*) and quasi-diurnal modulation of H_2 degassing (*Di Martino et al., 2021*)

A very simple and (apparently) basic question:

Which parts of the volcanic system (shallow vs. deep) respond to external forcing?

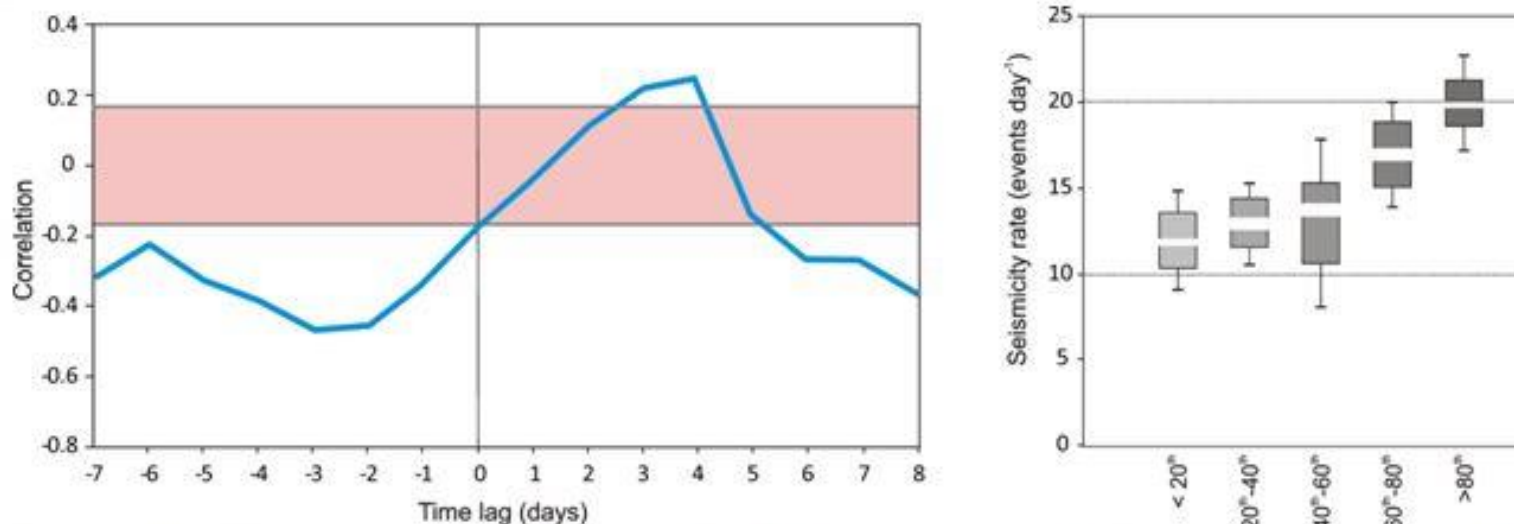
Correlation analysis between LSET and measured crustal deformations and volcanic signals, including low- and high-frequency earthquakes, eruptive and degassing behaviour

Which parts of the volcanic system (shallow vs. deep) respond to tidal forcing?



Correlation analysis between LSET and measured crustal deformations and volcanic signals, including low- and high-frequency earthquakes, eruptive and degassing behaviour

VLP rates vs. Shiva number (quasi-diurnal East component): Stromboli 2019 eruptive period



(Left) Correlation coefficient between Shiva number (quasi-diurnal East component) and VLP (events per hour) as a function of the time lag. The lag is reckoned as negative when Shiva number variations precede the VLP events. The pink band represents the 96.5% confidence interval as determined from 10^5 Monte Carlo simulations.

(Right) Boxplots of VLP values corresponding to five percentile classes of Love number. The bottom and top of the boxes correspond to first and third quartiles, respectively. The bottom and top whiskers represent the minimum and maximum values, respectively. The white, horizontal line is the median.

Selection of long time series of geophysical data, near or in areas with significant geological hazard risk due to volcanic activity

The Mount Etna study case:

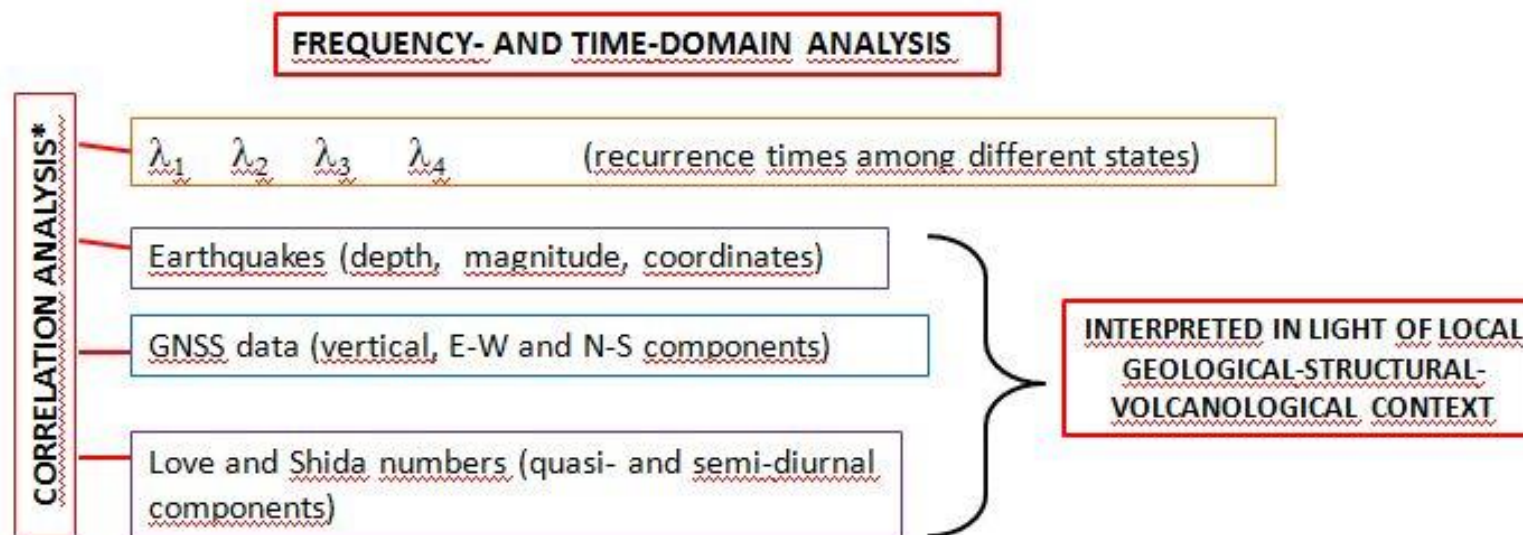
Mount Etna, one of the most active volcanoes in the world, is known for its spectacular effusive activity; however, violent Strombolian activity characterised recent eruptive periods from 1989 to present.

At least one plinian and 24 subplinian eruptions occurred in the last 13 kyr.

The structural setting of Mount Etna is characterised by an eastward sliding of the eastern volcano flank, which is possibly attributed to ongoing gravitational spreading concomitant to repeated refilling of shallow magma reservoirs [e.g., Borgia et al., 1992; Rollin et al., 2000; Tibaldi and Groppelli, 2002].



Correlation analysis between LSET and measured crustal deformations and volcanic signals, including low- and high-frequency earthquakes, eruptive and degassing behaviour

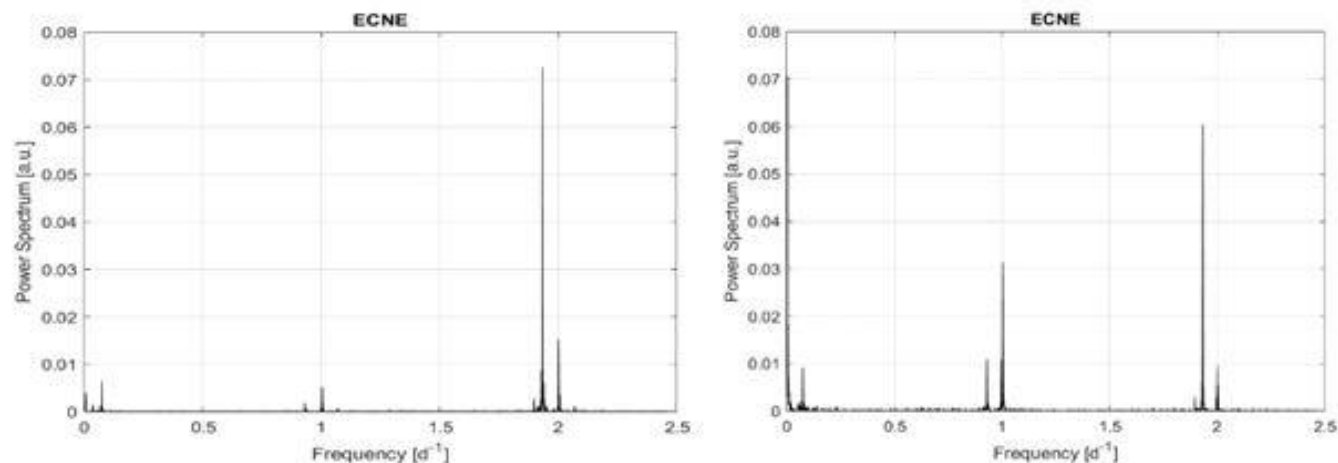


Conceptual workflow for the correlation analysis at Mount Etna (2015 to present activity)

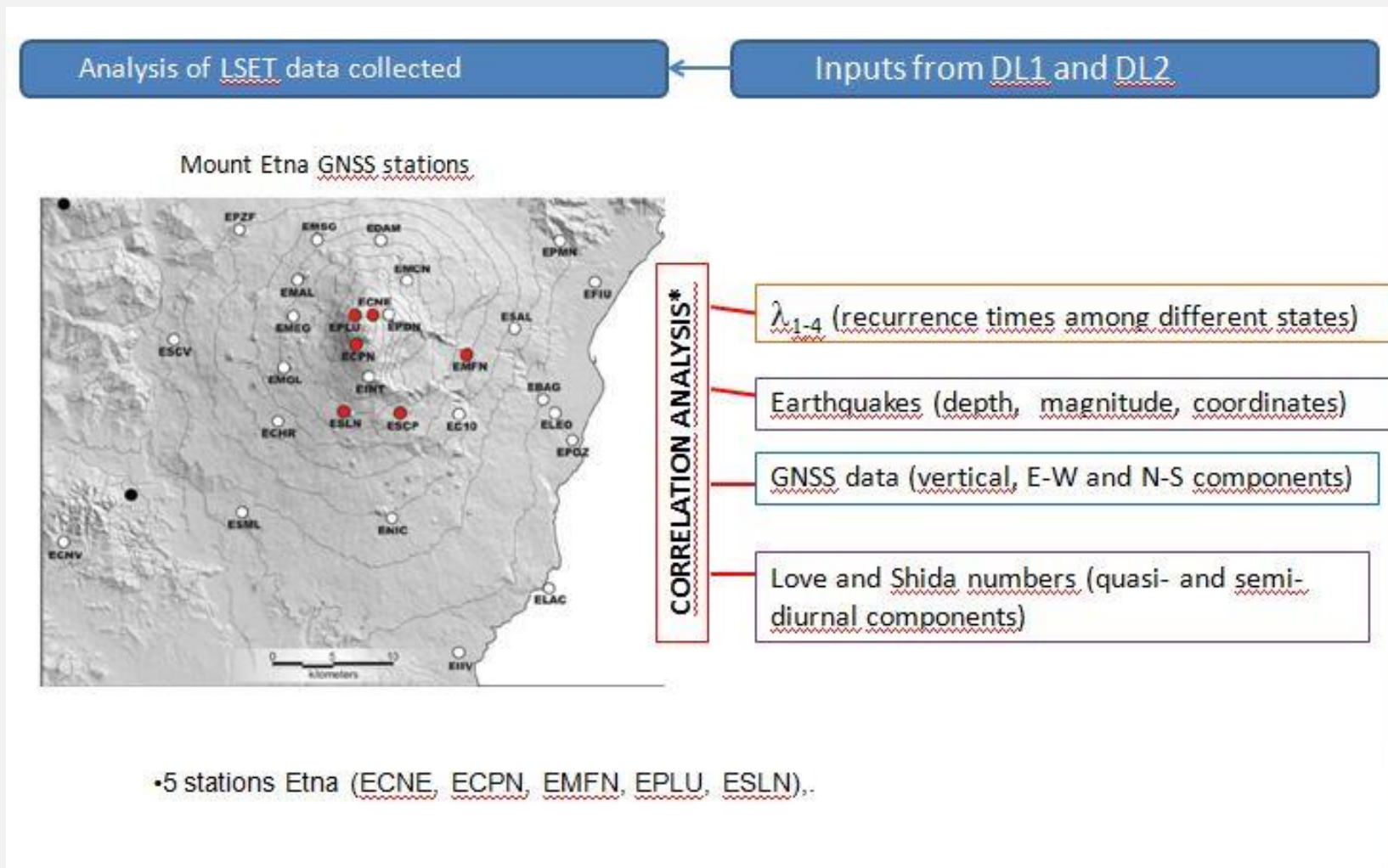
Correlation analysis between LSET and measured crustal deformations and volcanic signals, including low- and high-frequency earthquakes, eruptive and degassing behaviour

FREQUENCY- AND TIME-DOMAIN ANALYSIS

GNSS data (vertical, E-W and N-S components) at 5 stations Etna (ECNE, ECPN, EMFN, EPLU, ESLN),

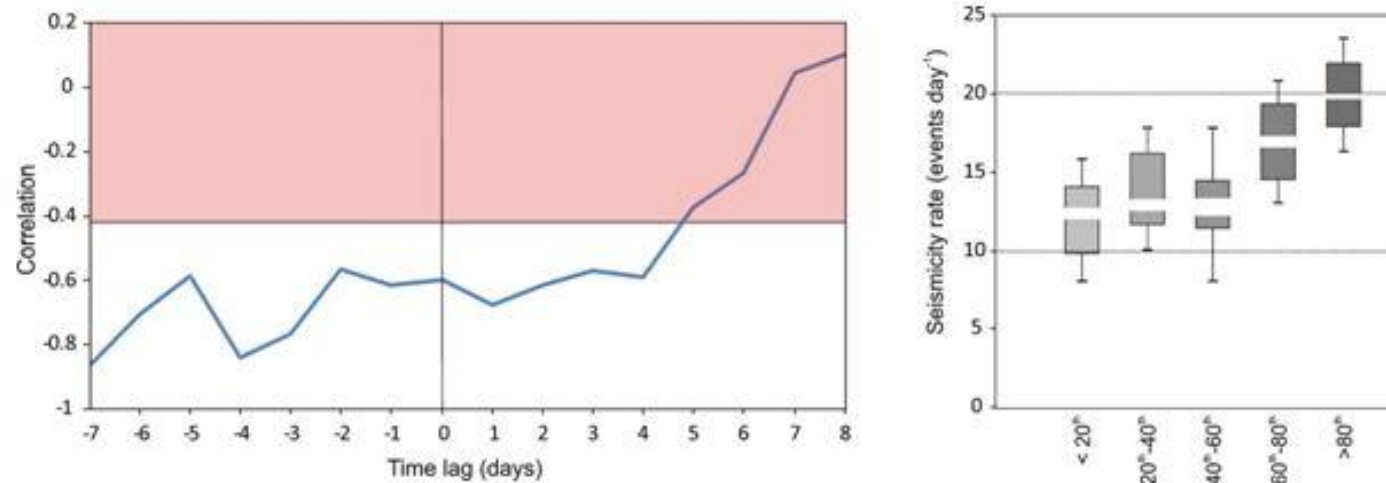


Examples of spectra of GNSS displacements measured at the ECNE (ETNA) station (North, and Up components of GNSS sample)



Correlation analysis between LSET and measured crustal deformations and volcanic signals, including low- and high-frequency earthquakes, eruptive and degassing behaviour

Seismicity rates vs. Love numbers (semi-diurnal components): the 2017 sequence at Mount Etna



(Left) Correlation coefficient between Love number (semi-diurnal component) and seismicity rates (events per day) as a function of the time lag. The lag is reckoned as negative when Love number variations precede the seismic events. The pink band represents the 96.5% confidence interval as determined from 10^5 Monte Carlo simulations.

(Right) Boxplots of seismicity rates values corresponding to five percentile classes of Love number. The bottom and top of the boxes correspond to first and third quartiles, respectively. The bottom and top whiskers represent the minimum and maximum values, respectively. The white, horizontal line is the median.

Evidence from Stromboli and Mount Etna

- the eruptive system of Stromboli during open-vent phase of activity, shows a clear quasi-diurnal modulation of VLP signals. The modulation of “deep” VLP signals suggest that the portions of the volatile saturated magma reservoir can be extremely sensitive to small pressure perturbations. The frequency of VLP is associated to –and preceded by– a statistically significant negative relationship with Love and Shida numbers.
- The stress release during unrest phases at Mount Etna (i.e., volcanic period characterised by magma recharge, crustal deformations and seismicity) suggests an influence of the tidal semi-diurnal and quasi-diurnal stresses on the geophysical signals. Specifically, the seismicity rates during the 2017 show a statistically significant correlation with changes in Love and Shida numbers. Also, significant variations in Love numbers have been also observed during phases of intense deformations (magma upraise just before the onset of eruptive episodes).

- Global network with a sampling rate of 1 day with LPT switched off and SPT on (Should reduce the noise level) has been used as well
- Global Network with a sampling rate of 3 hours with Tides switched off to estimate SPT K1 and M2
- ***The processing confirm a correlation between Love Numbers of LPT (half year, monthly and 13.66 days) and T.E. latitudes;***
- There is no correlation with K1 and M2 SPT and T.E. On the contrary M2 decrease close to TE
- The values of Love M2 are meaningful different from IERS nominal values: smaller than 15%
- For almost the stations the trend of M2 increases with time; while those of K1 slightly decreases
- The values of K1 are very close to nominal values
- ***The anomaly why Love M2 Nbrs have this strange behaviour has to be fully investigated***
- ***The behaviour of LPT against the latitudes needs to be confirmed using many more global stations***

- We have selected about 50 EQ events close (<200 Km) to global stations
- The selected EQs have been classified as compressive or extensive in the range 6.-7.5 of Richter magnitude. Range where the relationship with tides is expected to be still strong;
- For each stations a stack of M2 and K1 Love Nrs one year long, centered around the EQ event, have been estimated. Love nrs have been estimated every 15 days using the GNSS data with a sampling rate of 3H
- ***For each EQ event the anomalies in the behaviour of Love has been detected around the EQ occurrence.***
- ***It seems that such anomalies don't depend from the type of EQ.***

- **Almost the events seem to be got ahead by a downfall of L-N!**
- **It seems that the increasing of the rigidity of crust/mantle could play a major role (i.e. low values of Love Nrs)**
- **Particularly meaningful is l'Aquila EQ the epicenter of which was far 12 Km only from the GNSS station**
- **The approach, after a more refined tuning, has to be applied to many other cases very similar to l'Aquila (epicenter far from GNSS stations only few km)**
- **The topic is worthwhile to be faced applying A.I. machine learning approach (Unsupervised) because they can depend on other local information and , in particular, the degree of rigidity of the crust/mantle**
- **The last GNSS solutions achieved in Kinematic mode with high sampling rate (30 sec) has not been still processed but they will be very helpful to improve the quality and frequency resolution of daily and subdaily tidal constituents analysis;**
- **Definition of a very dense GNSS global network to provide a series of EQ precursors: TEC, ZTD, Strain Rate and L-S numbers evolution could be a global service to launch**

Do we open the Pandora pot ?

