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2007–13 OP Výzkum a vývoj pro inovace

INVESTICE DO VAŠÍ BUDOUCNOSTI

On a Feasibility of Vertical Surface Movements Studies in the Light of ECGN: Capabilities of available Geodetic Tools

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Outline

1. Introduction
2. Geodetic tools – a review
3. Repeated levellings
4. GNSS and heights
5. Gravimetry
6. Data used for comparisons
7. Results of comparisons
8. Conclusions

Introduction: reference frames in geodetic science

- Caporali: In the future we´ll need gravity related coordinates, not just heights and timing, with an indication of the value of real gravity
- Ihde: Inconsistencies between geometric and physical quantities must be removed
- ECGN: maintenance of the long term stability of TRS at the level of 10^{-9}, esp. for the height component … e.g. Ihde et al., 2005, Poutanen et al., 2015

Introduction (2): Users´ needs of reference frames

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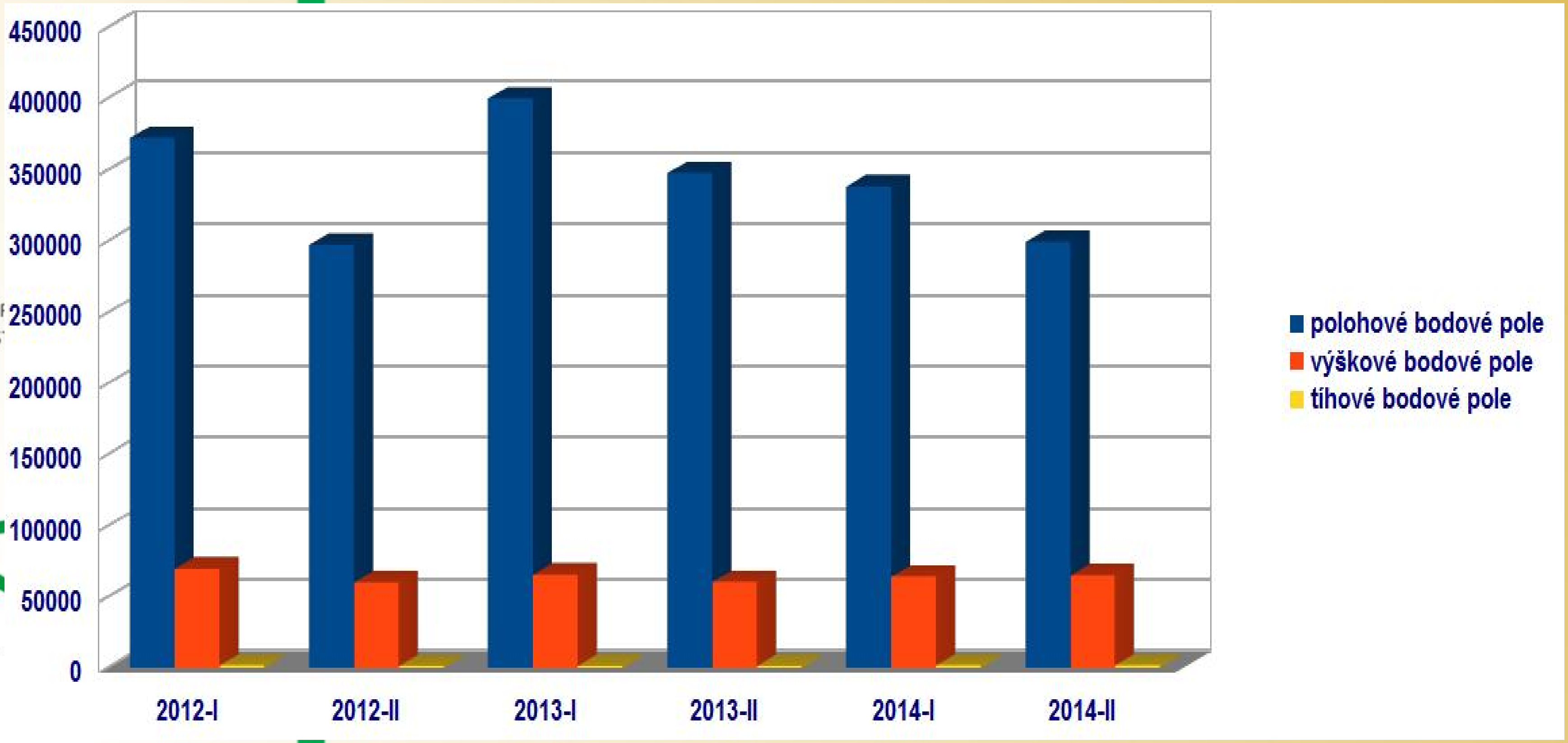

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Data sources for surface kinematics studies in Central Europe

- Surface kinematics is a spatial problem, but usually treated separately for horizontal and vertical components
- For Central Europe we have the following:

1. CERGOP, CERGOP 2 1993 – 1998, 2002 – 2006; CEGRN Consortium since 2001 → Caporali et al., JoGD 2008, Tectonophysics 2009
2. EUREF/EPN (since 1995)
3. UELN95/98; EVRF2000, EVRF2007)
4. ECGN (2002 – present day)
5. UNIGRACE (1997 – 2001)

2. Available Geodetic Tools – a Review

- Repeated levelling (1960s – 1990s)
- GNSS based height components (time series)
- Absolute gravimetry (1990s – now)
- Terrestrial 3D geodesy (1960s -1980s)
- Integrated approach (after 2000) – EVRS (realizations EVRF2000 and EVRF2007), ECGN

3. Repeated Levellings – Strengths and Weaknesses

- Accuracy 1 mm x km$^{-1/2}$; for 20 y interval between epochs velocities of height differences 0.07 mm x km$^{-1/2}$
- General availability
- Excellent precision and accuracy of national blocks
- Long-standing
- Demanding methodology (observations, monumentations, equipment calibrations)
- Long realization time
- Poor homogenity of the networks consisting of national blocks
- Detection of systematic effects
- Demanding detection of disturbing effects (exogenous deformations)

4. GNSS and heights – Strengths and Weaknesses

- Daily repeatabilities N/E/U → 2 mm/2 mm/6 mm, std of velocities is < 1 mm/y
- Accuracy of GNSS-based heights rms 7 mm
- Vertical velocity 1.0 mm/y is significantly detectable after 3 years GNSS observation period
- General availability
- Continuously operating networks
- Variations of position in space
- Vertical component less accurate than horizontal positions
- Many error sources affecting the height: correlation between parameters and satellite distribution, tropospheric refraction, reference frame, geocenter, orbit errors, site displacements due to ocean and atmospheric loading and due to exogenous deformations, antenna PCV, multipath)
- Sophisticated processing strategies needed to overcome or mitigate the impact of biases

5. Gravimetry

Strengths and Weaknesses

- Long-term reproducibility of FG5 < 1.6 μGal
- Standard uncertainty 2.5 μGal
- Std of offsets obout 1.0 μGal; offset range up to 10 μGal
- Absolute gravimetry is methodologically quite independent (purely physical quantity)
- Independent of any reference frame
- No network effect (error propagation) in the processing
- Liable to environmental effects associated with the near-surface mass re-distribution (especially with hydrology)
- It is difficult to separate disturbing effects from the signal
- Instrumental effects (e.g. offset) enter directly to the measured quantity
- Instruments and observations are very expensive and demanding

6. Data used for comparisons

Repeated levellings

- Data collected in the ICRCM/RIGTC by P. Vyskočil (1934 – 2006)
- Data coming from KAPG and GNSS collaboration of East European countries (1960s – 1980s)
- Data from Austria and Bavaria provided by the BEV Wien and LVA München in early 1990s

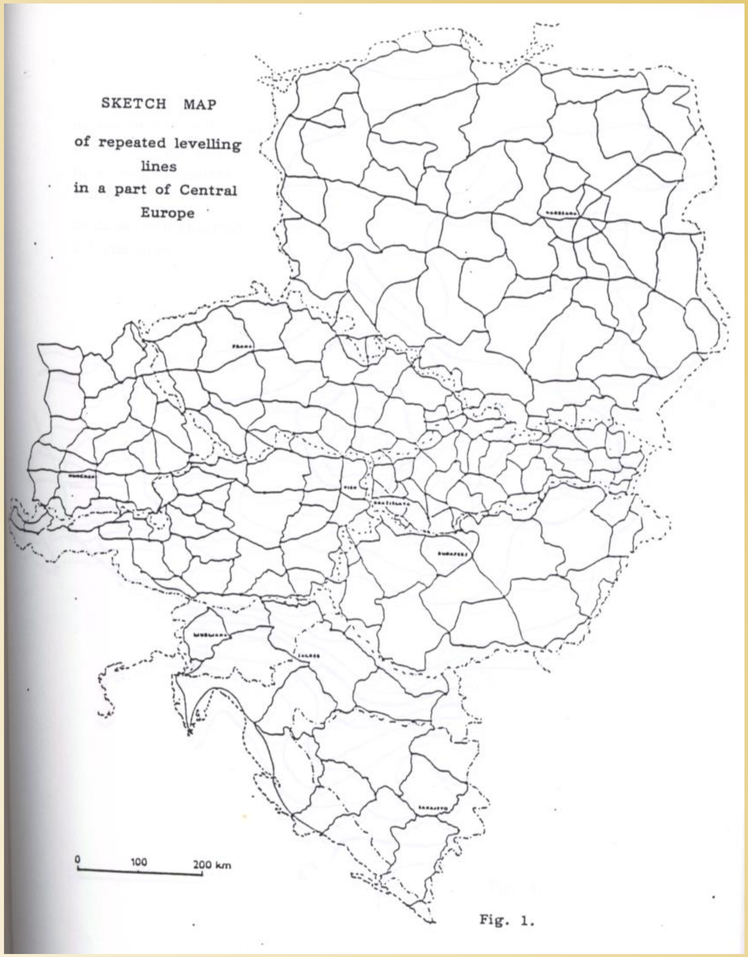
GNSS

- Class A EPN station positions and velocities, ETRF2000, epoch 2005.0, cummulative solution of GPS (A. Kenyeres, FÖMI)
- CZEPOS time series 2007 - 2013

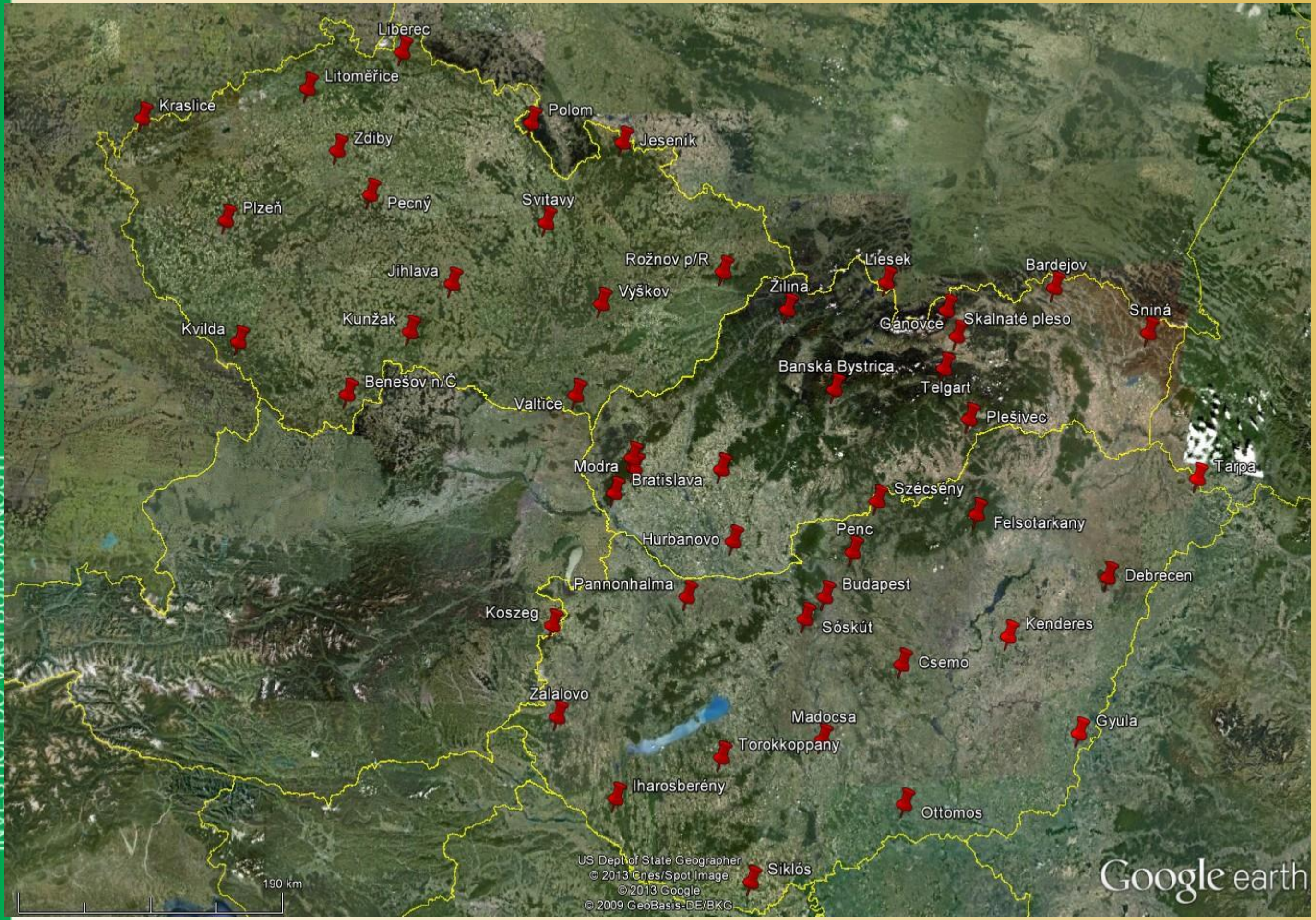
Absolute gravimetry

- Absolute measurements by FG5 No 215 at 29 stations in the Czech Republic, Slovakia and Hungary in the period 2001 – 2011 (J. Kostelecký, V. Pálinkáš, RIGTC/GOP), repeated absolute measurements at the Pecný station

Levelling lines of repeated levellings in Central Europe, P. Vyskočil, ICRCM 1994



Distribution of sites with repeated absolute gravity measurements by FG5 No 215, RIGTC/GOP



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A list of absolute gravity stations in CZ, SK, HU with repeated measurements by FG5 No 215

Table 1 List of repeated absolute gravity measurements before and after 2001 ($g_{(old)}$ and $g_{(FG5\#215)}$) at the date shown in third and fifth columns of the table with corresponding gravity differences $\Delta g = g_{(FG5\#215)} - g_{(old)}$

Station	State	Date	Instrument	Date FG5#215	Δg (µGal)	δg_{hydro} (µGal)	Δg_h (µGal)
Benešov n. Č.	CZ	19.10.1995	JILAg-6	30.7.2002	−6.4	−0.3	−6.1
Jeseník	CZ	23.11.1999	JILAg-6	22.6.2004	−7.2	−0.3	−6.9
Jihlava	CZ	25.11.1999	JILAg-6	17.6.2004	**−21.0**	−0.3	**−20.7**
Kraslice	CZ	17.11.1995	FG5#101	15.6.2004	−8.3	0.0	−8.3
Kvilda	CZ	18.10.2001	JILAg-6	14.7.2005	1.4	0.1	1.3
Litoměřice	CZ	17.10.1995	JILAg-6	16.7.2002	−8.0	0.0	−8.0
Pecný	CZ	11.2.1992	JILAg-6	28.10.2005*	2.5	−1.8	4.3
Pecný	CZ	21.2.1995	FG5#101	28.10.2005*	−3.0	−1.9	−1.1
Pecný	CZ	12.9.1993	FG5#107	28.10.2005*	−1.4	1.6	−3.0
Pecný	CZ	20.11.2000	FG5#206	28.10.2005*	1.3	0.2	1.1
Pecný	CZ	6.12.1998	JILAg-5	28.10.2005*	−0.6	−0.3	−0.3
Plzeň	CZ	16.10.2001	JILAg-6	12.7.2005	**−20.0**	0.1	**−20.1**
Polom	CZ	8.9.1993	FG5#107	21.9.2008*	−3.1	1.6	−4.7
Svitavy	CZ	8.11.1998	JILAg-6	24.6.2004	**−15.9**	0.0	**−15.9**
Valtice	CZ	22.10.1995	JILAg-6	8.4.2003	−3.4	2.6	−6.0
Banská Bystrica	SK	27.6.1996	FG5#107	28.9.2005	−7.4	−0.8	−6.6
Bardejov	SK	22.9.1994	FG5#107	9.10.2003	**−13.0**	0.2	**−13.2**
Bardejov	SK	29.6.1996	FG5#107	9.10.2003	−12.0	−0.6	−11.4
Bratislava	SK	3.9.1993	FG5#107	27.9.2005	**−18.4**	0.1	**−18.5**
Gánovce	SK	8.3.1993	JILAg-6	20.8.2007*	**−14.0**	**−3.2**	−10.9
Hurbanovo	SK	29.9.1994	FG5#107	18.9.2004	**−13.7**	−0.2	**−13.5**
Liesek	SK	23.6.1996	FG5#107	18.5.2008*	−5.6	−0.6	−5.0
Modra	SK	10.3.1993	JILAg-6	22.12.2007*	−6.9	**−3.2**	−3.7
Modra	SK	7.6.2000	JILAg-6	22.12.2007*	**−12.9**	−1.2	**−11.7**
Modra	SK	15.8.2000	FG5#101	22.12.2007*	4.0	0.3	3.7
Plešivec	SK	19.6.1996	FG5#107	30.9.2005	−10.6	−1.0	−9.6
Žilina	SK	4.3.1993	JILAg-6	7.10.2005*	**−21.4**	**−3.2**	**−18.2**
Budapest	HU	28.5.1996	FG5#107	24.5.2007	1.2	0.1	1.1
Budapest	HU	11.8.2000	FG5#101	24.5.2007	3.7	1.9	1.8
Debrecen	HU	23.11.2001	JILAg-6	10.10.2008	−9.4	−1.1	−8.3
Iharosberény	HU	6.10.1994	FG5#107	3.6.2010	−4.6	1.5	−6.1
Kőszeg	HU	4.5.1993	JILAg-6	7.10.2008	**−18.2**	**−3.2**	**−15.0**
Penc	HU	26.11.2000	FG5#206	26.5.2007	**−9.6**	0.4	**−10.0**
Siklós	HU	12.12.1991	JILAg-6	22.5.2007	−7.9	0.1	−8.0
Siklós	HU	6.4.1995	JILAg-6	22.5.2007	−6.6	−1.1	−5.5
Sóskút	HU	20.11.2001	JILAg-6	4.6.2010	−6.7	0.3	−7.0
Szecsény	HU	23.7.1993	FG5#107	25.5.2007	−4.9	1.7	−6.6
Szecsény	HU	3.6.1996	FG5#107	25.5.2007	1.1	0.3	0.8
Zalalövő	HU	10.12.1997	JILAg-6	8.10.2008	0.8	−1.7	2.5

δg_{hydro} represents differences between continental hydrological effects related to two epochs of measurements—corrected gravity differences are $\Delta g_h = \Delta g - \delta g_{hydro}$. Gravity differences exceeding the margin of error at 95 % confidence (see Sect. 5) are highlighted in bold and so are δg_{hydro} higher than 3 µGal (it indicates that the gravity difference is computed from measurements carried out in epochs of hydrological maxima-minima). "*" means that an average gravity value computed from repeated measurements of the FG5#215 (see Fig. 3) has been used—followed by the average date of measurements

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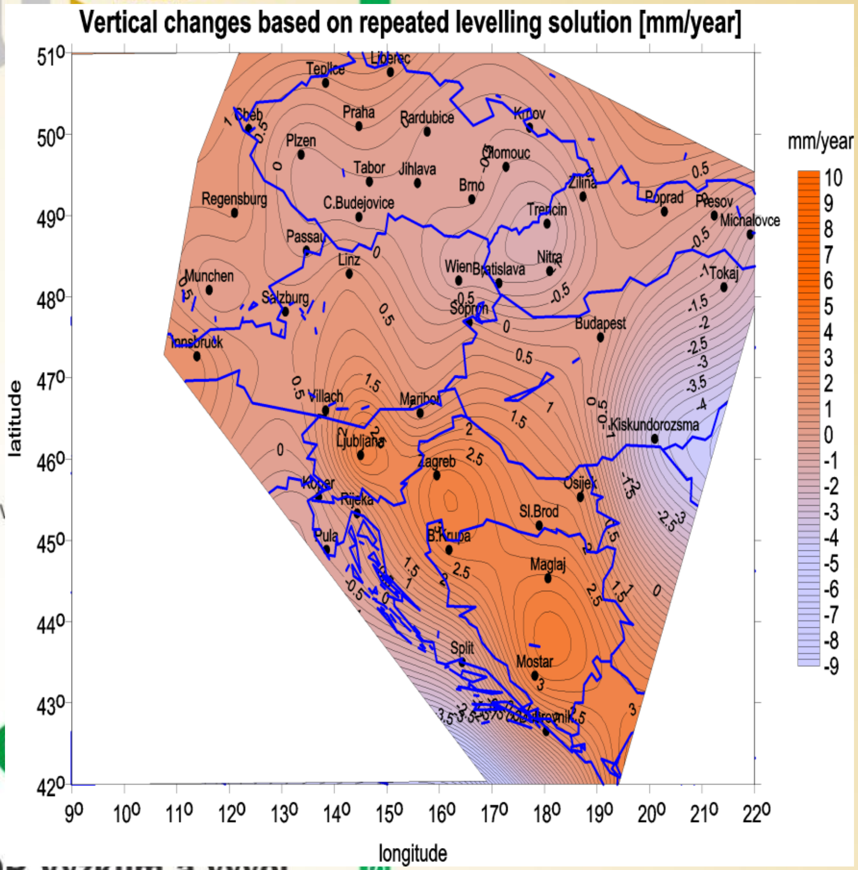
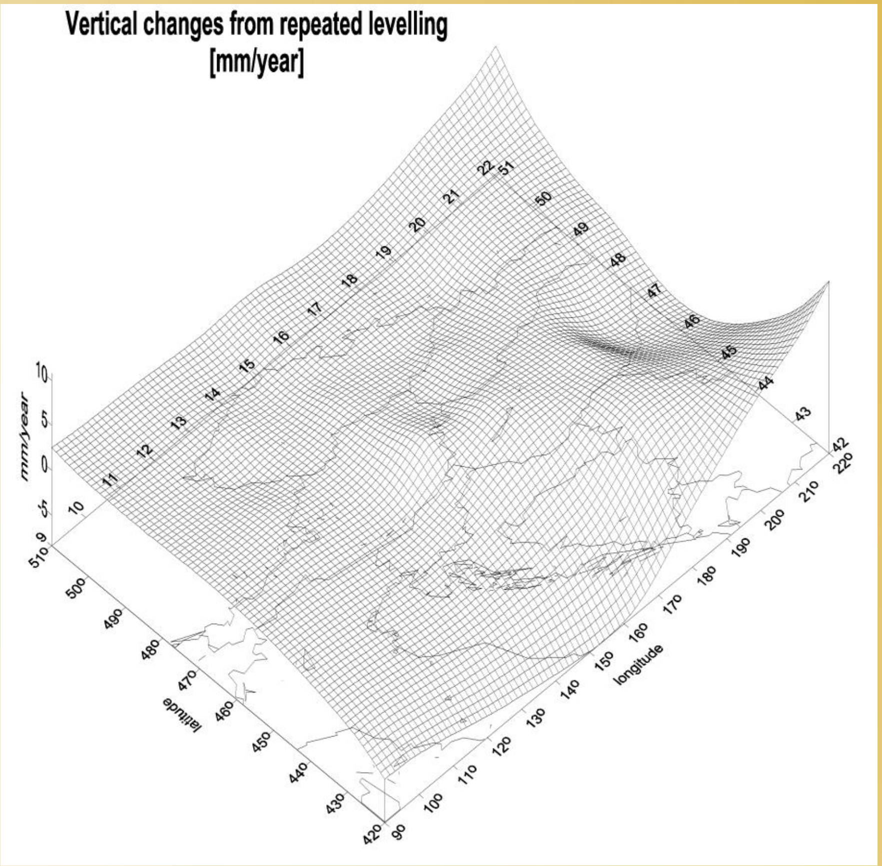
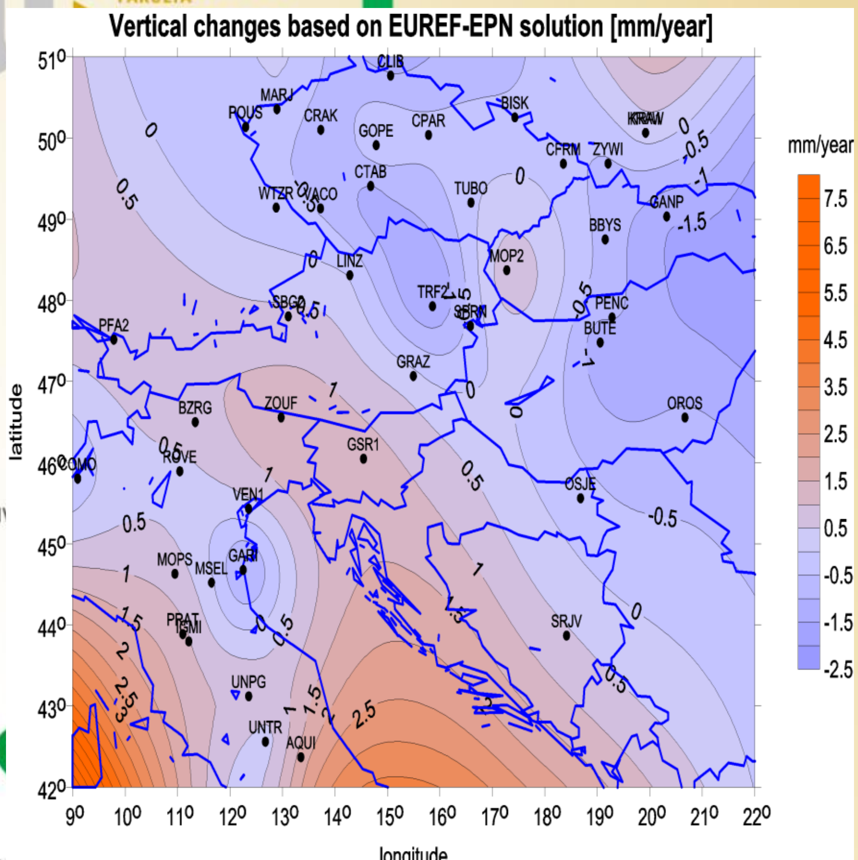
Map of vertical surface movements (mm/y)
ICRCM 1994 (P. Vyskočil)

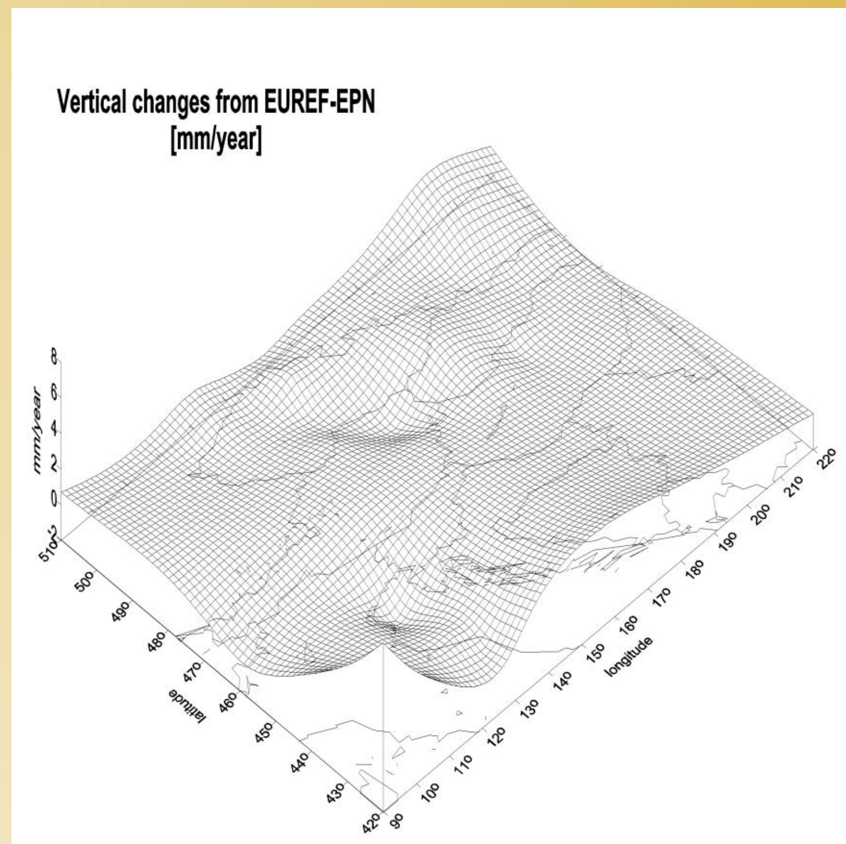
Vertical changes from repeated levelling





Vertical changes from EPN





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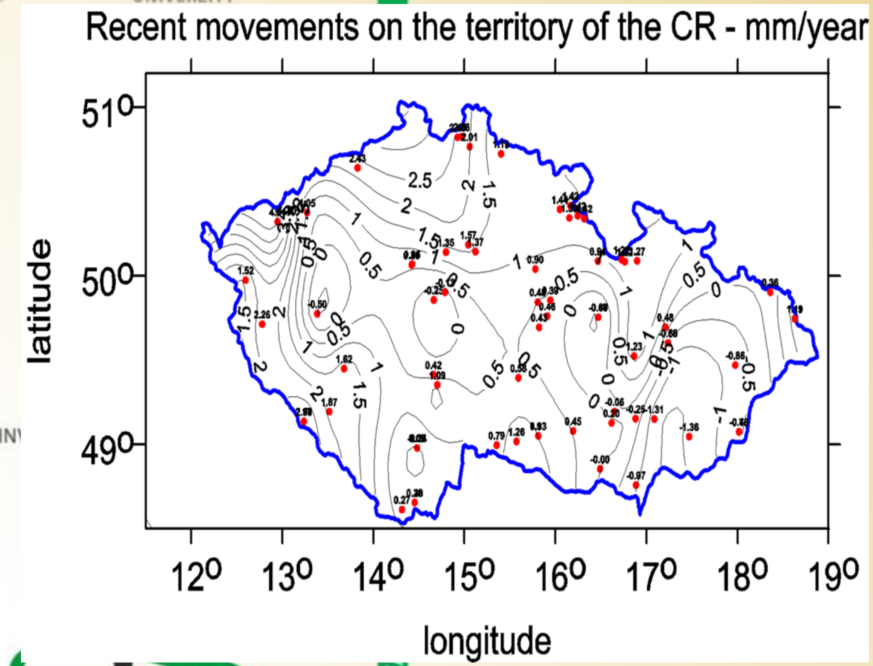
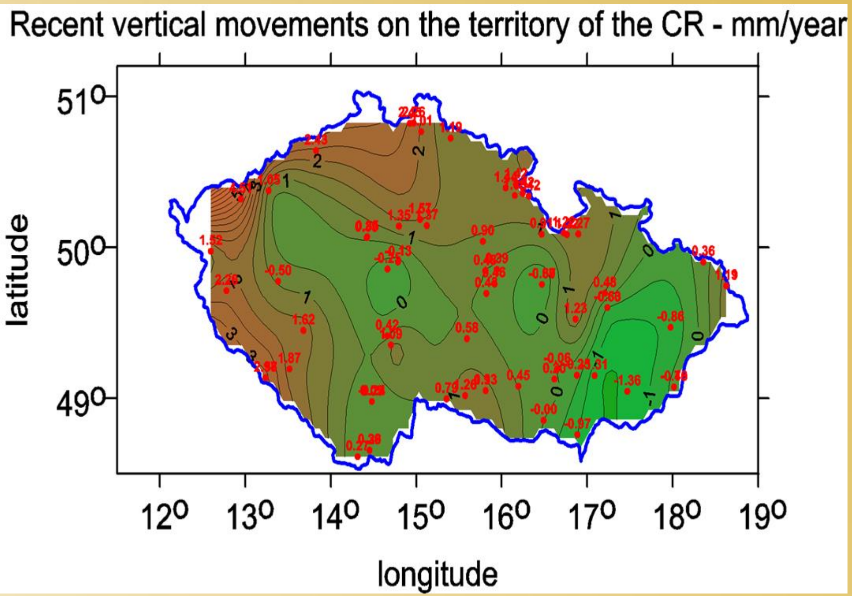
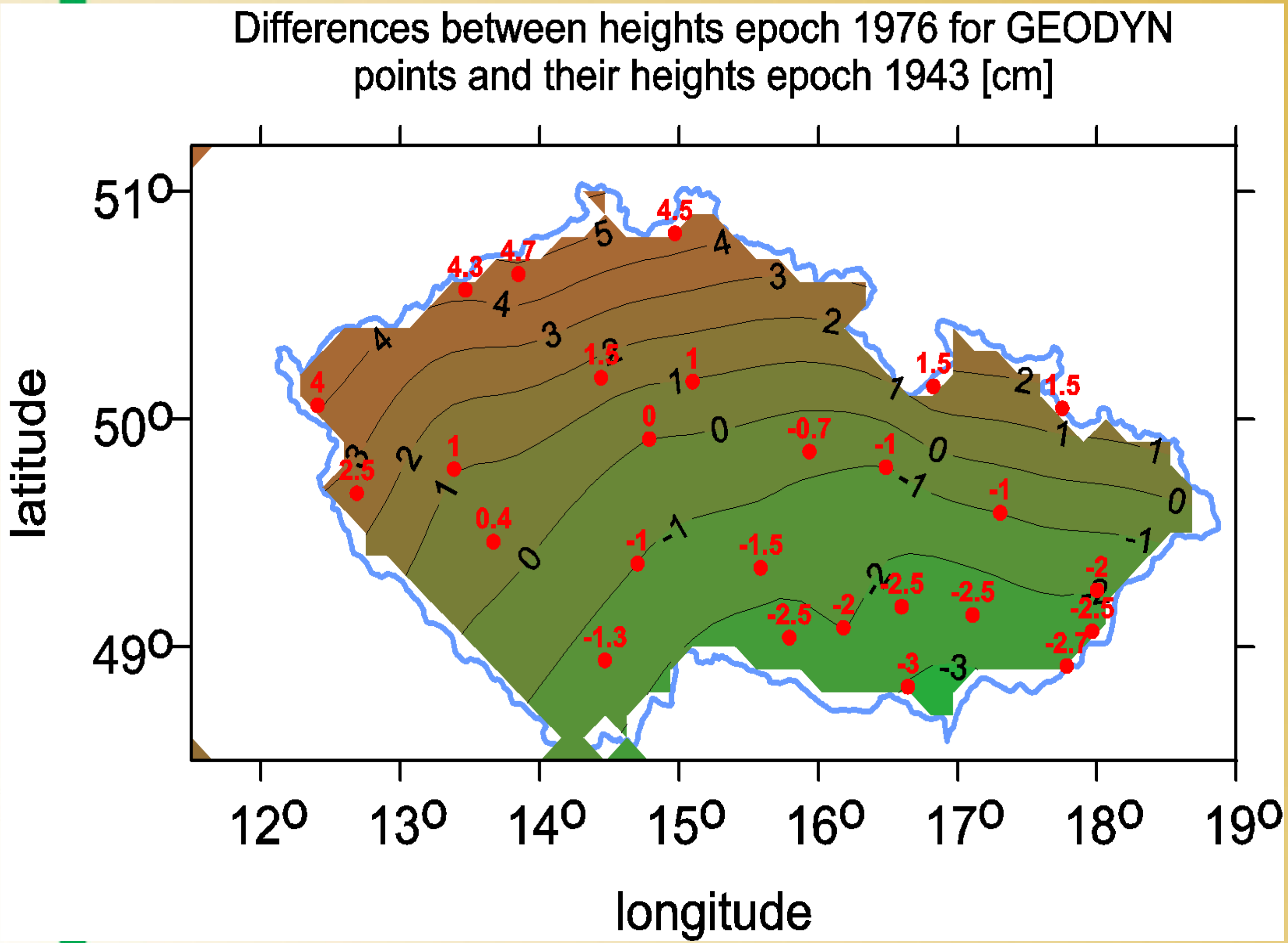
Vertical surface movements in the Czech Republic (mm/y)

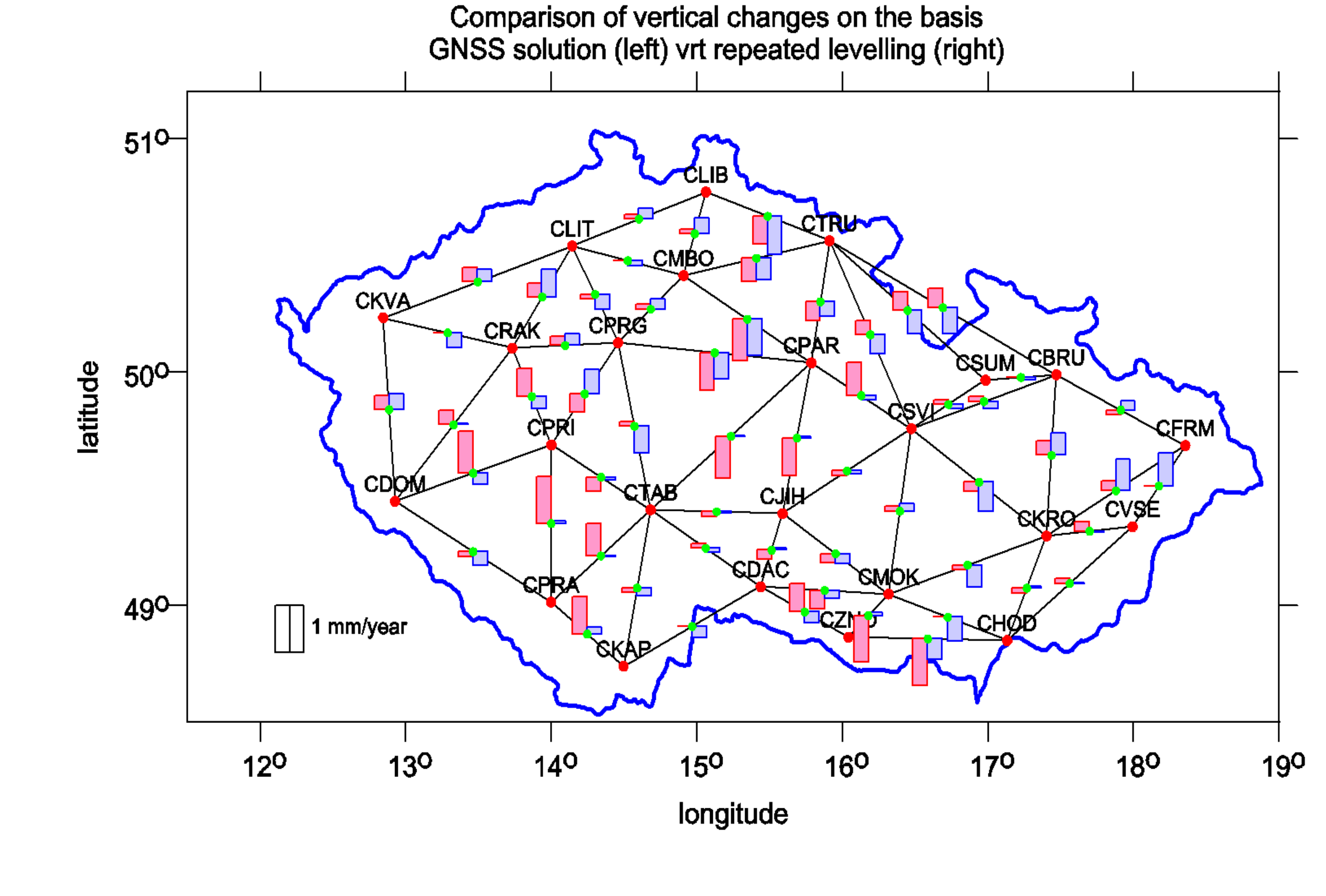




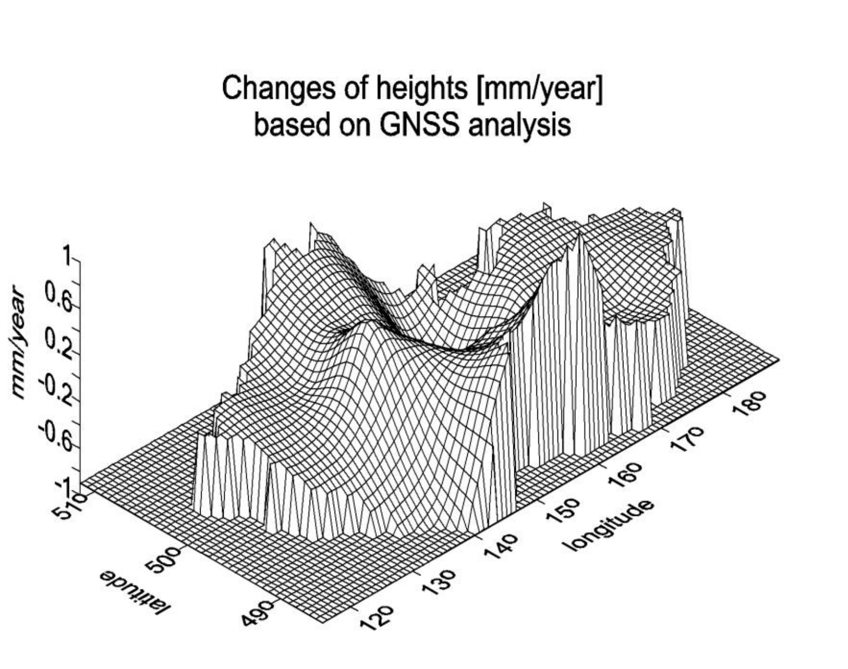
Differences between normal heights for the epochs 1943 and 1976 for the GEODYN stations (National Geodynamic Combined Network)

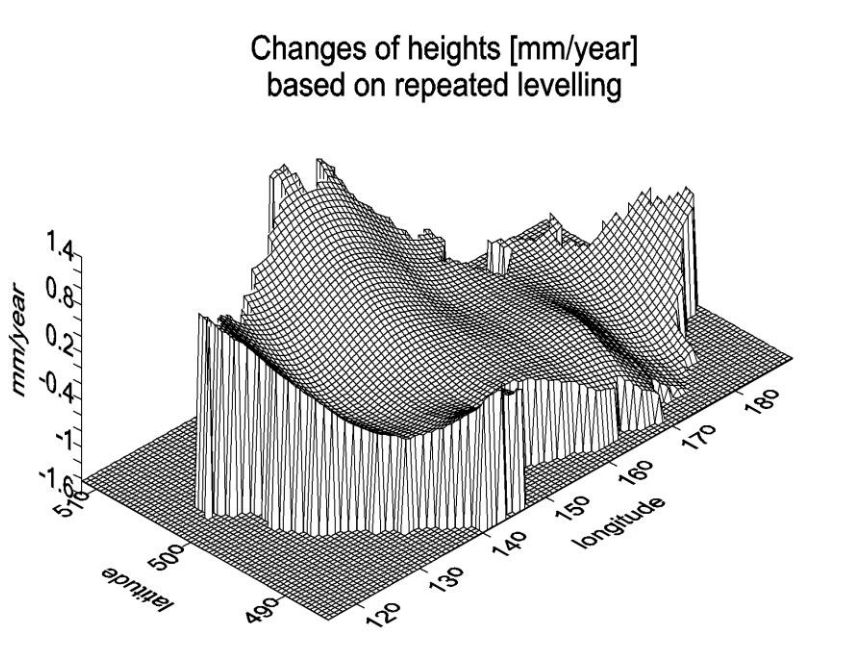


Vertical changes (tilts) of the baselines from GNSS and levelling

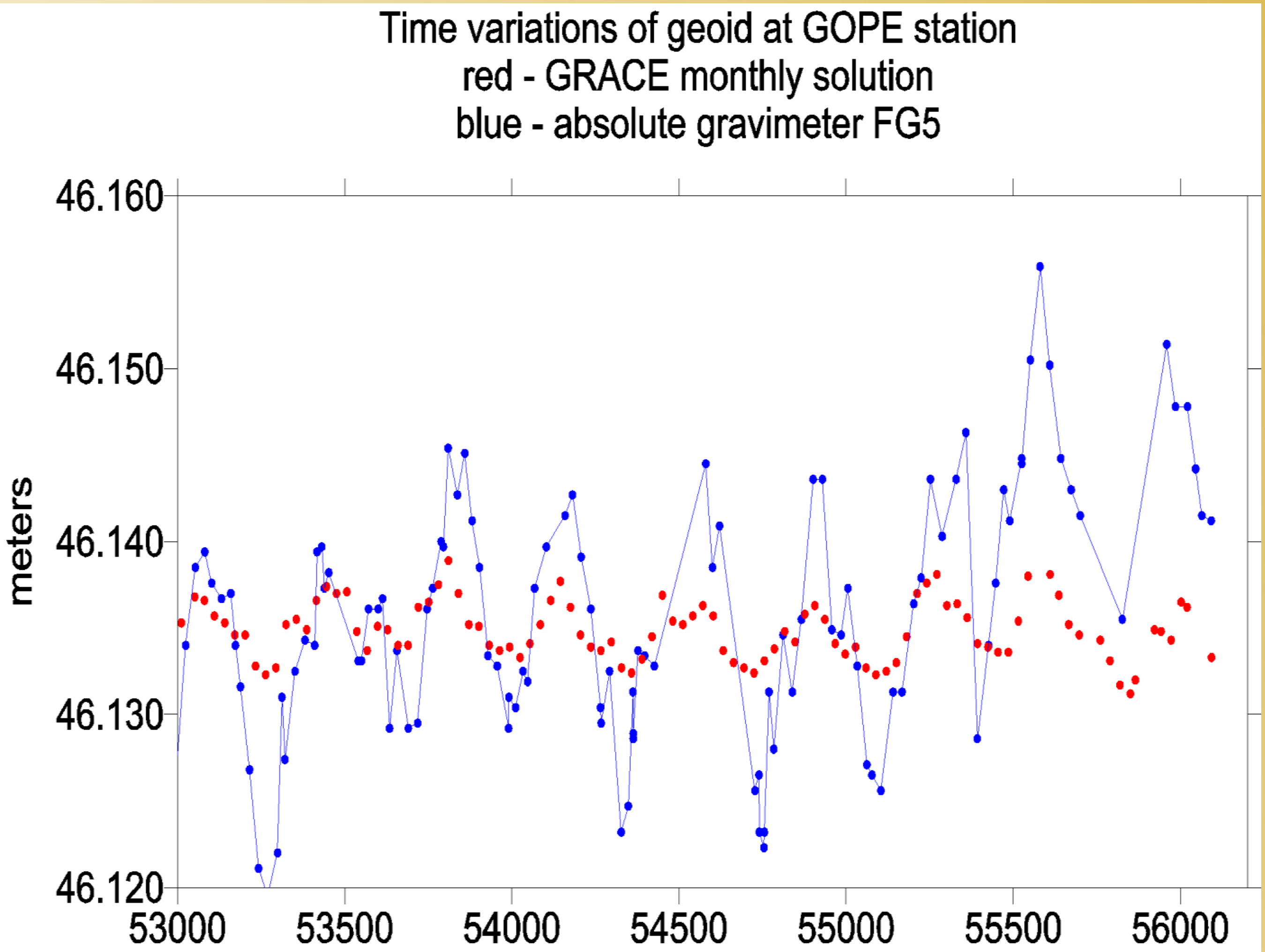


Changes of height differences (mm/y)





Changes of the gravity field (1): Time variations of the geoid heights at GOPE due to hydrology from GRACE (red) and repeated absolute gravimetry (blue)



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Uncertainties of AG Measurements

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Annex D - Calculation of uncertainty

Table 1. Instrumental uncertainty of the FG5 No. 215 gravimeter

Influence parameters x_i	Type A s_i	Type B a_i	Units	Variance $u^2(x_i)$	Sensitivity coefficients c_i	C…	
Distance measurement (He-Ne laser)	1.5E-11		m	2.3E-22	5.00E+01		
Clock (rubidium oscillator)	4.0E-12		s	1.6E-23	1.00E+02		
Beam verticality	3.0E-05		rad	9.0E-10	1.41E-04		
Test mass rotation		1.5E-02	rad/s	7.5E-05	6.00E-07		
Electronic phase shift		2.0E-08	s	1.3E-16	5.20E-01		
Residual air pressure		1.0E-04	Pa	3.3E-09	1.80E-05		
Magnetic field		5.0E-05	T	8.3E-10	7.00E-05		
Temperature change		5.0E+00	°C	8.3E+00	7.00E-10		
Coriolis effect		2.0E-04	m/s	1.3E-08	3.00E-05		
Determination of the Instrumental ref. height		2.0E-03	m	1.3E-06	3.00E-06		
Neglecting of non-constant gradient		4.0E-09	m/s^2	5.3E-18	1.00E+00		
Floor recoil effect		1.0E-08	m/s^2	3.3E-17	1.00E+00	3.3E-17	5.8E-09
Choice of the scaled fringes	1.0E-08		m/s^2	1.0E-16	1.00E+00	1.0E-16	1.0E-08
Measurement long-term reproducibility	1.0E-08		m/s^2	1.0E-16	1.00E+00	1.0E-16	1.0E-08
				Variance, $u^2(g)$		3.5E-16	m^2/s^4
				Stand. Uncert., $u(g)$		1.9E-08	m/s^2

Table 2. Uncertainty of the applied corrections

Influence parameters x_i	Type A s_i	Type B a_i	Units	Variance $u^2(x_i)$	Sensitivity coefficients c_i	Contribution to the variance $u_i^2(g)$	Contribution to the uncert. $u_i(g)$
Air pressure correction (admittance factor)		1.0E-11	$m/s^2/Pa$	3.3E-23	1.80E+03	1.1E-16	1.0E-08
Air pressure correction (pressure sensor)		2.0E+02	Pa	1.3E+04	3.00E-11	1.2E-17	3.5E-09
Earth tide correction		1.0E-08	m/s^2	3.3E-17	1.00E+00	3.3E-17	5.8E-09
Polar motion correction		5.0E-09	rad	8.3E-18	4.10E-02	1.4E-20	1.2E-10
Gradient correction	2.0E-08		s^2	4.0E-16	8.00E-02	2.6E-18	1.6E-09
Fringe size correction	2.0E-09		m/s^2	4.0E-18	1.00E+00	4.0E-18	2.0E-09
Diffraction correction		1.2E-08	m/s^2	4.8E-17	1.00E+00	4.8E-17	6.9E-09
Self attraction correction	3.0E-09		m/s^2	9.0E-18	1.00E+00	9.0E-18	3.0E-09
				Variance, $u^2(g)$		2.2E-16	m^2/s^4
				Stand. Uncert., $u(g)$		1.5E-08	m/s^2

Table 3. Combined uncertainty of the gravity acceleration determined at the height of 1.3 m above ground

Variance, $u^2(g)$	5.7E-16	m^2/s^4
Standard uncertainty, $u(g)$	2.4E-08	m/s^2
Confidence level, p	95	%
Coverage factor, k	2.0	
Expanded uncertainty, $U(g)$	4.8E-08	m/s^2
Relative expanded uncert., U_{rel}	4.9E-09	

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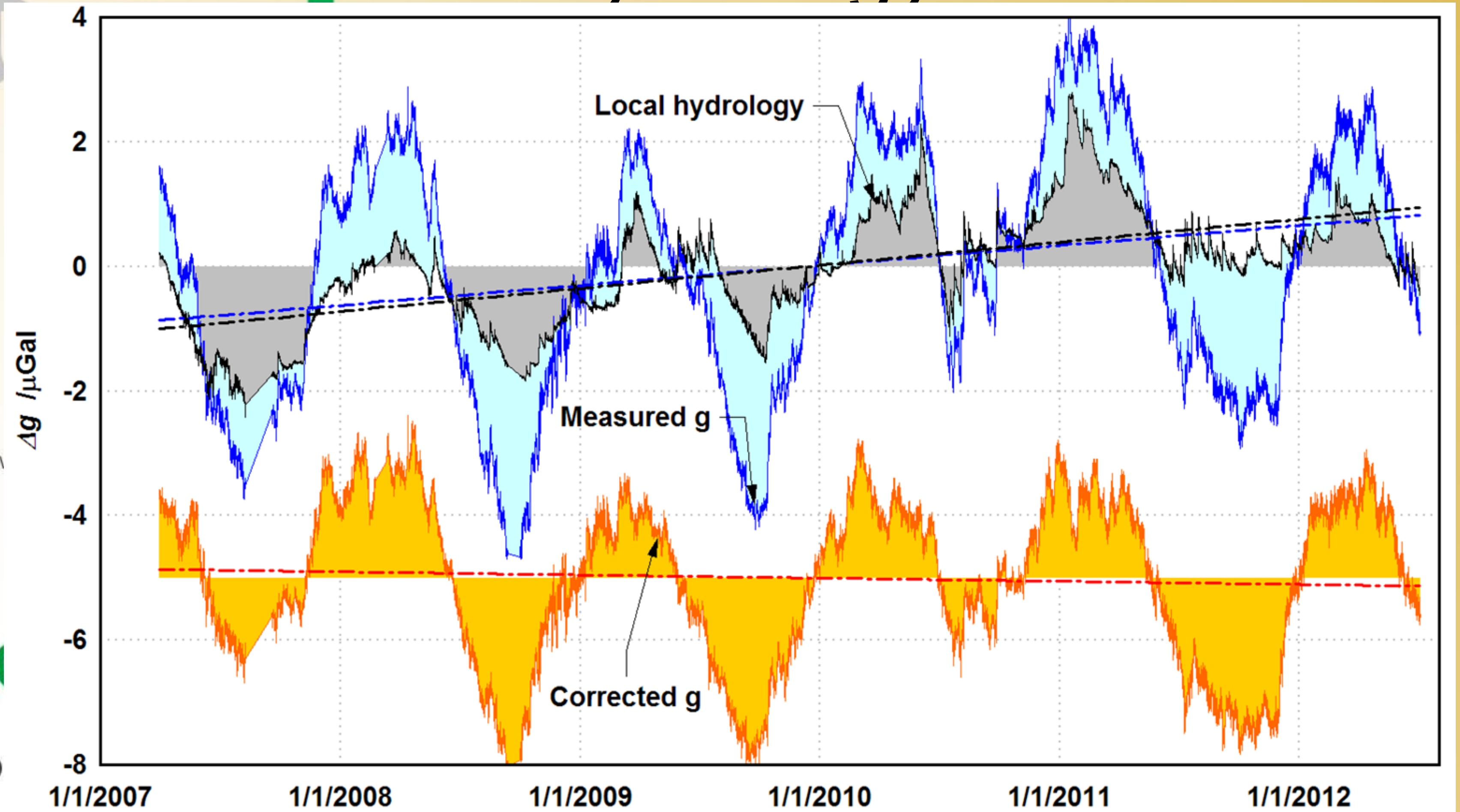
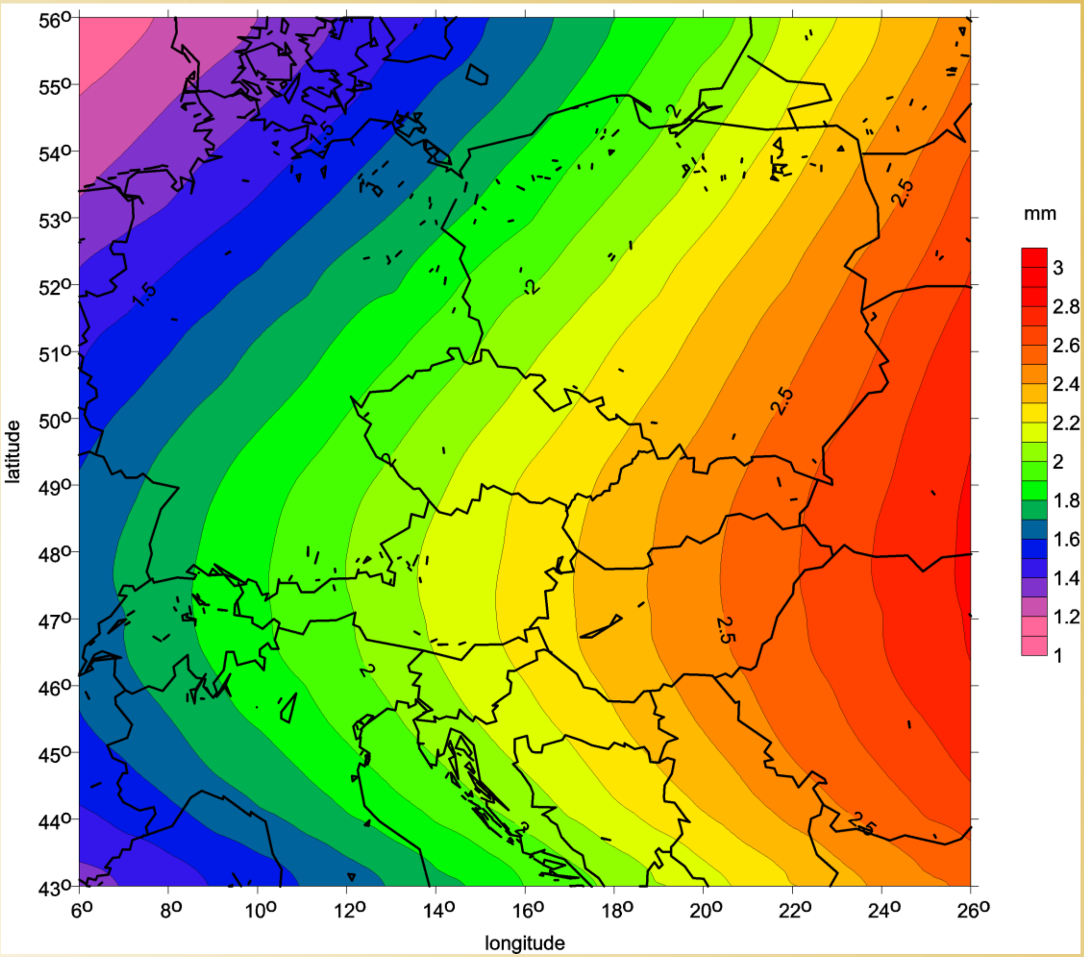
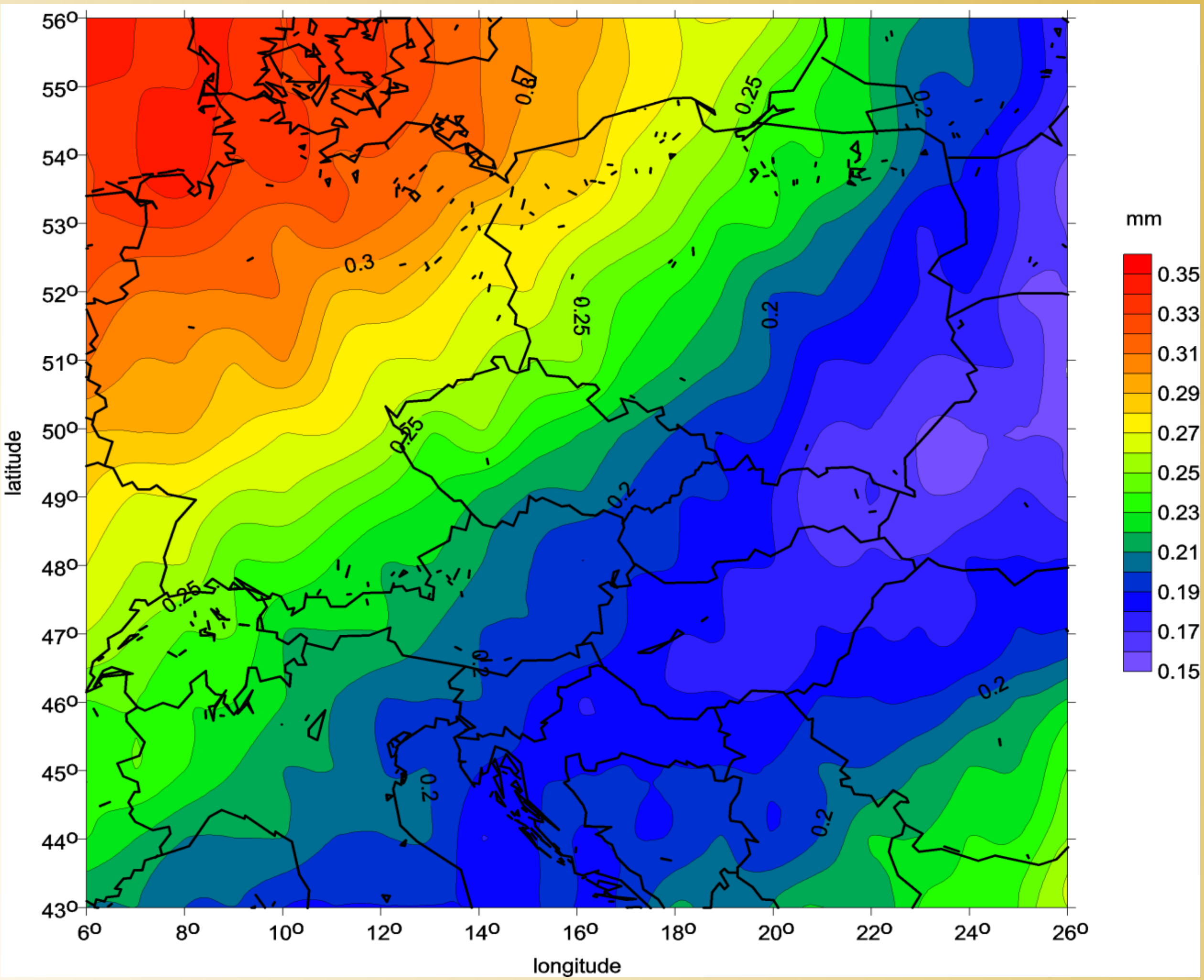
Absolute gravity reduced for local hydrology



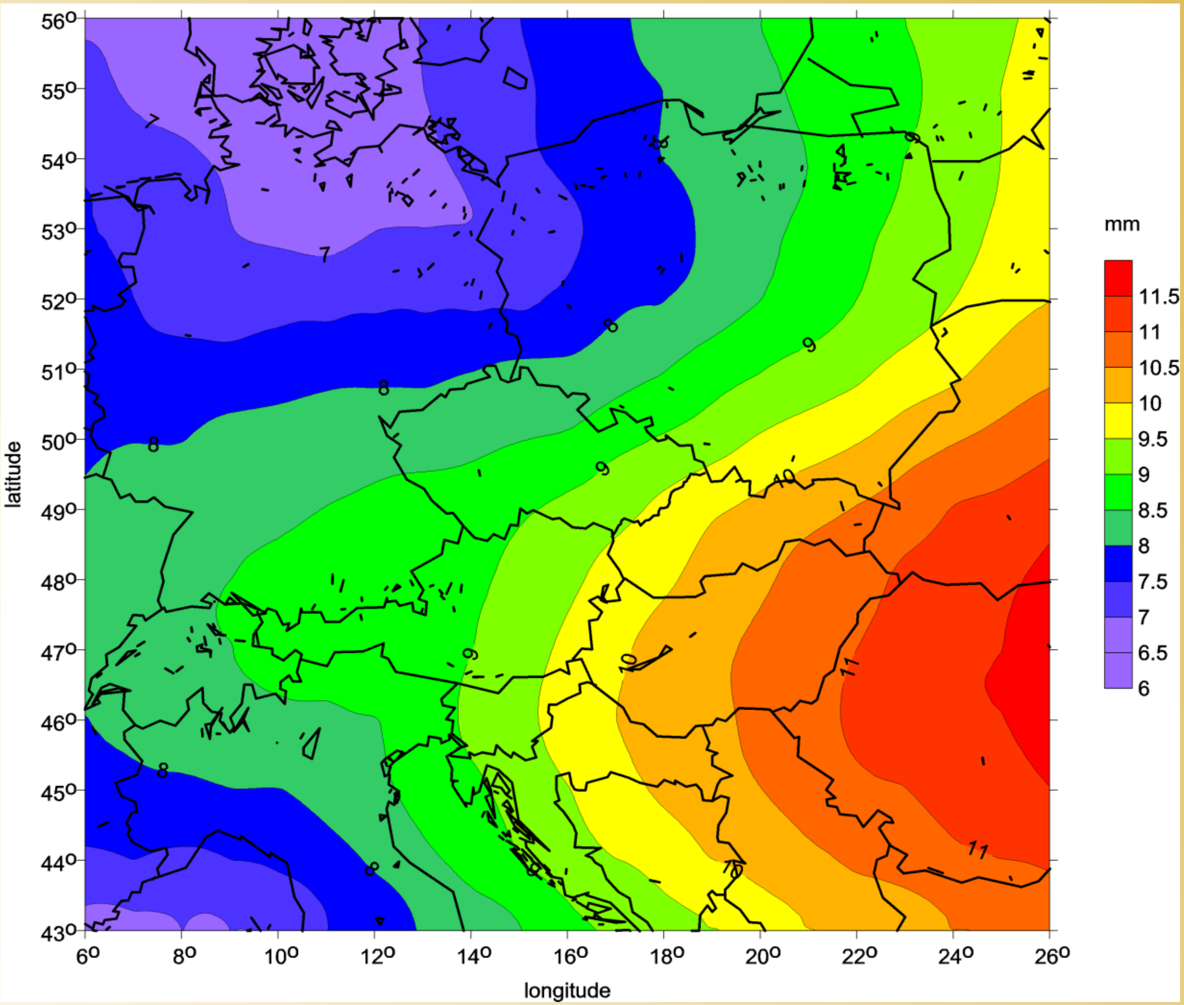
Geoid changes from GRACE 2002 – 2014: Annual amplitudes over the entire period



Geoid changes from GRACE 2002 – 2014: Semi annual amplitudes

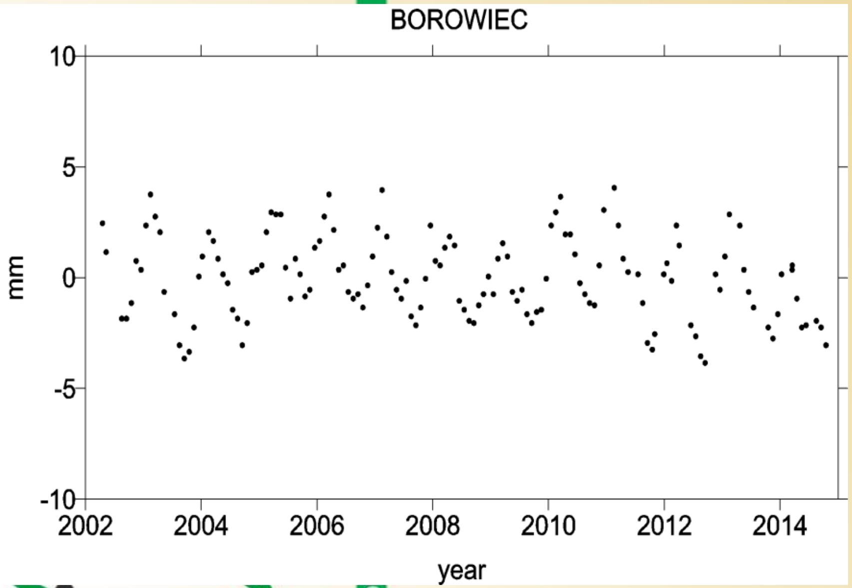


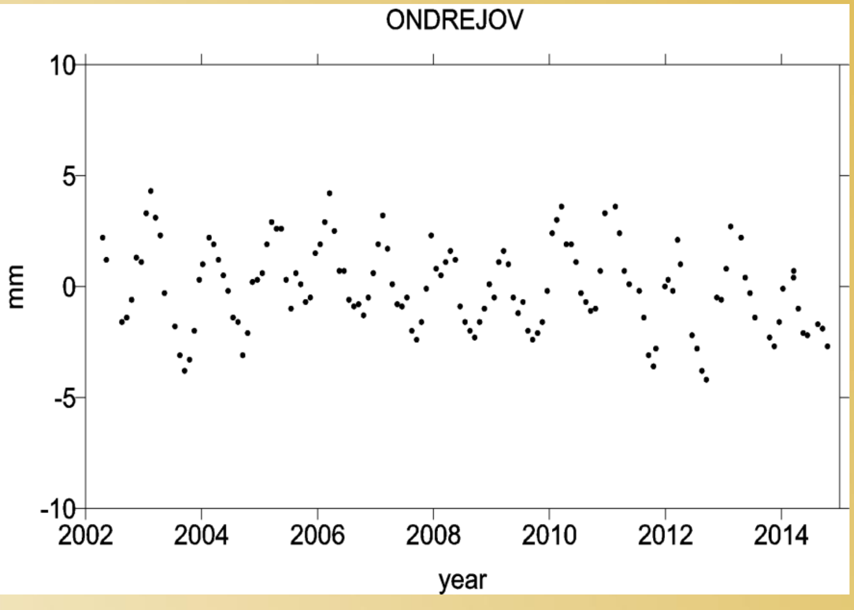
Differences MAX – MIN changes over the entire period



Geoid changes for permanent GNSS stations

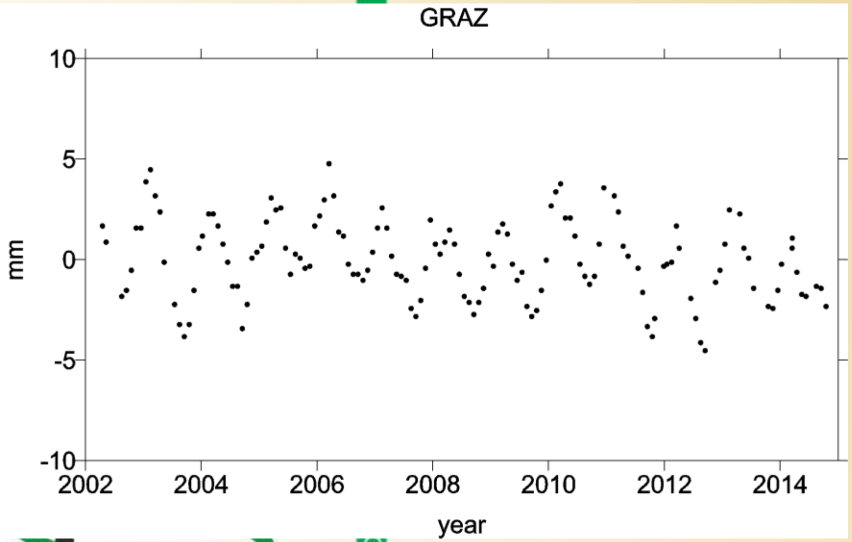
Borowiec **Pecný**

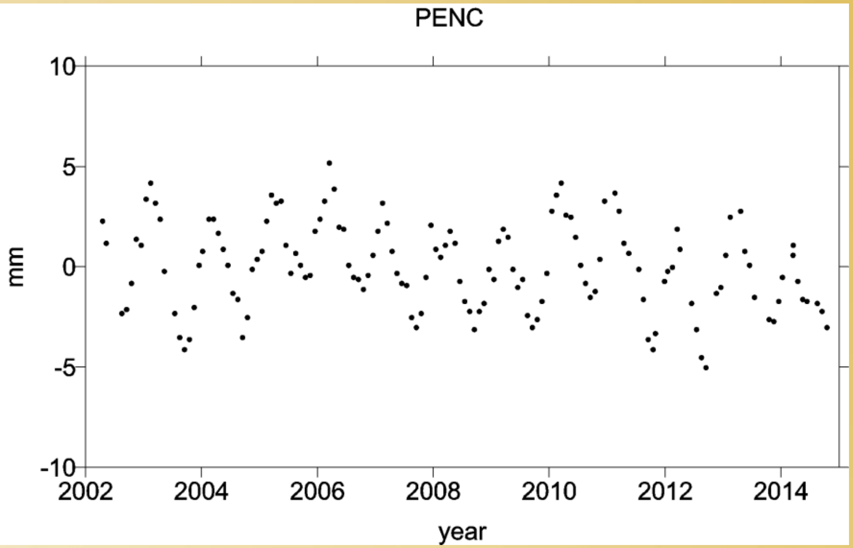




Geoid changes for permanent GNSS stations

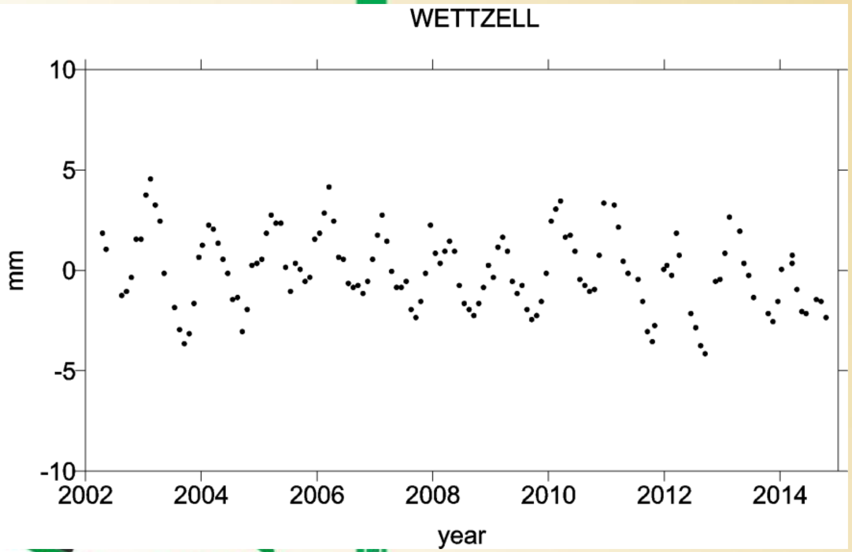
Graz **Penc**

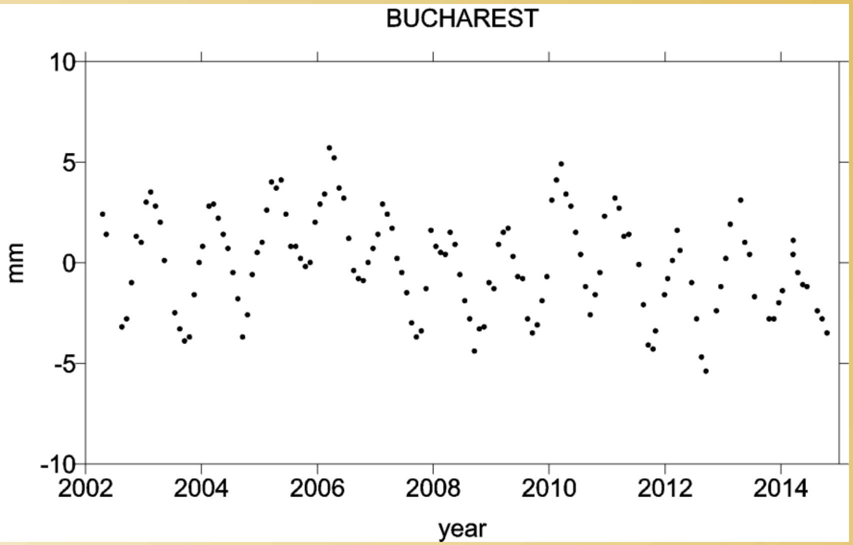




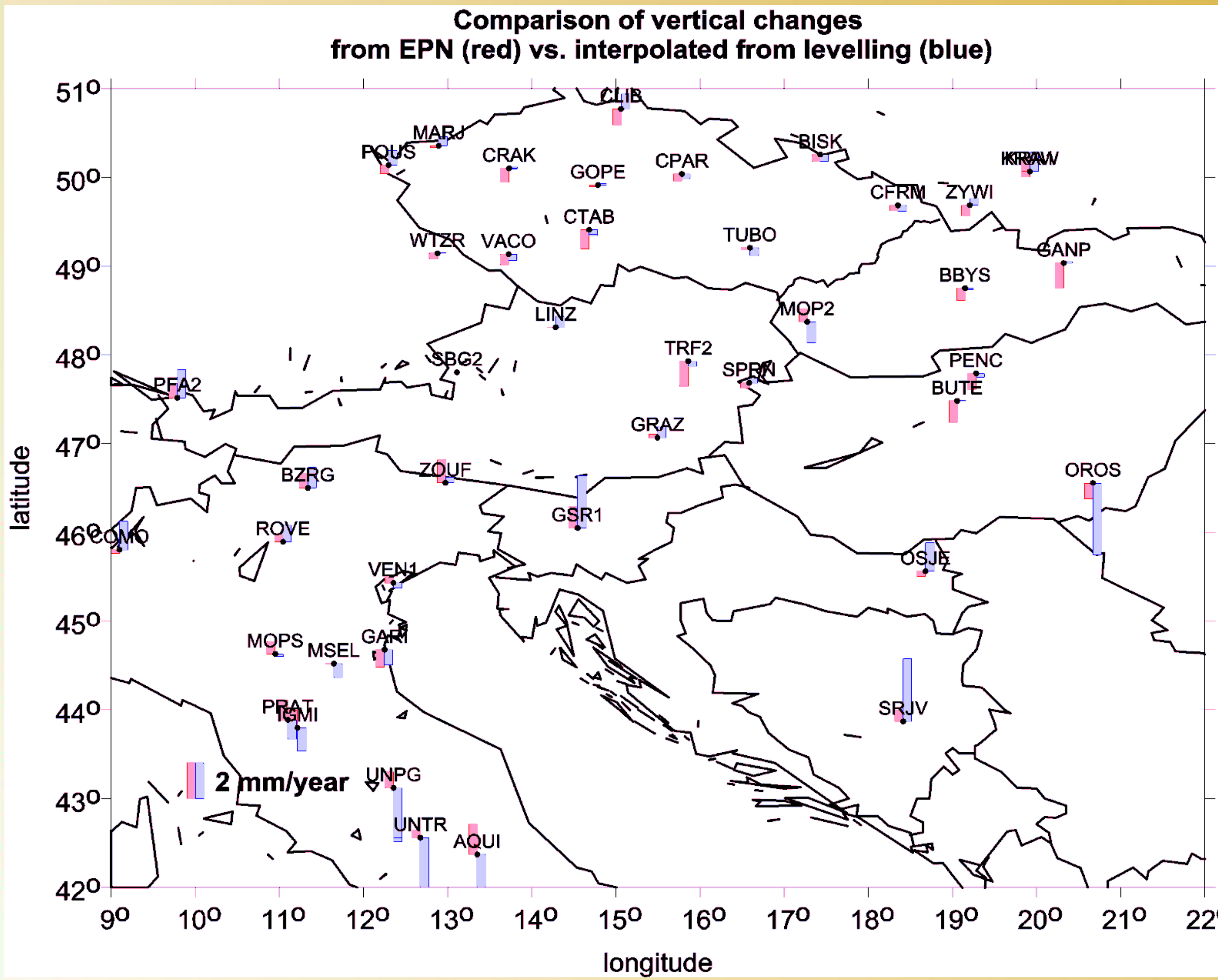
Geoid changes for permanent GNSS stations

Wettzell **Bucharest**

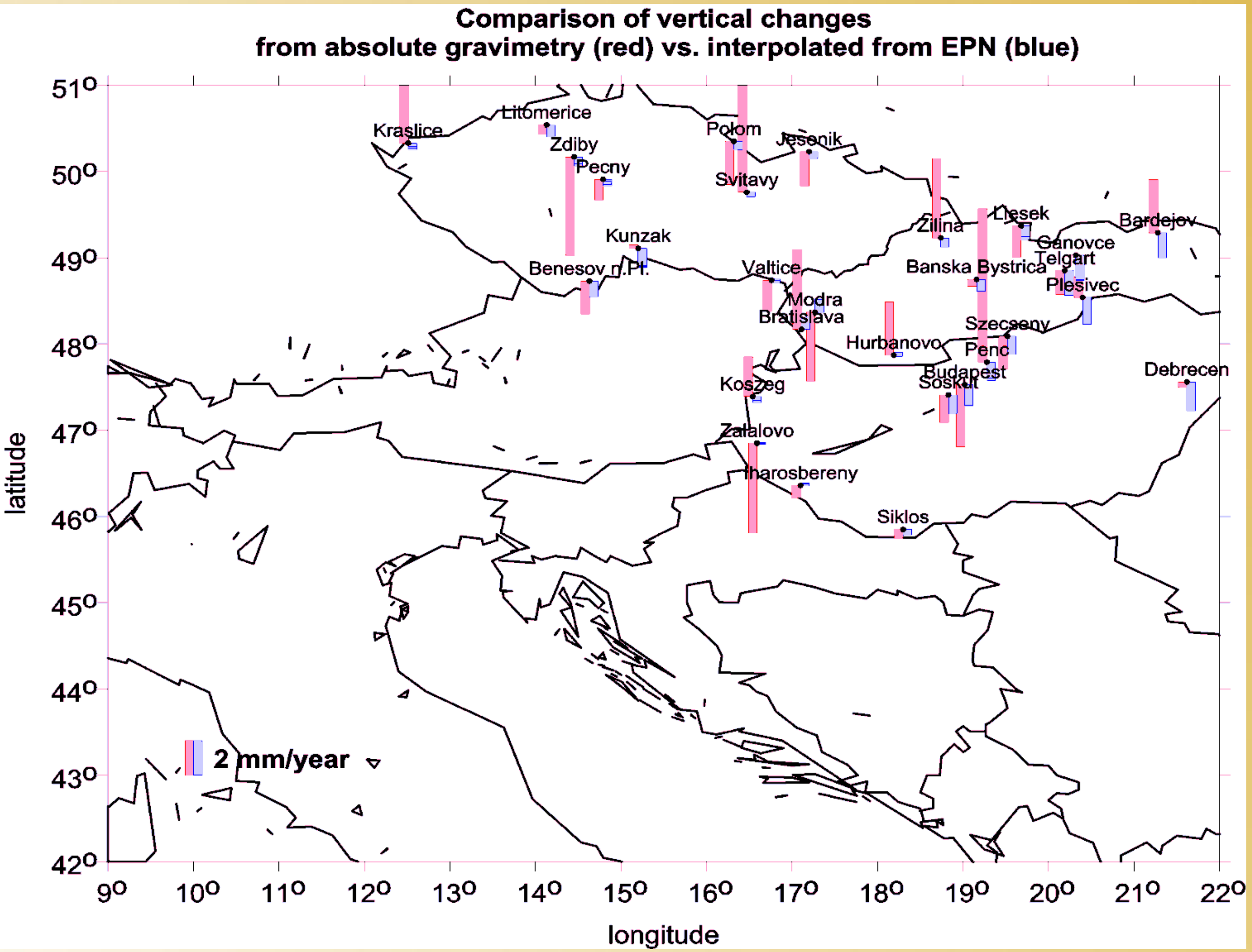




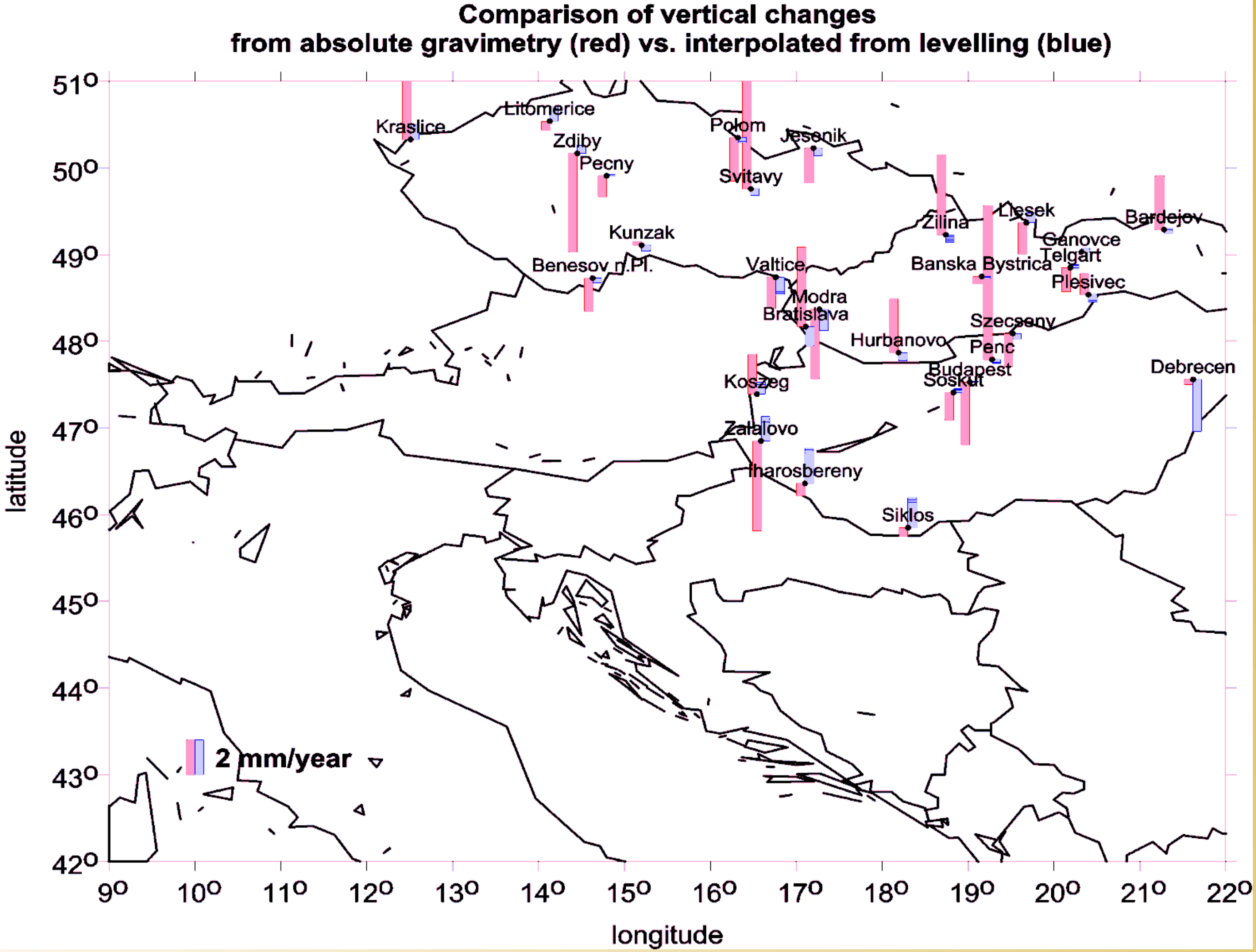
Comparison of vertical changes from EPN (red) vs repeated levellings (blue)



Comparison of vertical changes from absolute gravimetry FG5 No 215 (red) and EPN (blue)



Comparison of vertical changes from repeated absolute gravimetry (red) vs repeated levelling (blue)



Conclusions

1. Basic tendencies of vertical surface movements detected from repeated levellings and from GNSS observations coincide; absolute values differ within 2σ; results of repeated absolute gravity measurements do not generally coincide with levelling and GNSS, absolute values differ significantly; problem is probably in instrumental systematic effects and in hydrology
2. There is a little hope of extending repeated levellings over more countries in a coordinated way; BKG EVRS center can provide useful information resulting from EVRF development and maintenance
3. GNSS is the most promising tool for detection of surface movements – esp. with regard to the EPN development and increasing number of CORS networks; but numerous problems are to be solved
4. Gravimetry is a purely physical tool capable of detecting mass re-distributions in the Earth´s body, but it is liable to environmental disturbing effects (mainly hydrology); instrumental effects play also an important role;

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