Free Core Nutation parameters from hydrostatic long-base tiltmeter records collected at Sainte-Croix aux Mines (Alsace-Eastern France)

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Sainte-Croix-aux- Mines Tiltmetric station
(in the Vosges Mountains, Eastern France)

48.27°N
7.24°E

Two 100 m long hydrostatic tiltmeters
- N37°E direction
- N120°E direction

The 160 m high rock covering ensures the environment is very stable (temperature variations are around 10^{-1} °C over the year)

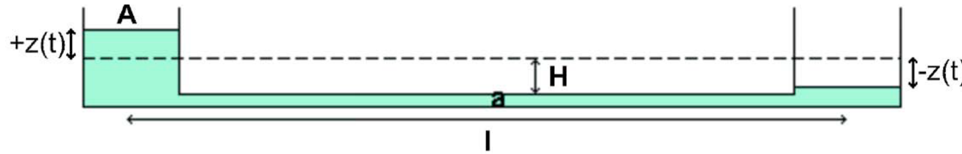
Installation Site

The instruments are installed in 2 orthogonal branches of an ancient silver mine, in a gneissic context.
A well-known fracture system intersects the hill quasi-orthogonal to the N37E instrument
(Longuevergne et al., 2009).

The measurement principle (the hydrostatic leveling):

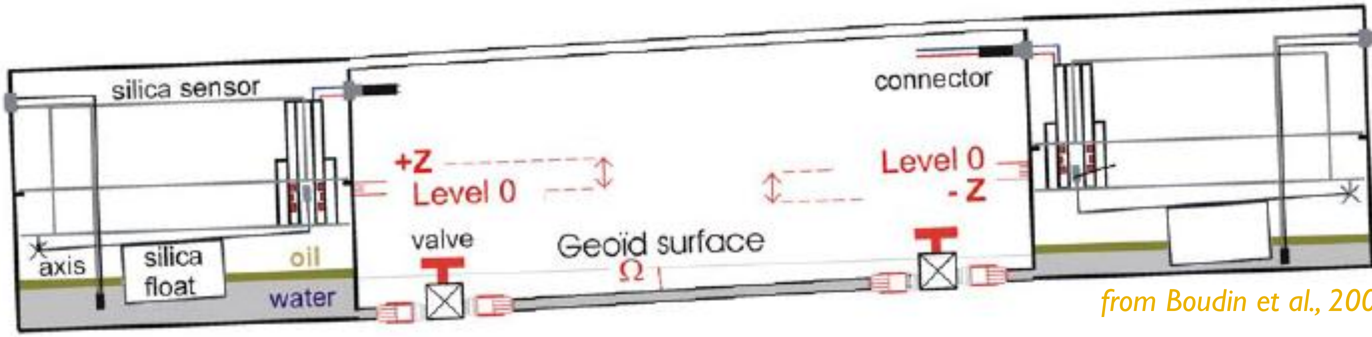
Two vessels linked by a pipe and filled with liquid.

A tilt deformation induces liquid transfer from one pot to the other one and therefore **liquid height variations (z_l, z_2)** (positive in a pot and negative in the other).



Sensoring/transducers devices:

Water level variations (z_l, z_2) are measured by silica **floats** attached to a **Linear Variable Differential Transformer** (**LVDT**) displacement sensor.



from Boudin et al., 2008

Tilt

$$\Omega \approx \tan\Omega = \frac{z_1 + z_2}{l}$$

Tilt Uncertainty

$$d\Omega \approx \frac{|dz_1| + d|z_2|}{l}$$

(Assuming no uncertainty on *l*)

where *l* is the distance between the vessels (≈100m).

A somewhat general rule: the longer the tiltmeter is, higher the sensitivity.

FCN or NDFW

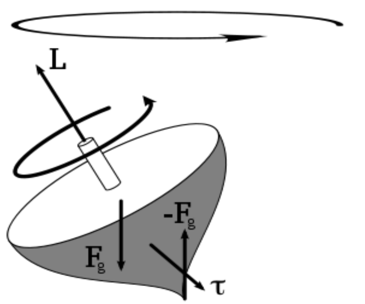
Since the Earth rotates about an axis that slightly departs (≈ 0.7 μrad) from its axis of symmetry (or greatest moment of inertia), the planet undergoes a gyroscopic torque inducing a **"Free"** Eulerian precession.

Accounting just for these rotational irregularities

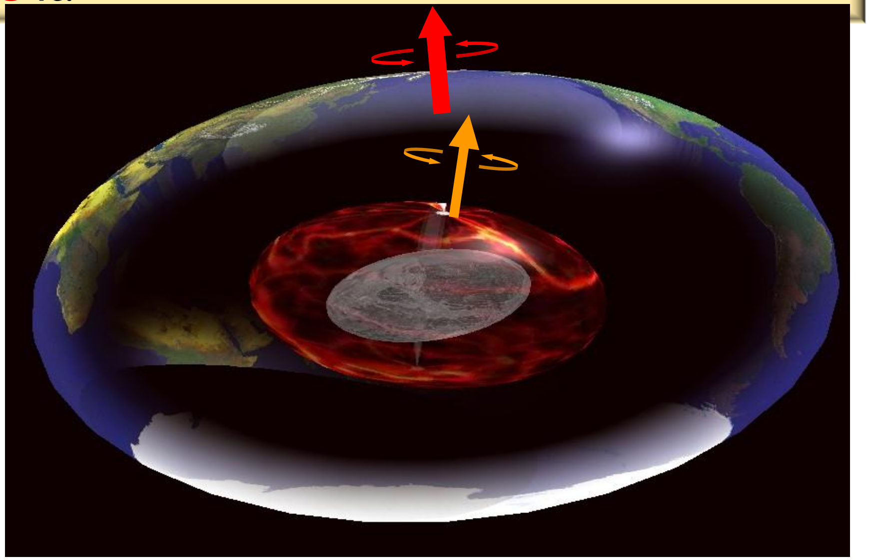
In principle no gravitational interaction with any other external body… so, strictly speaking, it is not a "nutation" (as the 18.6 years).

That's why we rather use "**Chandler Wobble**" or "**Free Nutation**"

Indeed a luni-solar tidal forcing on this phenomenon exists inducing resonance… and fortunately enabling us **to observe** it!

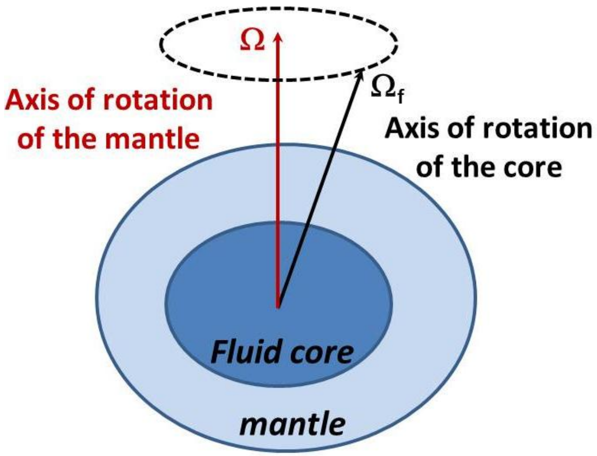


"Torque-induced" precession.



Nearly Diurnal Free Wobble

The mechanism in the Earth's interior:
Because of the slight ellipticity of the **CMB**, the misalignment of the instantaneous rotation axes of the **Mantle** and **Core** enables the pressure of the fluid outer core to exert a restoring torque on the mantle.



Free Core Nutation
T = -430 days; Q ≈ 20000
(inertial frame)

Nearly Diurnal Free Wobble
(terrestrial rotating frame)

FCN parameters from geophysical observations

What we can observe?

Resonance effects on:

1) **The forced nutations of the Earth's figure axis observable by** Very Long Baseline Interferometry (**VLBI**) network measurements

2) **Luni-solar tidal forcing of the Earth at diurnal periods observable by** whatever timeseries,

but the most accurate currently available are:

The diurnal tidal waves from tidal analysis of (P1,K1, **PSI1** and PHI1)

- **Gravity records by superconducting gravimeters (SG)**
- **Tilt records by high sensitivity long-base tiltmeters**

The FCN resonance as seen by tiltmetry

Resonance strength:transfer function through the mantle[1]

For tilt a<0; $\gamma_{obs} < \gamma_{ref}$

$$\tilde{\gamma}_{obs}(\sigma) = \tilde{\gamma}_{ref} + \frac{\tilde{a}}{\tilde{\sigma} - \tilde{\sigma}_{nd}} + loadings + \tilde{\varepsilon} + "strain - tilt"$$

Reference gamma factor (without resonance)

Tidal frequency

«Near-diurnal» resonance frequency

Errors of calibration, tidal analysis errors, ocean loading errors…

$$\tilde{\sigma}_{nd} = \sigma_{nd}^{R} + i\sigma_{nd}^{I}$$

$$Q = \frac{\sigma_{nd}^{R}}{2\sigma_{nd}^{I}} > 0$$

$$T_{bf} = \frac{2\pi}{\sigma_{nd}^{R}}$$ In a terrestrial rotating frame

$$T_{in} = \frac{1}{k\sigma_{nd}^{R} - 1}$$ In the inertial frame

Where, $k = 86164/86400/15$;

and σ in degree/hour

[1](Legros et al., 1993; Mathews et al., 2002)

FCN parameters retrieval (1)

FCN resonance (in tilt, as in gravity data)

Representable by a **damped harmonic oscillator model** that we **invert** in order to determine the FCN **period**, quality factor **Q** and the transfer function of the mantle (or the **resonance strength**)

Non-linear inverse problem

- **Levenberg-Marquardt optimization method** for non-linear L-S inversion (**Gaussian assumption**)
- **Bayesian approach** (**not exclusively Gaussian assumption**)

As the statistical distribution of Q is not Gaussian (Florsch & Hinderer, 2000)

Details on the Bayesian approach can be found in Rosat et al., (2009) J.Geodyn. 48:331-339; doi:10.1016/j.jog.2009.09.027

FCN parameters retrieval (2)

from tidal analysis of surface data (gravity and tilt)

Main difficulties

1) Weak amplitude of PSI1 tidal wave (the closest to FCN) on the Earth

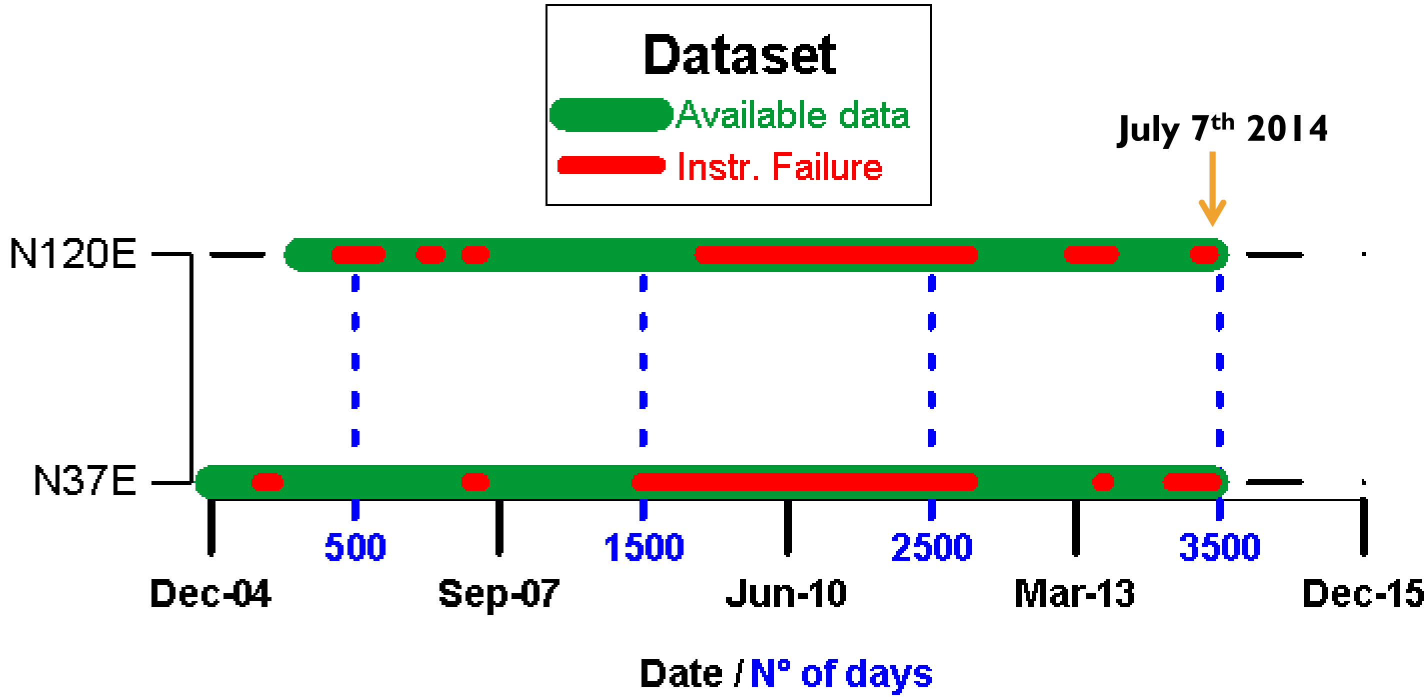
2) Closeness in frequency of the single constituents of the diurnal tidal band (**P1, K1, PSI1 and PHI1**)

Long (> 1 year) and "accurate" records as well as
Well calibrated, high sensitivity /stable instruments are needed !

The FCN quality factor (Q) is constrained by the imaginary part of the diurnal tidal factors (Rosat et al., 2009). However, the imaginary parts of the tidal δ & γ factors are poorly determined, especially for the small amplitude PSI1 and PHI1

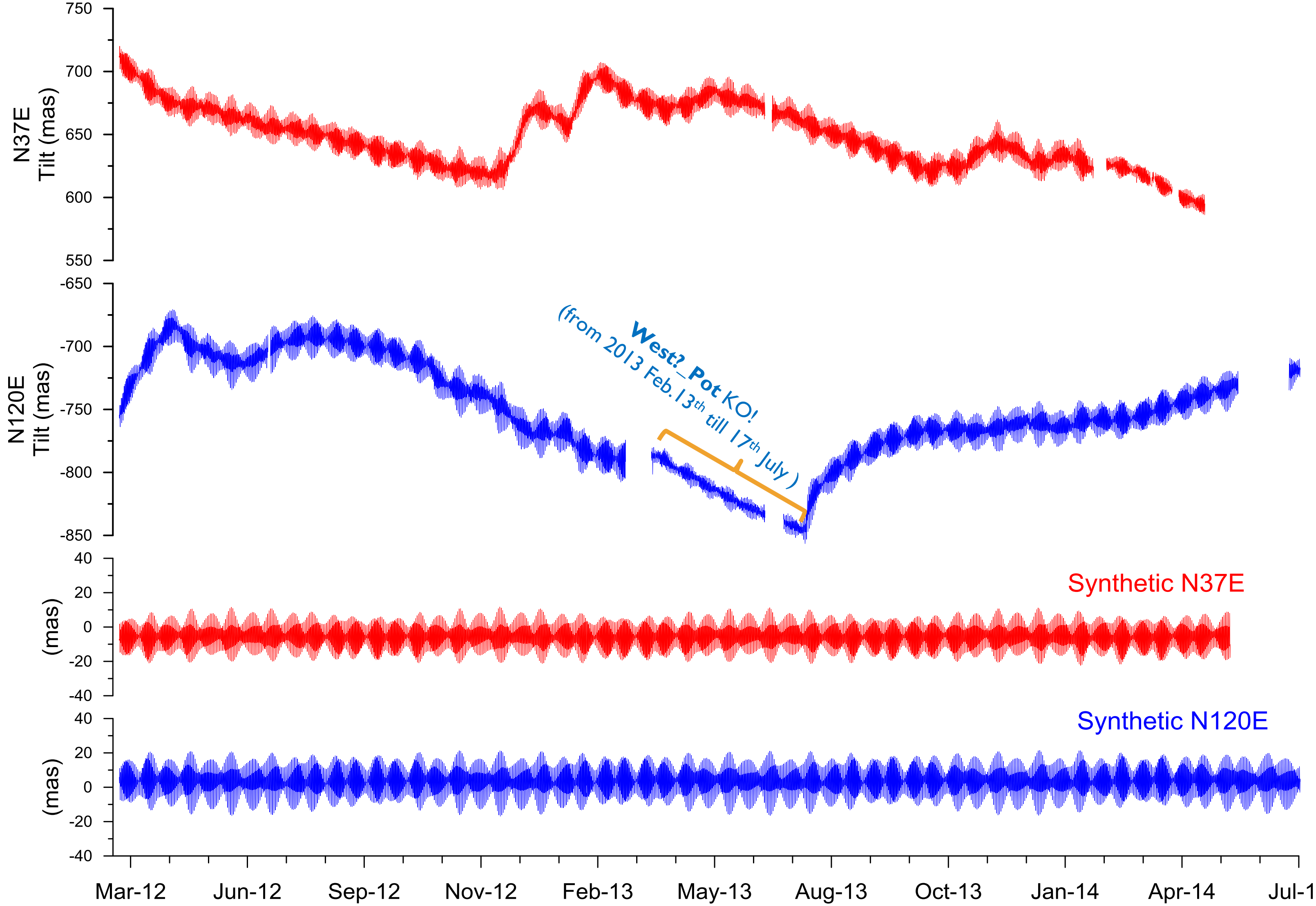
Inaccuracy of the available Ocean Loading correction

Important for near-coast sites

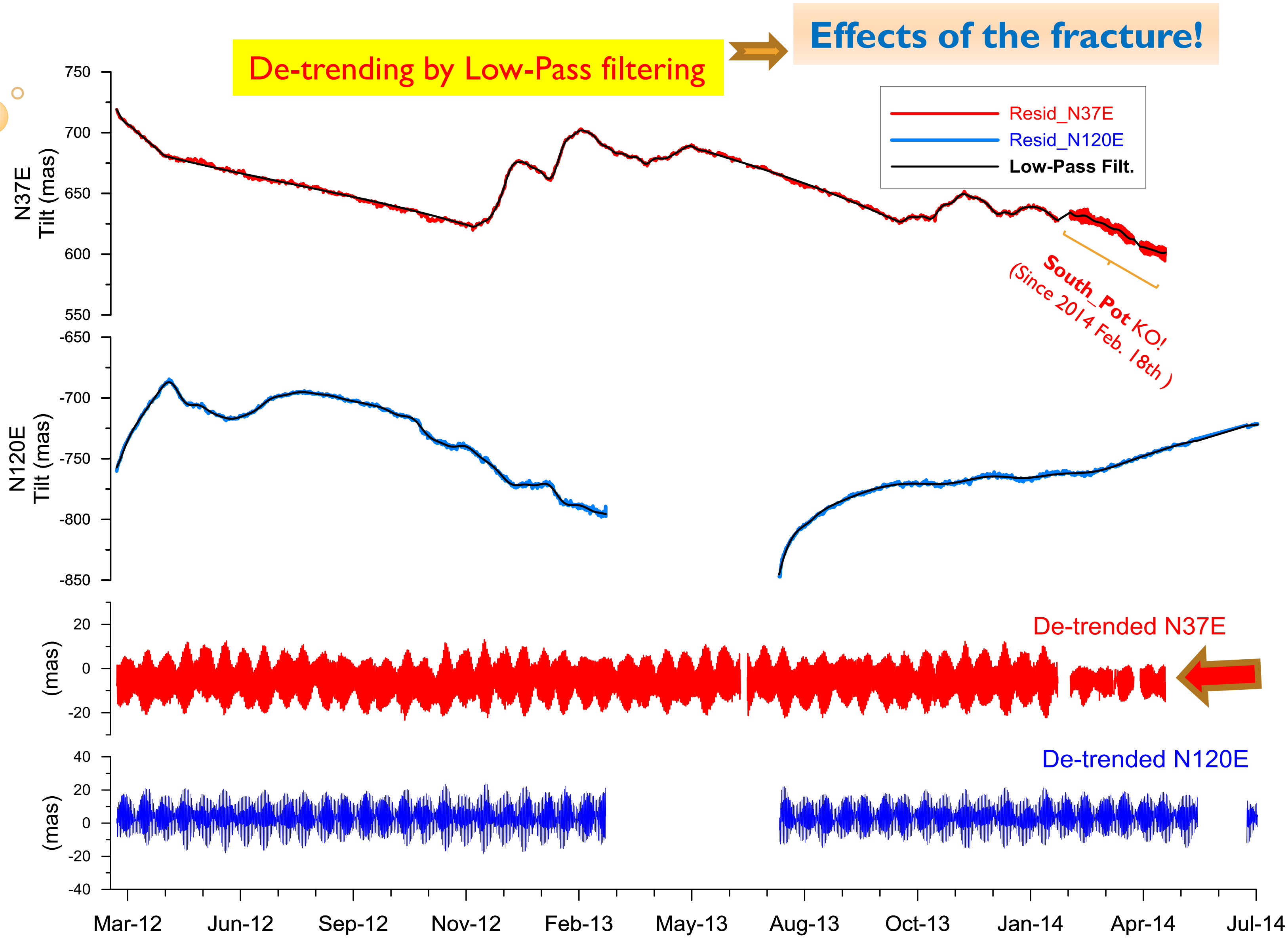


Tiltmeter	Installation date	Spanning days (07/07/2014)	Net Recorded days
N37E	Dec.20th 2004	3485	2102
N120E	Nov.11st 2005	3191	1807

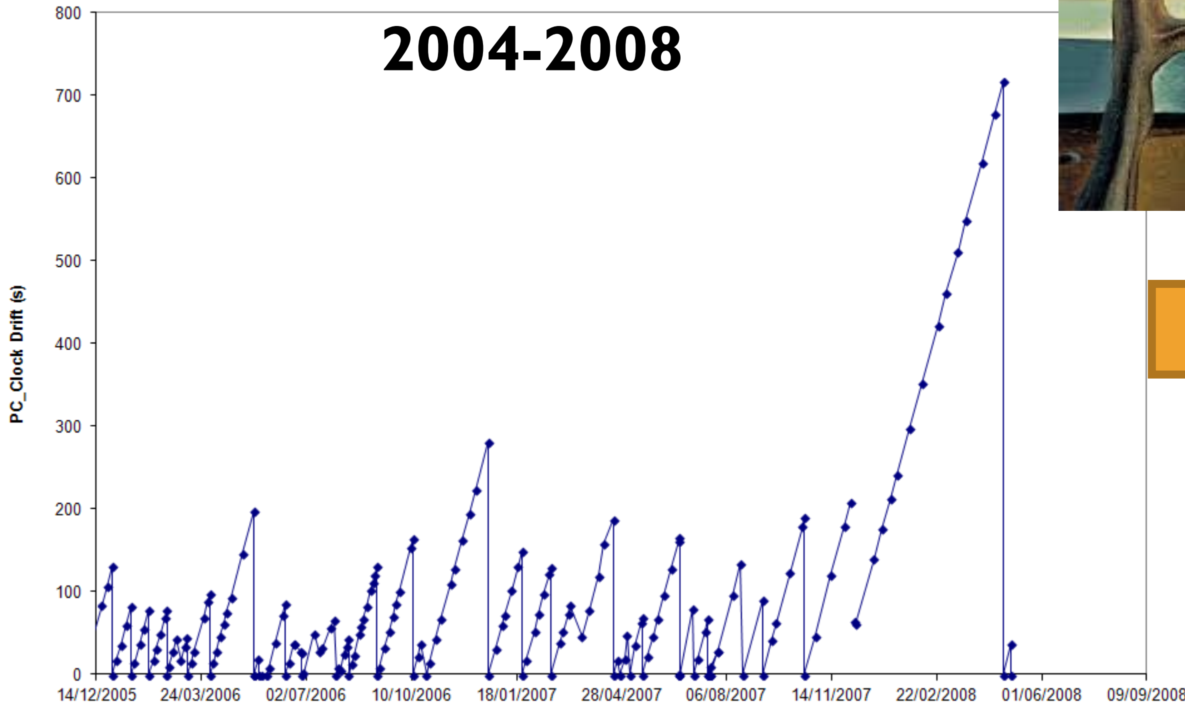
Sample Records
2012-2014



Tilt Residuals



DAS' Clock Drift 2004-2008

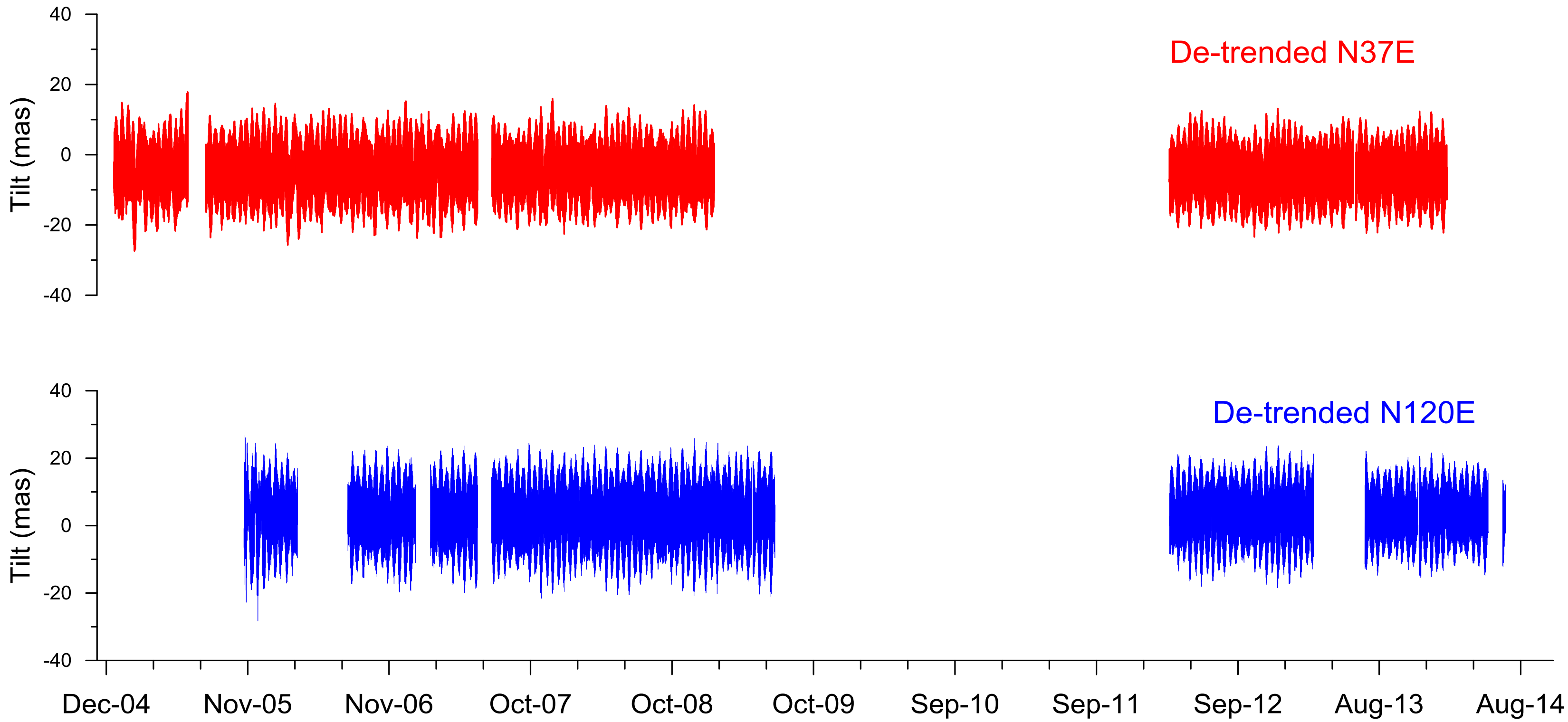


Accuracy of phases?

Data pre-processing (to prepare for tidal analysis)

- Rejected bad records (Malfunctioning of a pot/sensor): Tilt are differential!!!
- Raw data have been corrected for gaps, spikes and steps
- Correction of the Clock drifting in 2004-2008 records
- Data decimation to 1h samples

The Net Recorded Days



from [cpd]	to [cpd]	wave	[mas]	γ.fac.	stdv.	Ph.Lead [deg]	stdv. [deg]
0.000146	0.003426	SA	0.6756	0.07437	53.53278	54.4418	*********
0.004709	0.010952	SSA	0.7496	0.58963	1.25479	2.1978	120.4206
0.025811	0.031745	MSM	0.1627	0.97289	1.03756	0.9268	61.0149
0.033406	0.044653	MM	0.8511	0.71742	0.17337	-24.9564	13.7916
0.060131	0.068640	MSF	0.1412	0.48680	0.52159	54.2794	61.4030
0.069845	0.080798	MF	1.6113	0.68281	0.03436	-2.8926	2.8954
0.096422	0.104932	MSTM	0.0586	1.96203	0.65409	11.9610	19.1248
0.106136	0.115412	MTM	0.3085	0.70594	0.11950	-4.3629	9.7307
0.130192	0.143814	MSQM	0.0493	0.64563	0.57983	21.1727	51.4222
0.145166	0.249952	MQM	0.0408	0.46286	0.64234	-36.7100	79.4791
0.721499	0.833113	SGQ1	0.0220	0.85203	0.21611	-24.3969	14.5287
0.851181	0.859691	2Q1	0.0755	0.57699	0.07033	-6.3131	6.9836
0.860895	0.870024	SGM1	0.0911	0.58483	0.06066	-13.2610	5.9422
0.887326	0.896130	Q1	0.5709	0.61392	0.00960	-2.7442	0.8959
0.897806	0.906316	RO1	0.1084	0.62465	0.05086	-7.5838	4.6658
0.921940	0.930450	O1	2.9816	0.68246	0.00189	-0.7468	0.1583
0.931963	0.940488	TAU1	0.0389	0.61077	0.16468	-22.5465	15.4467
0.958085	0.966757	NO1	0.2344	0.71473	0.02586	-4.7423	2.0731
0.968564	0.974189	CHI1	0.0448	0.61252	0.12469	-1.5771	11.6629
0.989048	0.995144	PI1	0.0811	0.79859	0.07594	-6.3744	5.4484
0.996967	0.998029	P1	1.3871	0.75532	0.00445	-4.0834	0.3378
0.999852	1.000148	S1	0.0328	1.45439	0.27300	77.6810	10.7583
1.001824	1.003652	K1	4.1914	0.78567	0.00140	-4.7212	0.1018
1.005328	1.005624	PSI1	0.0328	0.49507	0.18340	-3.9700	21.2265
1.007594	1.013690	PHI1	0.0597	0.59461	0.10668	-0.9340	10.2795
1.028549	1.034468	TET1	0.0448	0.82960	0.12717	-9.1115	8.7840
1.036291	1.044801	J1	0.2344	0.73673	0.02586	-5.7157	2.0113
1.064840	1.071084	SO1	0.0389	0.62250	0.14376	7.8242	13.2308
1.072582	1.080945	OO1	0.1282	0.69591	0.03344	-9.4050	2.7534
1.099160	1.216398	NU1	0.0246	0.76735	0.16861	-3.9315	12.5889
1.719380	1.837970	EPS2	0.0658	0.90186	0.05494	-5.4817	3.4907
1.853919	1.862429	2N2	0.2258	0.91023	0.01829	-14.4364	1.1510
1.863633	1.872143	MU2	0.2725	0.88141	0.01509	-11.2962	0.9809
1.888386	1.896749	N2	1.7064	0.86711	0.00243	-18.5042	0.1606
1.897953	1.906463	NU2	0.3241	0.86628	0.01271	-19.3593	0.8408
1.923765	1.942754	M2	8.9120	0.80210	0.00046	-20.6587	0.0331
1.958232	1.963709	LAM2	0.0657	0.69099	0.06265	-25.0128	5.1945
1.965826	1.976927	L2	0.2519	0.68511	0.01305	-19.3551	1.0914
1.991786	1.998288	T2	0.2424	0.63758	0.01680	-15.8107	1.5092
1.999705	2.000767	S2	4.1459	0.68060	0.00098	-17.6958	0.0828
2.002590	2.013690	K2	1.1266	0.70490	0.00311	-18.6875	0.2527
2.031287	2.047391	ETA2	0.0630	0.64264	0.05056	-16.4917	4.5078
2.067578	2.182844	2K2	0.0165	0.67990	0.12438	-30.1150	10.4810
2.753243	2.869714	MN3	0.0320	0.84764	0.04264	-6.7584	2.8823
2.892639	3.081255	M3	0.1167	0.82742	0.01211	-7.0260	0.8386
3.791963	3.937898	M4	0.0014	15.50954	0.63373	31.5786	2.3410

NDFW

N37E Tidal Analysis (ETERNA3.4)

1h sampled Tilt data

Net Recorded days: 2102

Atmospheric Effects

W3, W4: Non-linear tides

N120E Tidal Analysis
(ETERNA3.4)

Net Recorded days: 1807

from [cpd]	to [cpd]	wave	[mas]	γ.fac.	stdv.	Ph.Lead [deg]	stdv. [deg]
0.000146	0.003426	SA	0.4229	0.06478	93.55751	-84.4327	*********
0.004709	0.010952	SSA	0.4692	0.62364	2.03291	-4.9475	185.4313
0.025811	0.031745	MSM	0.1019	0.52240	1.65992	19.1145	181.8013
0.033406	0.044653	MM	0.5329	0.75515	0.26564	-0.4011	20.2257
0.060131	0.068640	MSF	0.0884	1.13708	0.84393	-69.8063	42.6065
0.069845	0.080798	MF	1.0086	0.85174	0.05897	2.2544	3.9678
0.096422	0.104932	MSTM	0.0367	5.02892	1.14413	129.1079	13.0229
0.106136	0.115412	MTM	0.1931	1.23882	0.20197	-22.5509	9.3621
0.130192	0.143814	MSQM	0.0308	3.28678	0.98615	30.4740	17.2172
0.145166	0.249952	MQM	0.0255	2.74225	1.06678	-178.8107	22.3113
0.721499	0.833113	SGQ1	0.0312	0.72049	0.18387	-26.4905	14.6206
0.851181	0.859691	2Q1	0.1070	0.53493	0.06175	-6.9291	6.6128
0.860895	0.870024	SGM1	0.1291	0.61223	0.05043	5.3631	4.7194
0.887326	0.896130	Q1	0.8088	0.65193	0.00816	0.4063	0.7168
0.897806	0.906316	RO1	0.1535	0.67474	0.04214	-0.8927	3.5785
0.921940	0.930450	O1	4.2245	0.68753	0.00155	-1.2212	0.1296
0.931963	0.940488	TAU1	0.0551	0.90742	0.12531	-11.3922	7.9108
0.958085	0.966757	NO1	0.3321	0.71376	0.01846	-5.2834	1.4819
0.968564	0.974189	CHI1	0.0635	0.86980	0.10252	0.4399	6.7533
0.989048	0.995144	PI1	0.1148	0.63690	0.06135	1.3310	5.5180
0.996967	0.998029	P1	1.9653	0.73461	0.00362	-3.6890	0.2824
0.999852	1.000148	S1	0.0464	4.76427	0.22200	-169.1378	2.6695
1.001824	1.003652	K1	5.9389	0.76129	0.00115	-5.3518	0.0866
1.005328	1.005624	PSI1	0.0465	0.71870	0.14980	-8.6708	11.9455
1.007594	1.013690	PHI1	0.0846	0.48867	0.08560	-18.4346	10.0395
1.028549	1.034468	TET1	0.0635	0.71160	0.10322	-3.4857	8.3105
1.036291	1.044801	J1	0.3322	0.71238	0.01894	-6.3412	1.5233
1.064840	1.071084	SO1	0.0551	0.64038	0.11551	1.4628	10.3366
1.072582	1.080945	OO1	0.1817	0.67333	0.02813	-5.9440	2.3940
1.099160	1.216398	NU1	0.0348	0.65279	0.13246	1.0447	11.6285
1.719380	1.837970	EPS2	0.0733	0.85438	0.09128	-0.6739	6.1211
1.853919	1.862429	2N2	0.2514	0.86386	0.03021	-4.7872	2.0041
1.863633	1.872143	MU2	0.3034	0.92910	0.02506	-8.0887	1.5456
1.888386	1.896749	N2	1.8997	0.87626	0.00404	-8.4449	0.2639
1.897953	1.906463	NU2	0.3609	0.87792	0.02113	-7.9117	1.3790
1.923765	1.942754	M2	9.9221	0.84899	0.00077	-12.2461	0.0522
1.958232	1.963709	LAM2	0.0732	0.86947	0.10416	-7.1766	6.8641
1.965826	1.976927	L2	0.2805	0.77645	0.02388	-13.1318	1.7624
1.991786	1.998288	T2	0.2697	0.71908	0.02818	-8.7495	2.2448
1.999705	2.000767	S2	4.6158	0.77556	0.00166	-13.8933	0.1222
2.002590	2.013690	K2	1.2540	0.79118	0.00537	-15.7071	0.3886
2.031287	2.047391	ETA2	0.0701	0.70867	0.08056	-16.3385	6.5133
2.067578	2.182844	2K2	0.0184	0.62232	0.22318	-19.2065	20.5429
2.753243	2.869714	MN3	0.0356	0.80603	0.05351	-8.6899	3.8035
2.892639	3.081255	M3	0.1299	0.78685	0.01533	-7.5589	1.1163
3.791963	3.937898	M4	0.0016	4.52721	0.83792	156.6774	10.6056

Ocean Tide Loading (OTL) effect

Tilt effect computed using:

FES99 (cotidal maps) [Lefèvre et al., 2002]

Following Boy et al. (2003): J. Geophys. Res., 108, 2193, doi: 10.1029/ 2002JB002050, 2003;

OTL for the small waves (PSI1, PHI1)

11 harmonics, with the largest amplitude are mostly used to compute the OTL. In the diurnal band just **O1, Q1, K1** and **P1** are really modeled and assimilated using altimetry & tide gauges.
PSI1 & PHI1 are obtained by **interpolation** within the frequency band (“**admittance**”).

Some silly but annoying troubles…

Scratching the head…

Different convention for “Local” phase definition (φ_L)

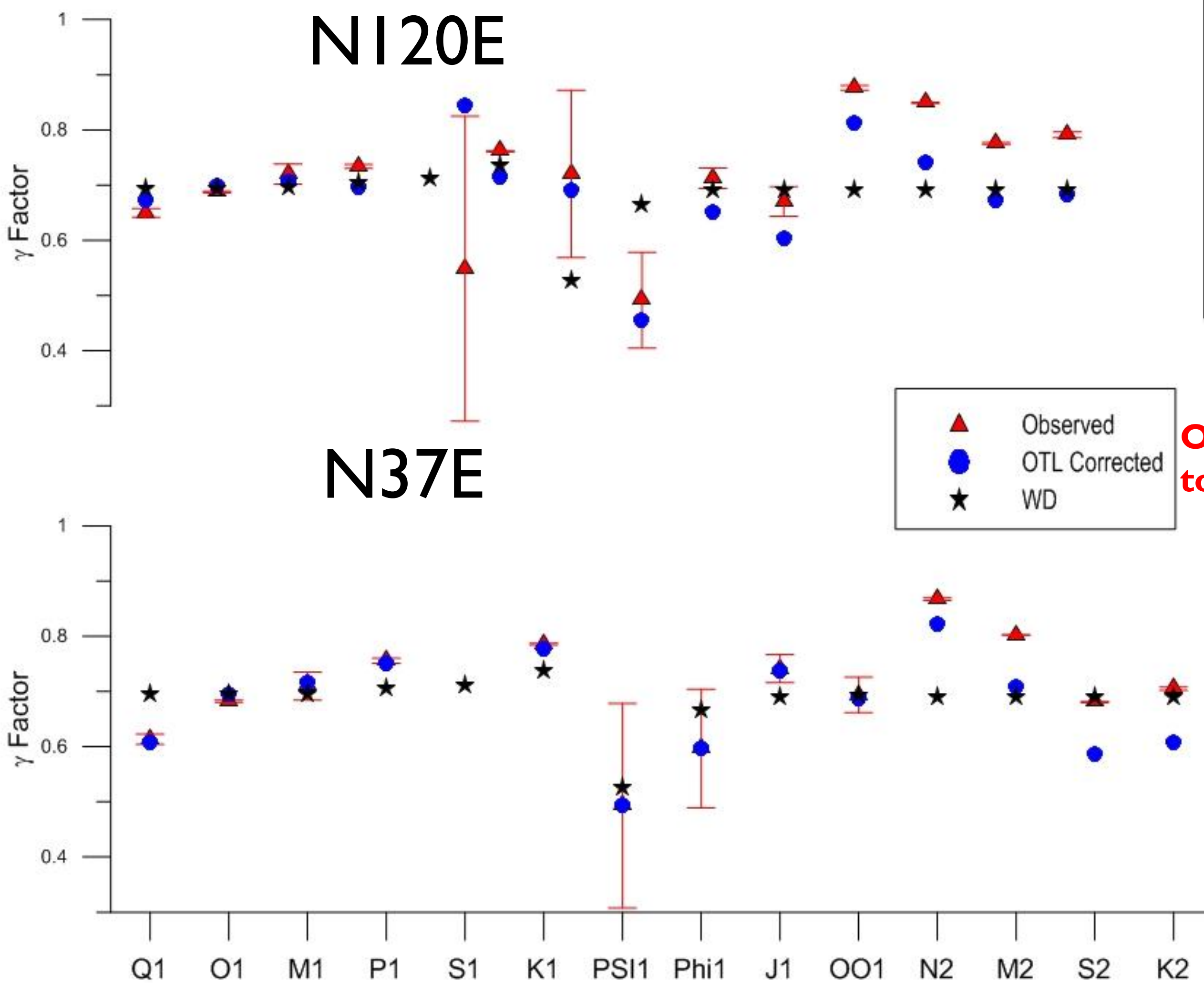
$$\varphi_L = -(\varphi_G + m * Long.)$$ **[Boy et al., 2003]**

$$\varphi_L = \varphi_G + m * Long.$$ **[GOTIC2]**

$$\varphi_L = \varphi_G - m * Long.$$ **[SPOTL]**

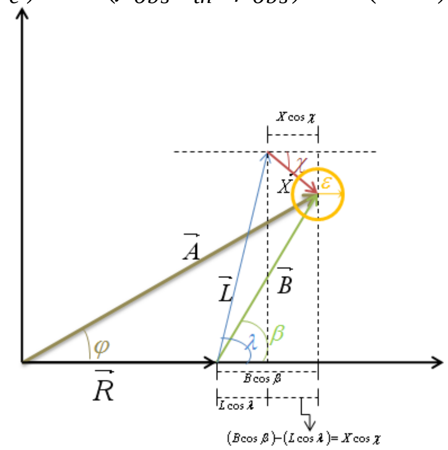
GOTIC2 +180° **[x Compatibility with Eterna]**

(OTL) Correction (FES99)



Principle of vector superposition

$$\vec{A}_C(\gamma_c A_{th},\varphi_c)=\vec{A}(\gamma_{obs} A_{th},\varphi_{obs})-\vec{L}(L,\lambda)$$



OTL projected according to the meters azimuths

N37E

Wave	Tidal Analysis					OTL Projection			
	γ_Obs	γ_std	A (mas)	φ (°)	φ_std (°)	N37E_L (mas)	λ_{N37E}_loc (°)	γ_cor	γ_WD
Q1	0.61328	0.00926	0.50452	-3.279	0.87	3.9564E-02	78.94	0.60864	0.69397
O1	0.68238	0.00191	2.930073	-0.750	0.16	1.0802E-01	116.65	0.69431	0.69438
M1	0.70974	0.02537	0.239175	-4.622	2.05	8.0630E-03	103.47	0.71753	0.69557
P1	0.75558	0.00448	1.485816	-4.097	0.34	4.6583E-02	-83.98	0.75178	0.70538
S1	1.46590	0.27618	0.06751	77.752	10.80	2.3485E-02	-164.43	1.76257	0.71221
K1	0.78568	0.00141	4.473104	-4.728	0.10	1.6202E-01	-76.17	0.77709	0.73620
PSI1	0.49304	0.18548	0.030756	-3.830	21.56	1.1194E-03	88.76	0.49417	0.52581
Phi1	0.59648	0.10777	0.053573	-0.700	10.35	2.0109E-03	87.42	0.59617	0.66470
J1	0.74116	0.02540	0.251641	-5.924	1.96	8.5394E-03	77.02	0.73849	0.69038
OO1	0.69371	0.03224	0.128552	-8.395	2.66	3.6241E-03	58.16	0.68616	0.69181
N2	0.86711	0.00243	2.140988	-18.506	0.16	4.2591E-01	-88.22	0.82335	0.69110
M2	0.80210	0.00046	10.34339	-20.661	0.03	2.0190E+00	-68.72	0.70712	0.69110
S2	0.68060	0.00098	4.082911	-17.698	0.08	6.2707E-01	-40.89	0.58596	0.69110
K2	0.70490	0.00311	1.149096	-18.689	0.25	1.7997E-01	-44.82	0.60773	0.69110

NDFW

Large errors on both amplitude and phase (mainly)

N120E

Wave	Tidal Analysis					OTL Projection			
	γ_Obs	γ_std	A (mas)	φ (°)	φ_std (°)	N120E_L (mas)	λ_{N120E}_loc (°)	γ_cor	γ_WD
Q1	0.64965	0.00784	0.757146	0.307	0.69	4.5263E-02	112.71	0.67255	0.69397
O1	0.68750	0.00158	4.182643	-1.222	0.13	5.6683E-02	-161.21	0.69992	0.69438
M1	0.72021	0.01814	0.343864	-4.920	1.44	4.1732E-03	-5.11	0.70783	0.69557
P1	0.73371	0.00362	2.044232	-3.648	0.28	9.4765E-02	-41.22	0.69613	0.70538
S1	4.76308	0.22473	0.310311	-168.780	2.70	2.8272E-02	-157.12	5.14089	0.71221
K1	0.76119	0.00116	6.140493	-5.349	0.09	2.9949E-01	-35.01	0.71595	0.73620
PSI1	0.72045	0.15171	0.063713	-9.428	12.07	1.8832E-03	2.73	0.69097	0.52581
Phi1	0.49158	0.08671	0.062566	-19.030	10.11	3.5308E-03	3.34	0.45547	0.66470
J1	0.71230	0.01865	0.342748	-6.249	1.50	2.0711E-02	4.77	0.65253	0.69038
OO1	0.67044	0.02701	0.176087	-5.247	2.31	1.2731E-02	5.83	0.60317	0.69181
N2	0.87627	0.00404	2.408696	-8.448	0.26	4.1305E-01	-70.77	0.81219	0.69110
M2	0.84899	0.00077	12.18892	-12.249	0.05	1.8288E+00	-49.63	0.74132	0.69110
S2	0.77556	0.00166	5.179901	-13.896	0.12	6.1686E-01	-14.71	0.67274	0.69110
K2	0.79119	0.00537	1.435613	-15.709	0.39	1.7605E-01	-15.09	0.68320	0.69110

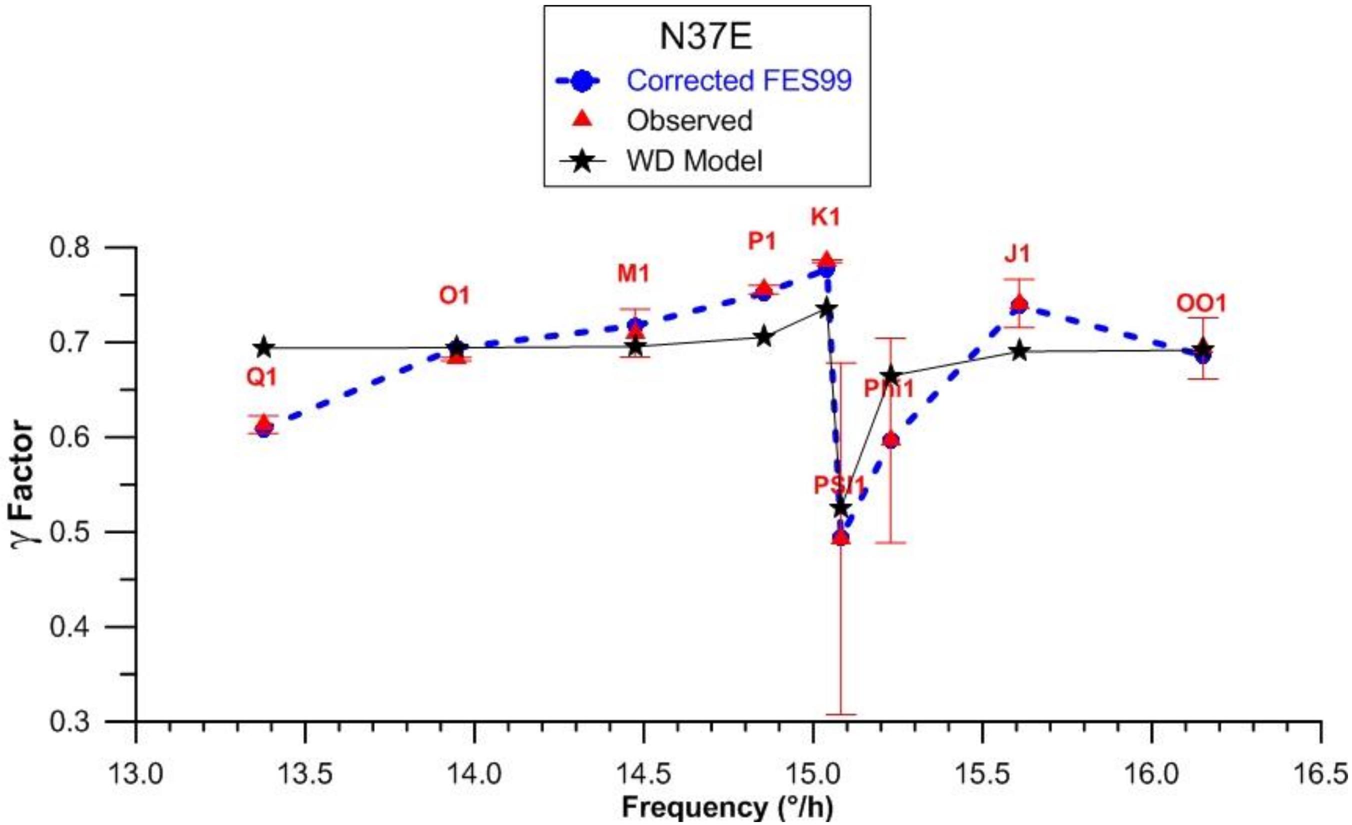
NDFW

Tidal Analysis

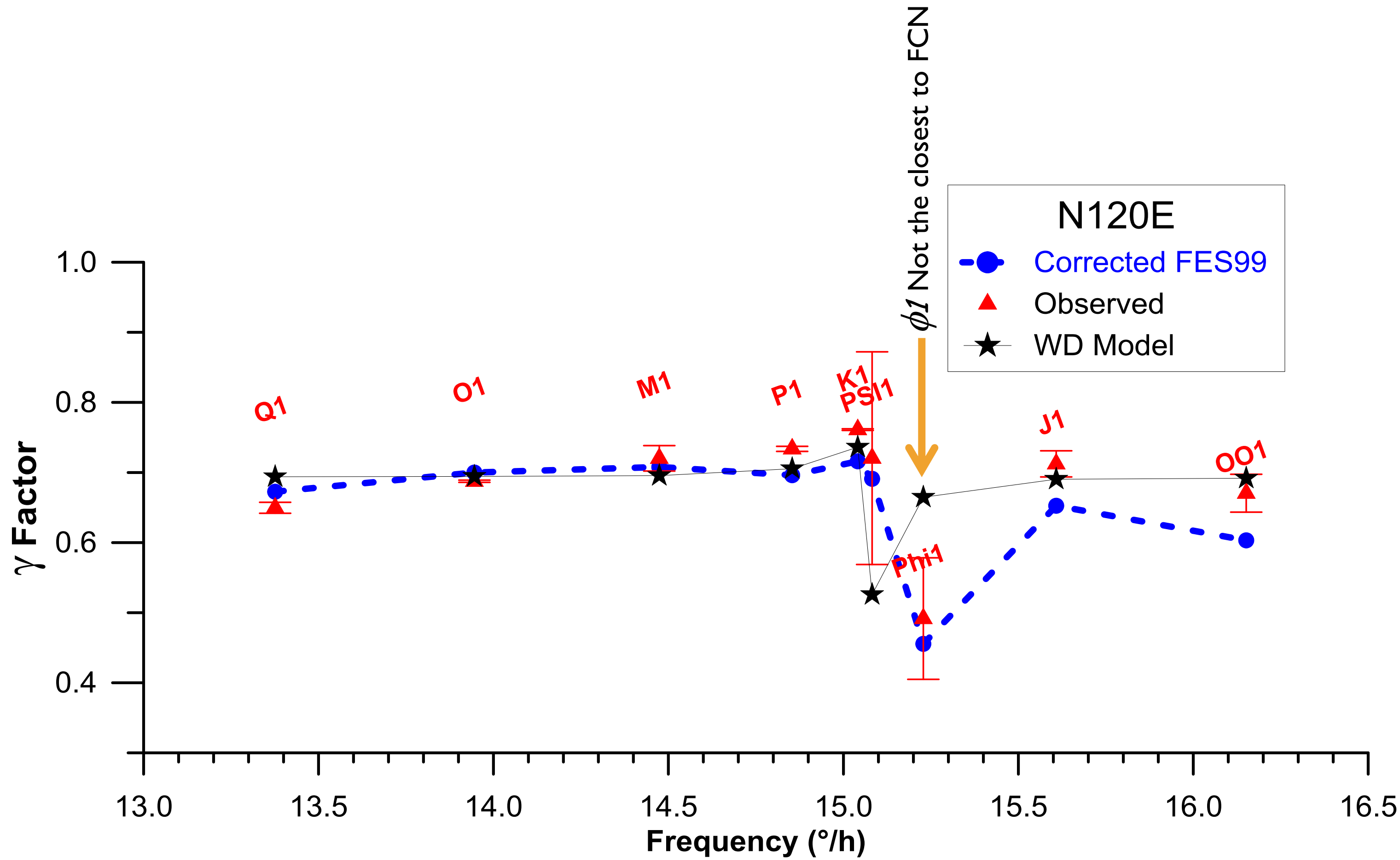
(main tidal waves)

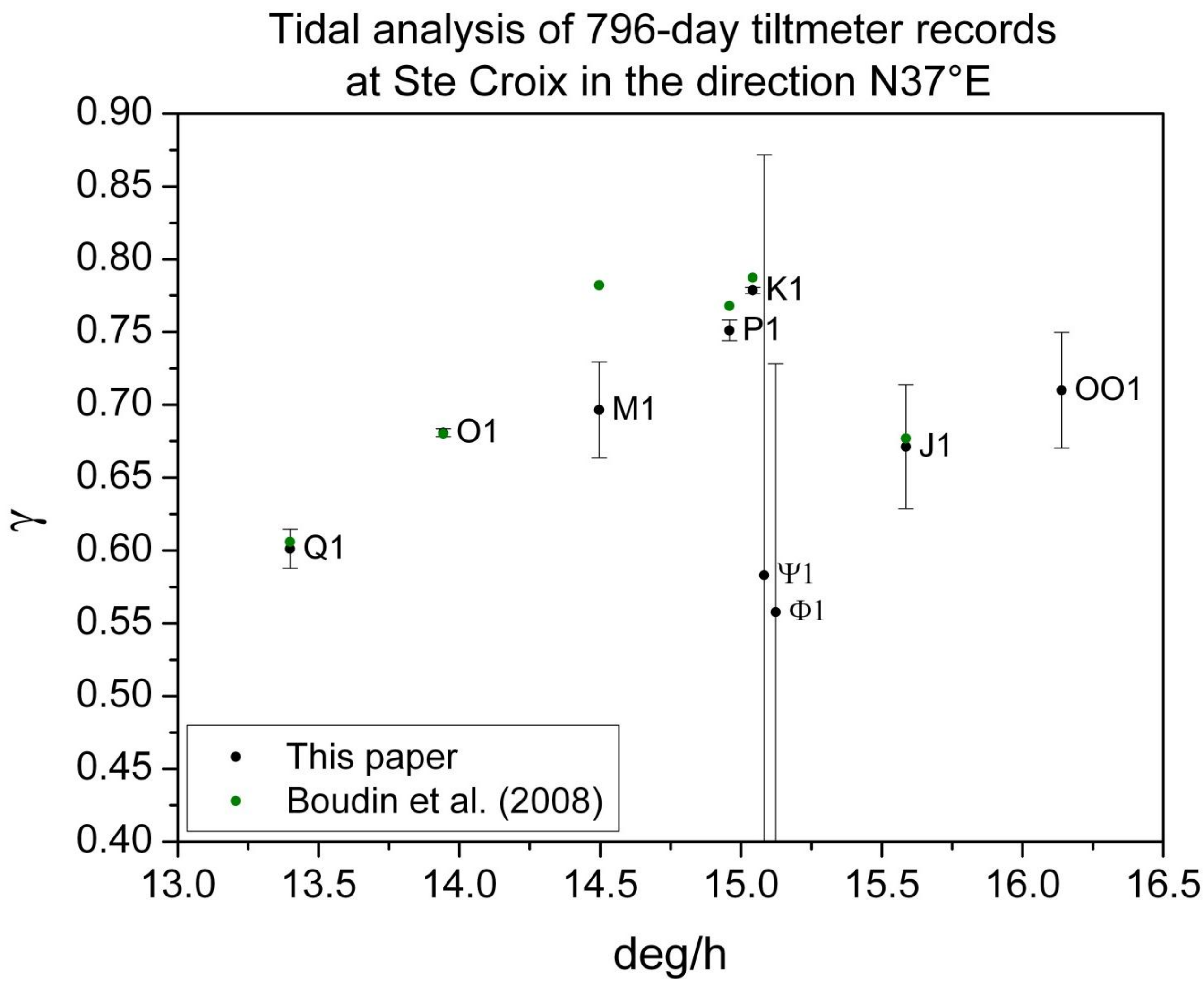
(ETERNA3.4)

Resonance in the Diurnal Band (1)



Resonance in the Diurnal Band (2)





Tidal analysis of 796-day tiltmeter records
at Ste Croix in the direction N37°E
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
γ
K1
P1
M1
O1
OO1
J1
Q1
Ψ1
Φ1
This paper
Boudin et al. (2008)
13.0
13.5
14.0
14.5
15.0
15.5
16.0
16.5
deg/h

Results (1)

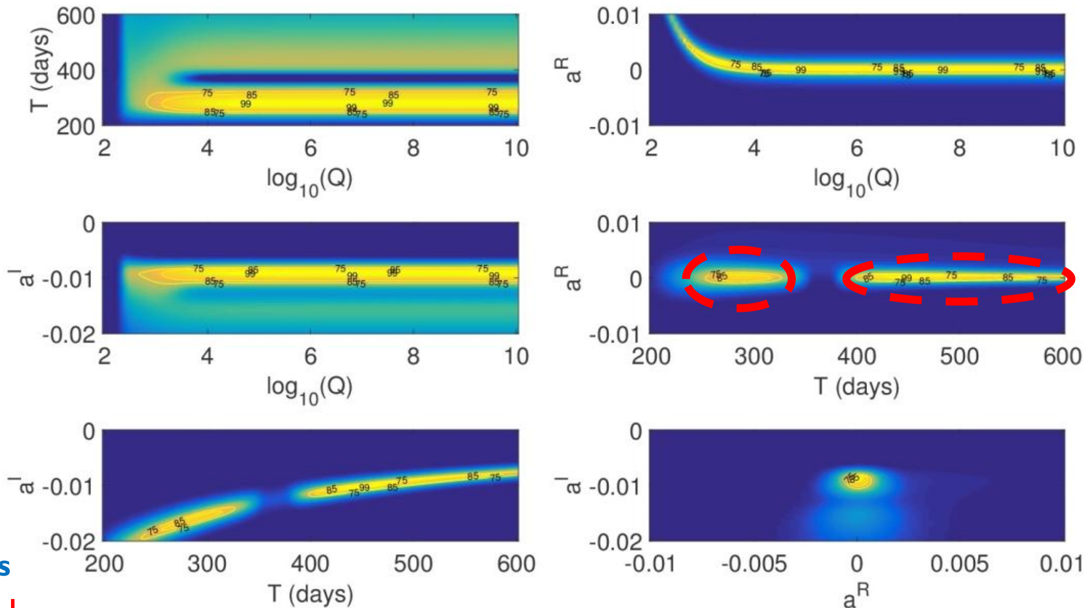
N37E

Bayesian inversion

following Rosat et al. (2009); Florsch & Hinderer, (2000)

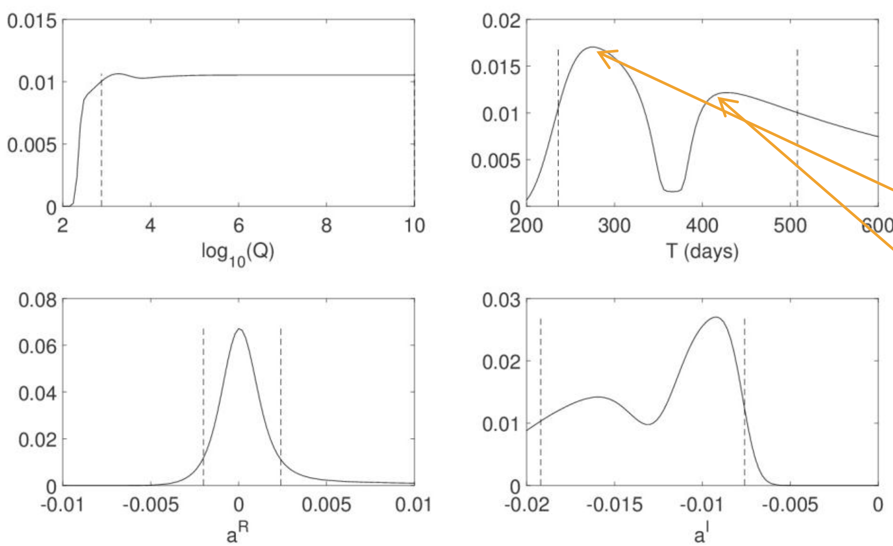
As less as possible contstrains on the a-priori model

2D joint (logQ,T,a^R, a^I) probability density functions (pdfs) (Q1, Q1, P1, K1, Q1, Ψ1, ϕ1, J1, OO1)



Marginal laws for single parameters

Dashed lines correspond to the 90% C.I.



a^R; a^I = Resonance Strength

T = Period

Q = Quality Factor

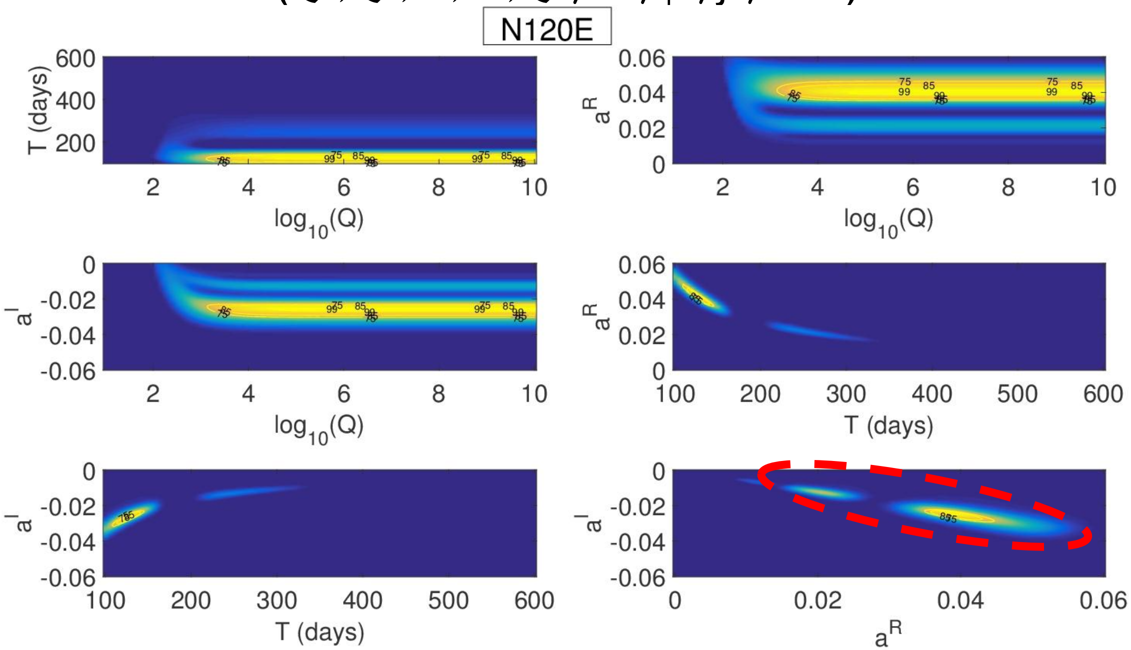
Multiple bumps (in marginal laws) or patches (2D pdfs) indicates the difficulty to constrain the FCN parameters.

Results (2)

N120E

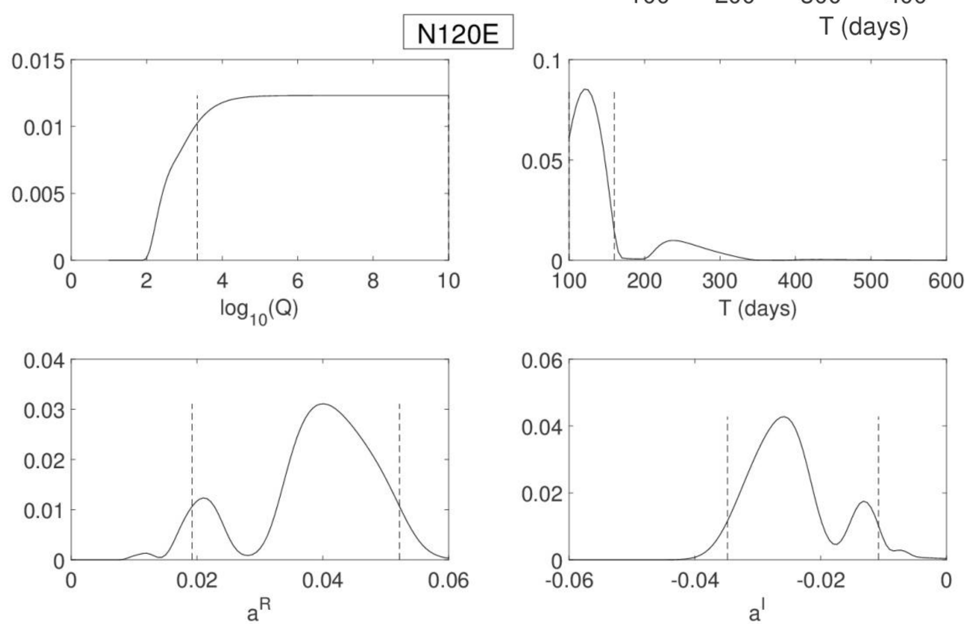
Bayesian inversion

2D joint probability density functions (pdfs)
(Q1, Q1, P1, K1, Q1, Ψ1, ϕ1, J1, OO1)



Marginal laws for single parameters

Dashed lines correspond to the 90% C.I.



Tilt-shaped: strange correlation between a^R and a^R.
It leads thinking about other effects (tilt-strain coupling) that should jointly works

Conclusions (1)

For the N120E inst. we obtain non satisfactory results:
a period of FCN around 150 days (far from the expected 430 days) and "divergent" Quality factor. So not in agreement with VLBI and SGs gravimeters determination.
More promising results on the N37E instrument (**2 Max in marg. pdf: 250 & >400**).
As shown by the joint pdfs forcing al to values closer to 0 we could force the inversion towards T values larger than 400 days.

Looking at the relevant errors on both amplitude and phase of the waves PSI1 & PHI1, there is a general concern on the quality of the N120E tilt data

Possible sources of noise:

Comment: Local effects (**strain-tilt coupling**) could be relevant (Neuberg & Zürn, 1986) in affecting the observed long-term trends and different on both N37 and N120 directions. (Fracture effect?). Indeed the N37E is orthogonal to a main known fracture largely affecting the long-term tilt change, with very minor effect on the N120E, quasi-parallel to the fracture (Longuevergne et al., 2009).

Unaccounted loading effects due to the **Atmosphere** and subordinately Hydrology

SGs' Calibration accuracy (better than **0.3%**) [Amalvict et al., 2001;Riccardi et al., 2012]

SCX Tiltmeters Calibration accuracy (**3.5 - 4%**) [Boudin et al., 2008;]

Conclusions (2)

Some possible improvements we are going to atten

- Fixing the problem of the South Pot at Sainte Croix;
- Accounting for the noise induced by the Atmosphere (models);
- A better monitoring of the time variability of the instrumental sensitivity, through a sequential tidal analysis;
- Trying an inversion with other tiltmetric data made available by colleagues from Black Forest Observatory (Thanks to Walter and Ruedy).

L. Longuevergne PhD thesis, 2008