Can we reliably detect SG scale factor changes far below the one permille accuracy level?

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Michel Van Camp, Olivier Francis and Vojtech Pálinkáš
for providing 1h gravity time series

Problem:

- Repeatability of a single SG/AG calibration experiment is approx. 1‰
- Can we improve the accuracy of the SG scale factor (SF)?

Solution:

- Weighted averaging over several experiments
- 7 experiments needed for providing a scale factor (SF) estimate at the 1‰ level with 99% confidence (Van Camp et al. 2015)

Assumption:

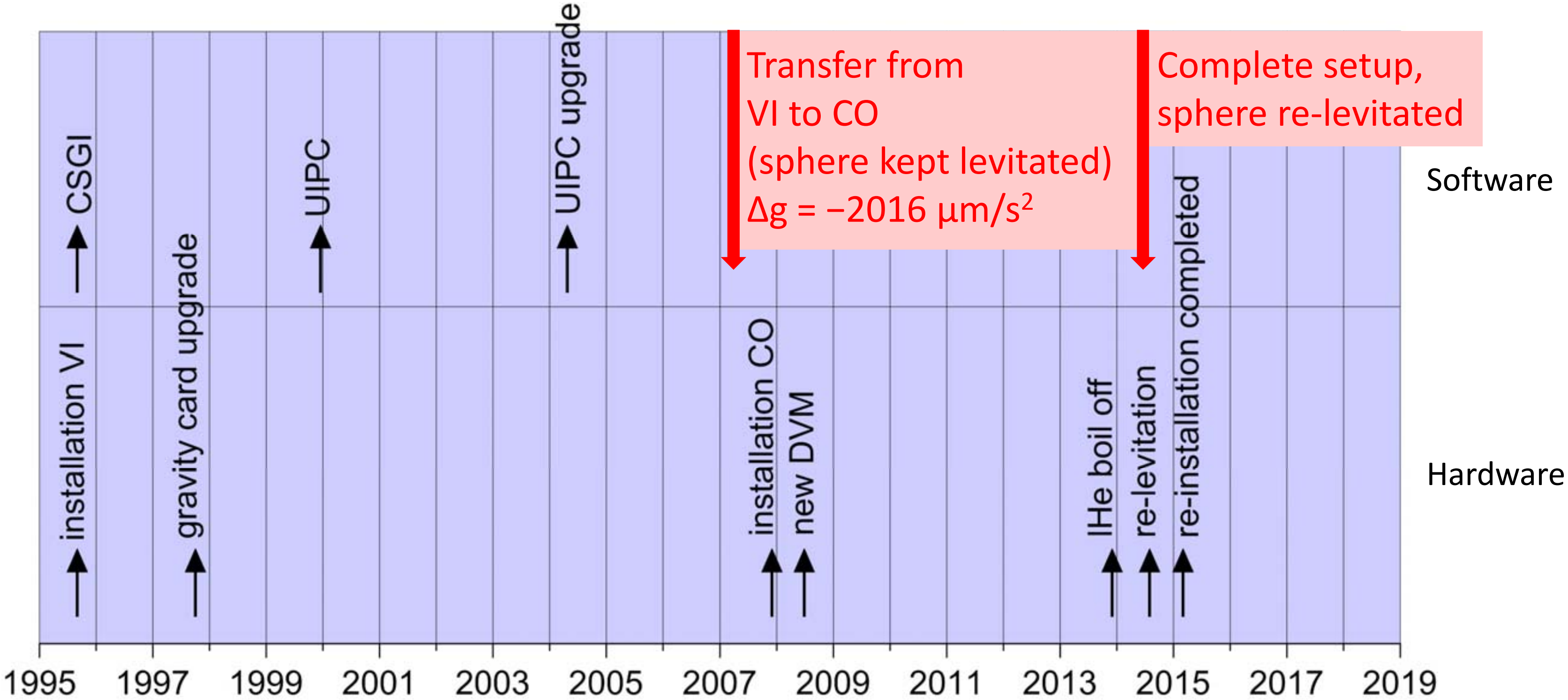
- Single experiment results scatter randomly around the average (i.e. no systematic SF change)

Reasons for SF (and transfer function) change ?

- SF is fixed by the geometry of the coils and suspended mass (Goodkind 1999)
- Gradient of supporting magnetic field?
- Voltmeter stability
- TL: data acquisition software, anti-aliasing filter

Questions:

- How can we reliably detect systematic SF changes below 1 ‰?
- At which accuracy level the basic assumption is justified?
- Can well-calibrated spring gravimeters help at stations with low AG availability?



Hard- and software history of SG GWR C025

CO: Instrumentation available for calibration:

- Jila-g, FG-5: SG/AG experiment only twice a year
- Scintrex CG-5: permanently since 2008

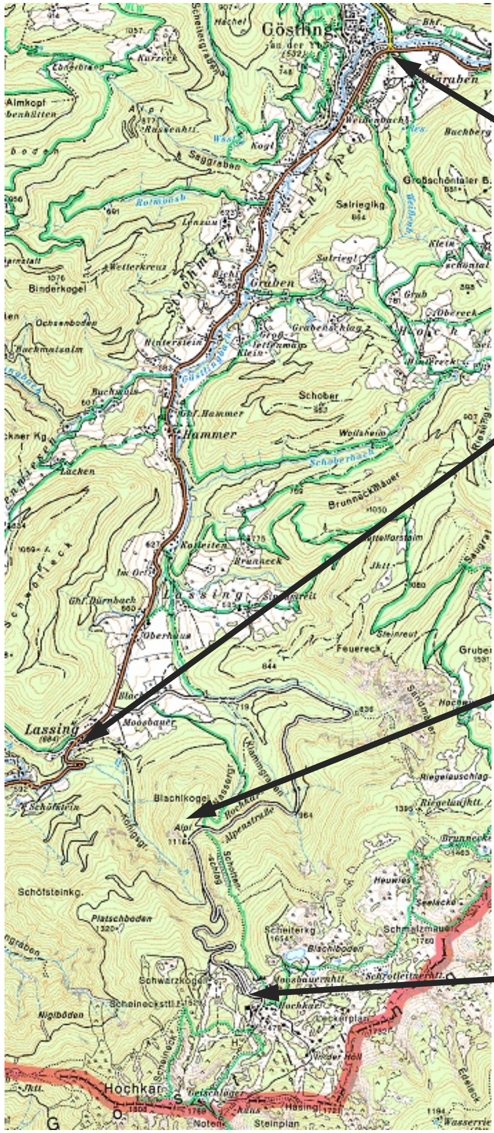
CG-5 calibration:

- Hochkar calibration line established in 1988 by AG observations
- Repeated AG measurements 1995 and 2014 prove high temporal stability (Ruess and Ullrich 2015)
- Vertical gradients determined by LCR/CG-5 observations
- Gravity change (2013, < 200 nm/s^2) due to building reconstruction
- Permanent control of CG-5 instrumental properties (drift, tilt offset, tilt sensitivity)

SG/CG-5 experiments:

- Specific evaluation scheme required due to large and irregular instrumental drift (Meurers 2012, 2018)

Hochkar Calibration line (Austria)

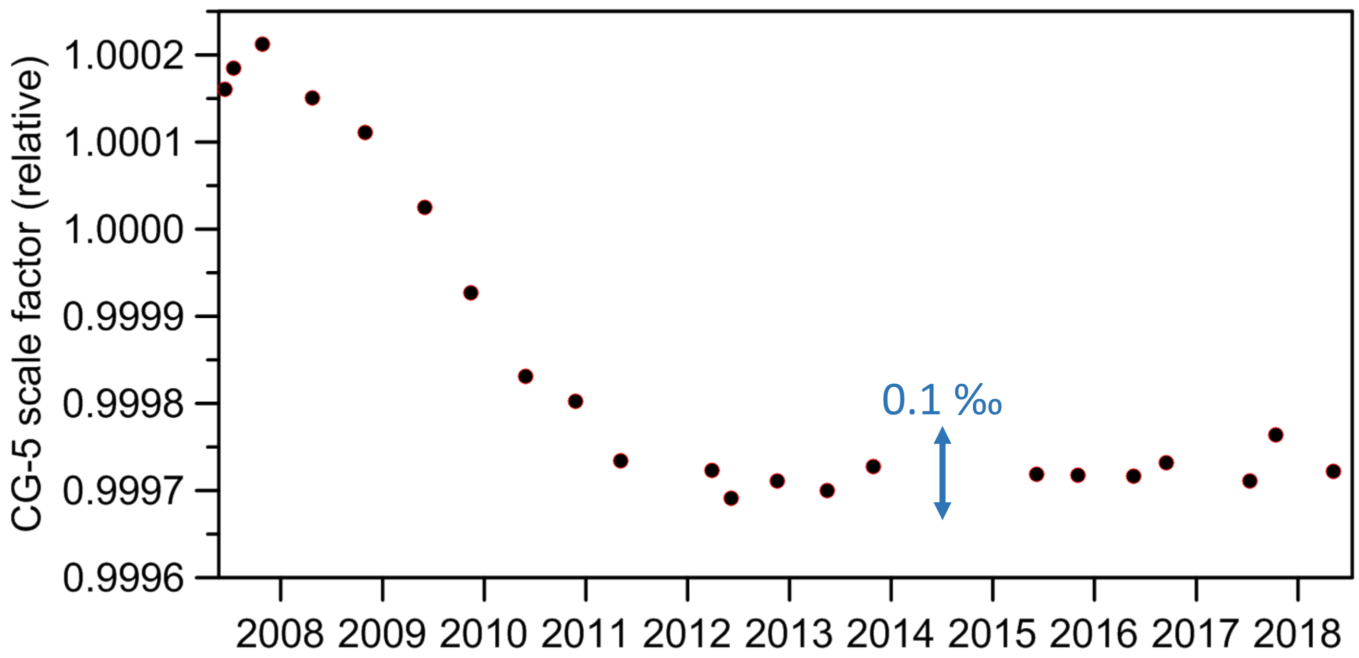


ID	H [m]	g [$\mu m/s^{-2}$]	Δg [$\mu m/s^{-2}$]	Dist. [km]
1-071-00	529	9806831.475	0	0
1-101-10	685	9806420.072	−411.403	8
1-101-20	1116	9805562.716	−1268.759	13.3
1-101-37	1490	9804847.930	−1983.545	16.7

SF of instruments with mechanical feedthrough might be biased by the buoyancy effect

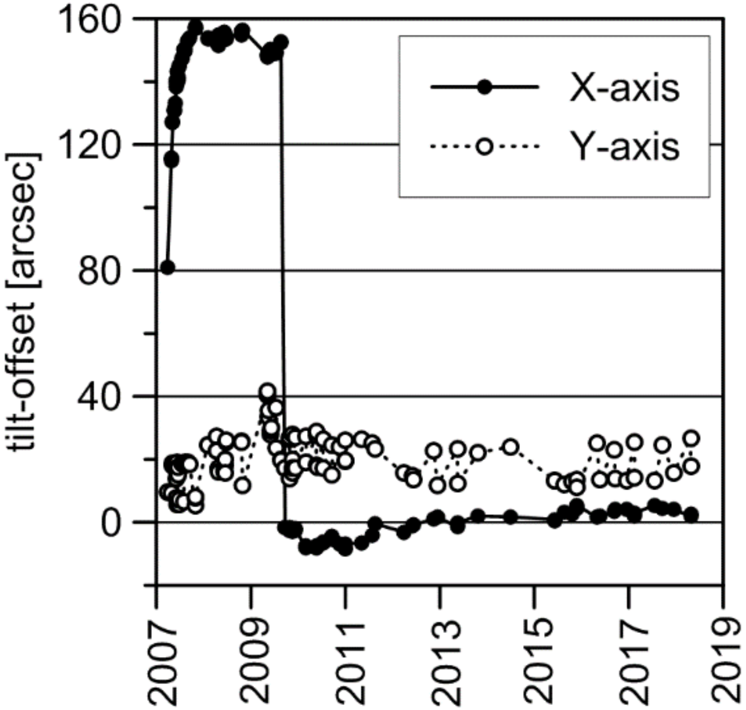
Uncertainty of gravity due to unknown hydrological site effects: 50 nm/s^2
Uncertainty of SF(CG-5) due to unknown hydrological site effects: 0.025‰
Uncertainty of SF(CG-5) estimated from scatter: < 0.05‰

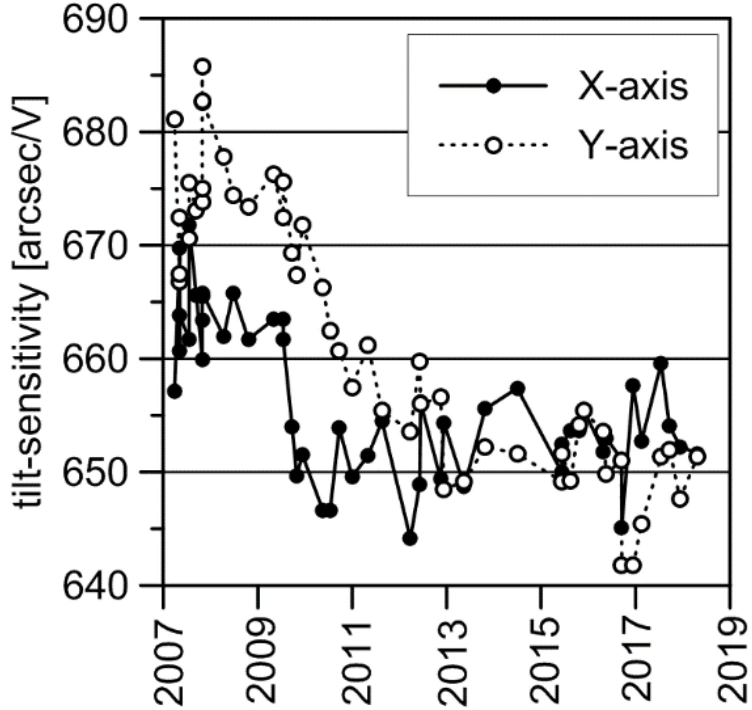
Two campaigns per year (late spring, autumn)



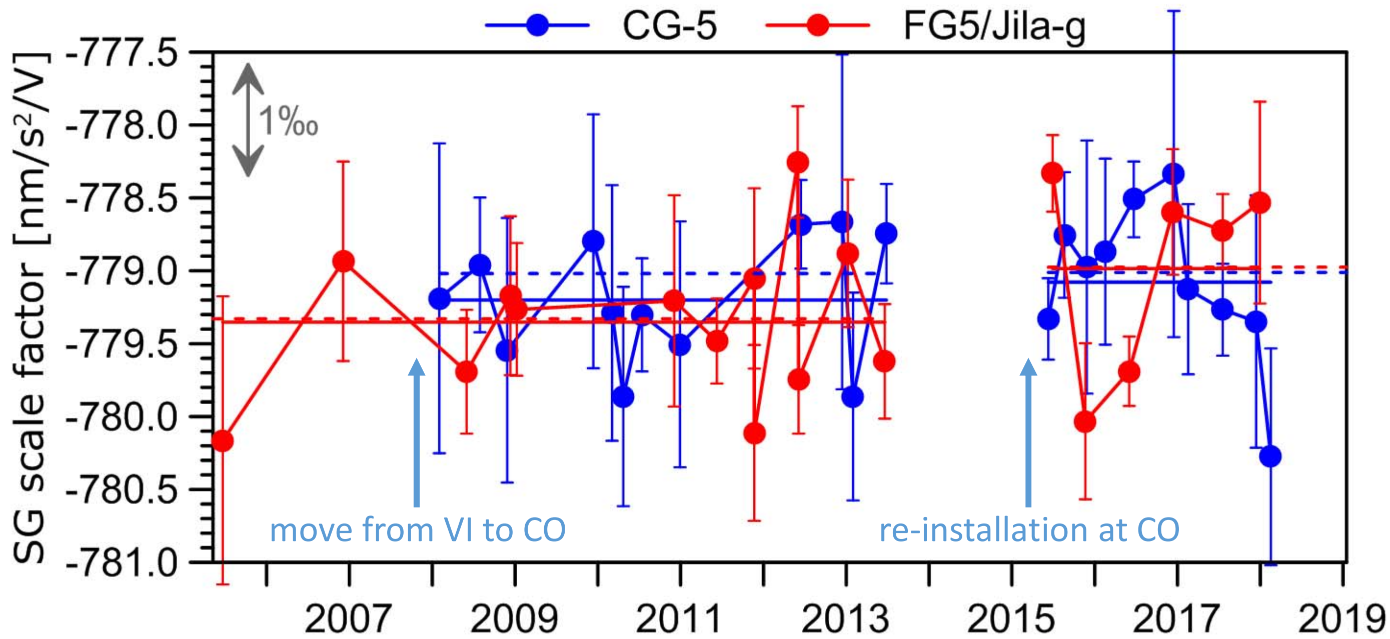
Results from observations at the Hochkar calibration line

Uncertainty of gravity due to unknown hydrological site effects: 50 nm/s^2
Uncertainty of SF(CG-5) due to unknown hydrological site effects: 0.025‰
Uncertainty of SF(CG-5) estimated from scatter: < 0.05‰
Uncertainty of SF(SG) due tilt instability: < $3 \cdot 10^{-6}$ ‰





Calibration results of SG/FG5/Jila-g/CG-5 experiments

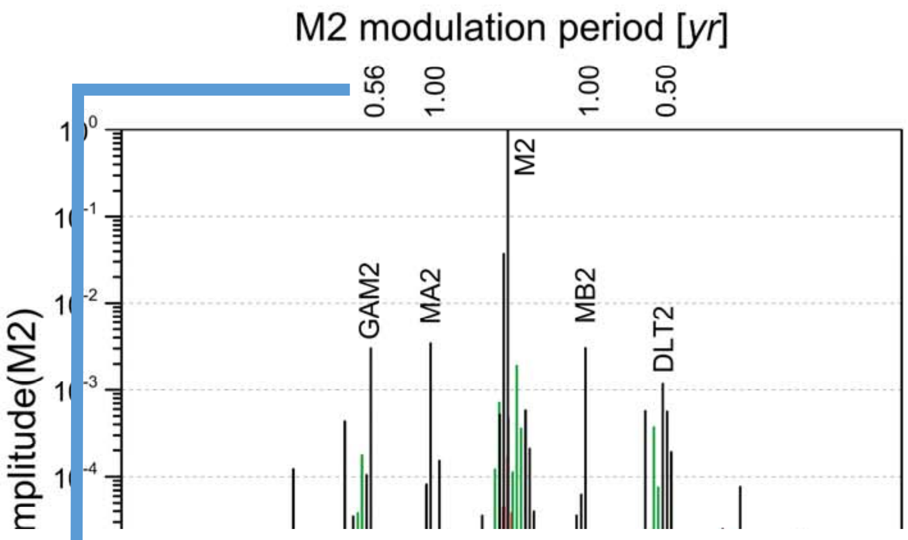


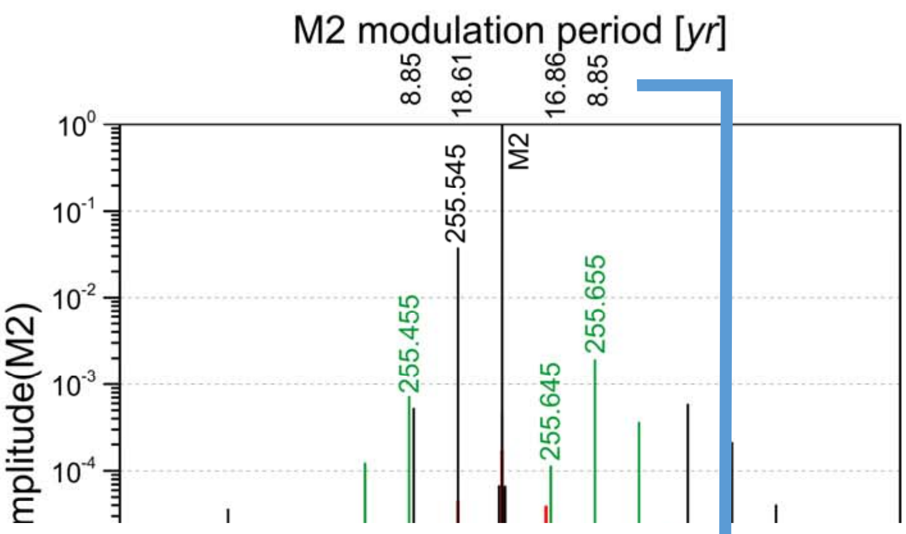
	SF(SG) [nm/s²/V]	Error [nm/s²/V]	Error [‰]			$\delta_{SF(SG)}$ [nm/s²/V]	$\delta_{SF(SG)}$ [‰]
VI	−779.3338	0.5628	0.72	FG5			
CO	−779.3284	0.1322	0.17	FG5/Jila-g	< 2015	0.0054	0.01
VI+CO	**−779.3287**	0.1287	0.17	FG5/Jila-g			
CO	−778.9752	0.1304	0.17	FG5	> 2015	0.3535	0.45
CO	−779.0193	0.1555	0.20	CG-5	< 2015		
CO	−779.0114	0.1406	0.18	CG-5	> 2015	0.0079	0.01
CO	**−779.1480**				δ_{SF}/ave	0.1807	0.23

dashed lines: weighted mean
solid line: arithmetic mean

→ try to confirm by comparing the M2 modulation of 1 yr tidal analyses
(Meurers et al 2016)

Comparison of M2 modulation at neighboring sites





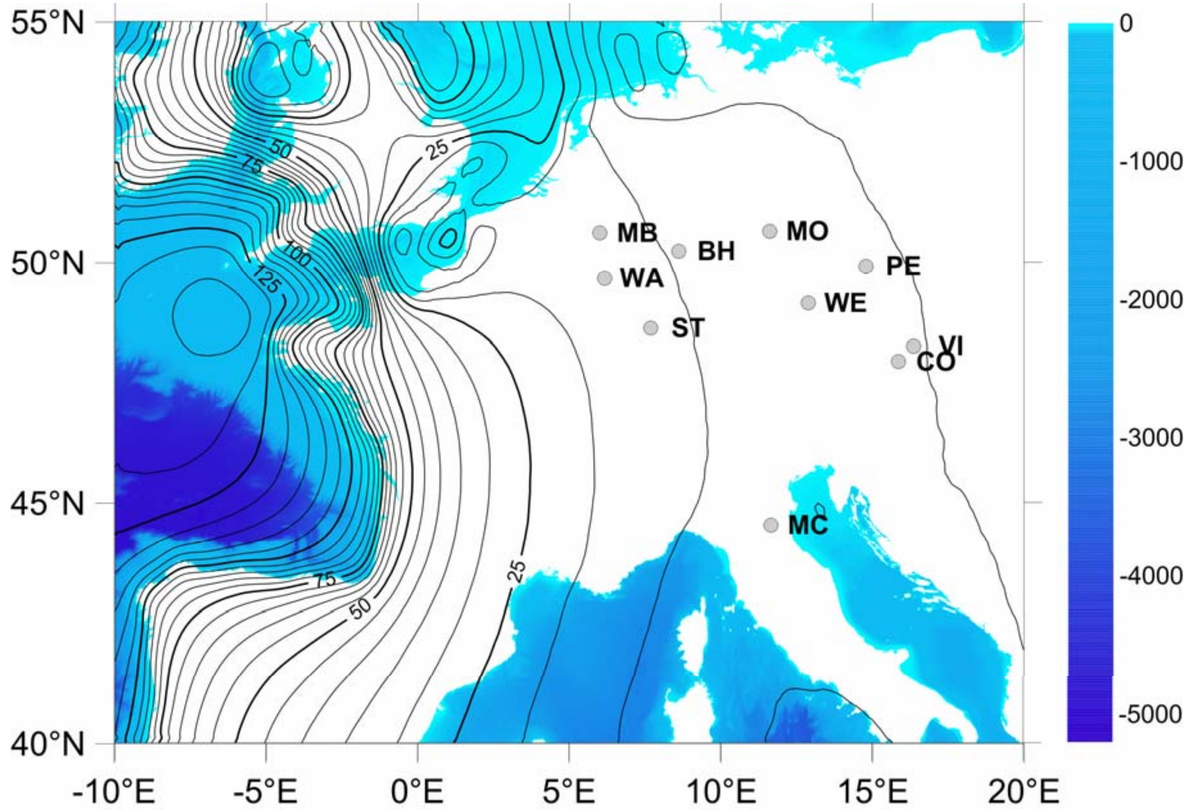
Cancel out when using analysis intervals of ΔT = n yr, $n \in \mathbb{Z}$

Do not cancel out except for very long analysis intervals (> 20 yr)

$\Rightarrow$ M2 tidal parameters depend on the analysis period (interval length, central epoch) and therefore cannot directly be used for detecting small SF changes

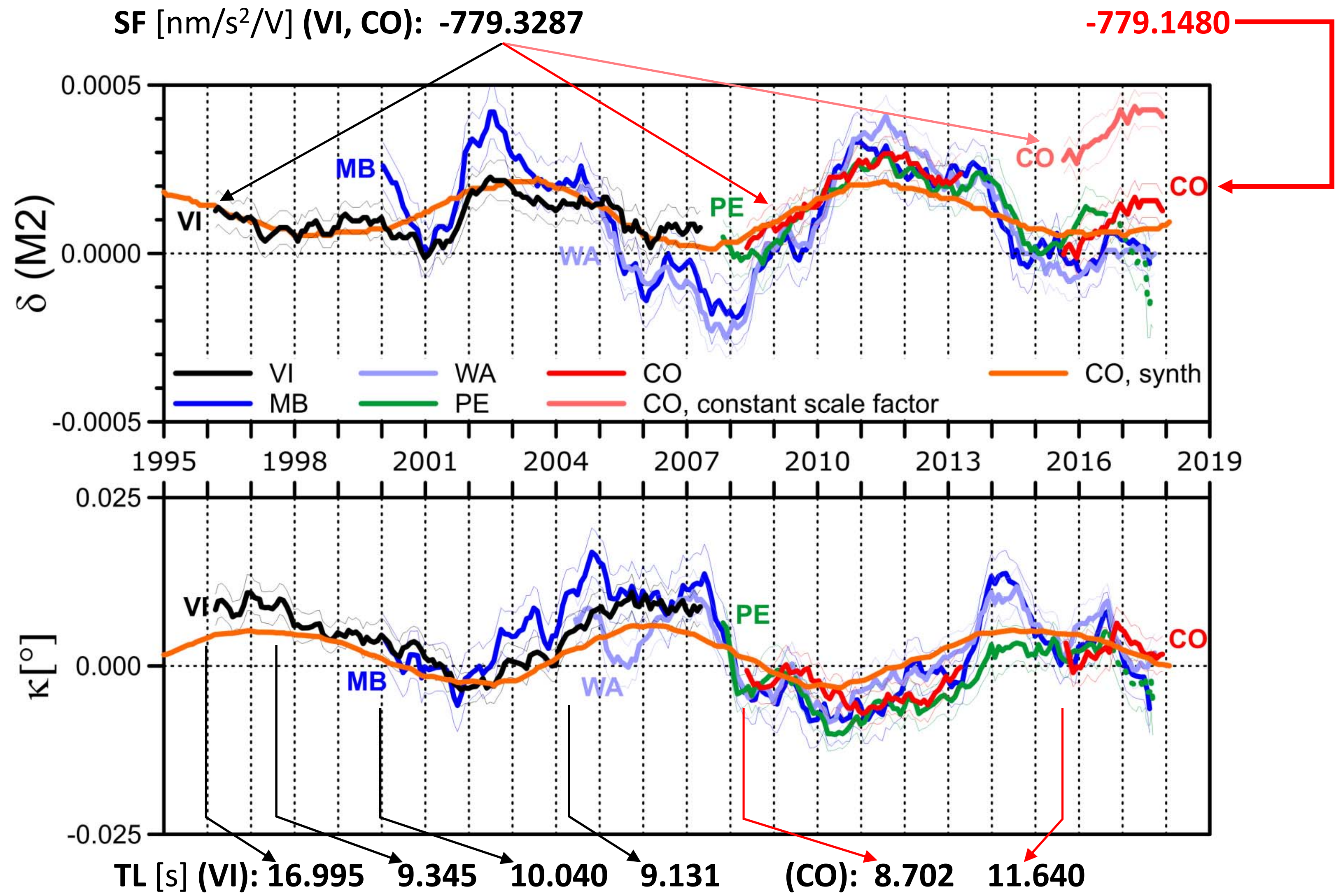
However comparison of M2 modulation patterns between neighboring stations is a valuable tool for assessing the temporal SF stability

Comparison of M2 modulation at neighboring sites



European SG stations and M2 ocean load amplitude (TPXO7.2) [nm/s^2].
Colors: ocean depth [m] (GEBCO 2014, http://www.gebco.net/)

Comparison of M2 modulation at neighboring sites



Comparison of tidal parameters at CO and PE

Wave	Station	Load vector		Tidal parameters				
		length [nm/s²]	phase lead [°]	ampl. fac.	phase lead [°]	ampl. fac.	phase lead [°]	M2/O1
				observed		corrected		
O1	CO	1.35	146.94	1.1497 ±0.0004	0.071 ±0.021	**1.1533**	−0.048	
	PE	1.37	144.71	1.1499 ±0.0003	0.113 ±0.014	**1.1536**	−0.016	
M2	CO	10.58	46.58	1.1832 ±0.0001	1.097 ±0.003	**1.1615**	−0.005	1.0071 ±0.0004
	PE	10.65	47.32	1.1851 ±0.0001	1.225 ±0.003	**1.1617**	0.011	1.0071 ±0.0003

Tidal analysis (ET34-X-V61), Hartmann&Wenzel (1995) TGP, numerical filter: N60M60M2
CO: 20071116 – 20180507, recorded days in total: 3310
PE: 20070216 – 20171029, recorded days in total: 3744
Red numbers: SF change by +0.23 ‰ since 2015 considered

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				observed		corrected		
O1	CO	1.35	146.94	1.1497 ±0.0004 1.1488	0.071 ±0.021 0.056	**1.1533** 1.1525	−0.048 −0.062	
	PE	1.37	144.71	1.1499 ±0.0003	0.113 ±0.014	**1.1536**	−0.016	
M2	CO	10.58	46.58	1.1832 ±0.0001 1.1830	1.097 ±0.003 1.091	**1.1615** 1.1613	−0.005 −0.012	1.0071 ±0.0004 1.0076
	PE	10.65	47.32	1.1851 ±0.0001	1.225 ±0.003	**1.1617**	0.011	1.0071 ±0.0003

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Red numbers: SF change by +0.23 ‰ since 2015 considered, light red numbers: constant SF

Conclusions

- Systematic SF changes < 1‰ can be detected reliably by studying the M2 modulation of successive tidal analyses (1 yr intervals)

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- Compare observed M2 modulation to results of neighboring stations and of model tides time series

Conclusions

- Systematic SF changes < 1‰ can be detected reliably by studying the M2 modulation of successive tidal analyses (1 yr intervals)
- if the SF change is > 0.1-0.2 ‰
- Compare observed M2 modulation to results of neighboring stations and of model tides time series
- Well-calibrated spring gravimeters can help in assessing the temporal SF stability at stations with low AG availability

Comparison of tidal parameter at CO and PE

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				observed		corrected		
O1	CO	1.35	146.94	1.1496	0.077	1.1533	-0.042	
	PE	1.37	144.71	1.1500	0.095	1.1537	-0.033	
M2	CO	10.58	46.58	1.1832	1.098	1.1615	-0.005	1.0071
	PE	10.65	47.32	1.1851	1.225	1.1617	0.011	1.0070

Tidal analysis (ET34-X-V61), Hartmann&Wenzel (1995) TGP, numerical filter: N60M60M2
CO: 20071116 – 20171116, recorded days in total: 3137
PE: 20070216 – 20170226, recorded days in total: 3555
data extending over 10y period

Comparison of tidal parameter at CO and PE

Wave	Station	Load vector		Tidal parameters				
		length [nm/s^2]	phase lead [°]	ampl. fac.	phase lead [°]	ampl. fac.	phase lead [°]	M2/O1
				observed		corrected		
O1	CO	1.35	146.94	1.1496	0.077	1.1533	-0.042	
	PE	1.37	144.71	1.1494	0.105	1.1531	-0.024	
M2	CO	10.58	46.58	1.1832	1.098	1.1615	-0.005	1.0071
	PE	10.65	47.32	1.1850	1.220	1.1616	0.006	1.0074

Tidal analysis (ET34-X-V61), Hartmann&Wenzel (1995) TGP, numerical filter: N60M60M2
CO: 20071116 – 20171116, recorded days in total: 3137
PE: 20071029 – 20171029, recorded days in total: 3471
data extending over the same 10y period