Postglacial rebound in Estonia: Constraints from the measurements of Estonian geodetic networks

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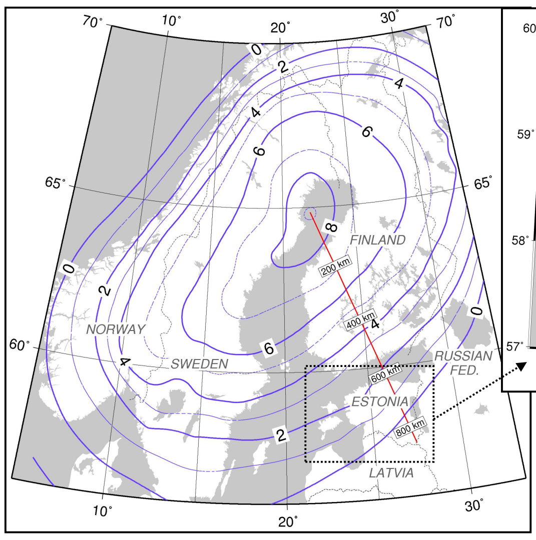
Introduction

Noticeable crustal movements in Estonia result mainly from the postglacial rebound (PGR) of northern Europe (fig.1).



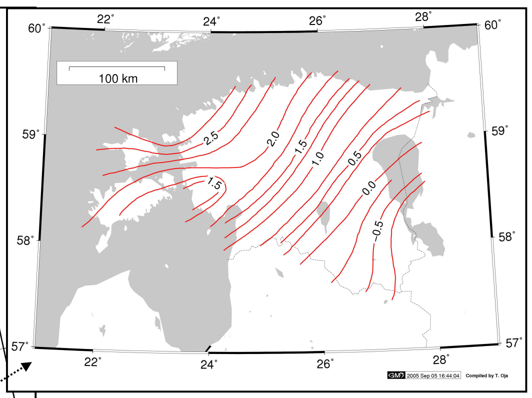


Figure 1. Postglacial rebound of northern Europe according to Ekman (1996) (left) and of Estonia (Torim 1998) (right). The isobases show crustal uplift rates (mm/yr) relative to mean sea level (apparent uplift)

The PGR has a clear impact on the maintenance of national geodetic networks (see fig. 2) because geodetic coordinates, gravity and geoid surface change in time.

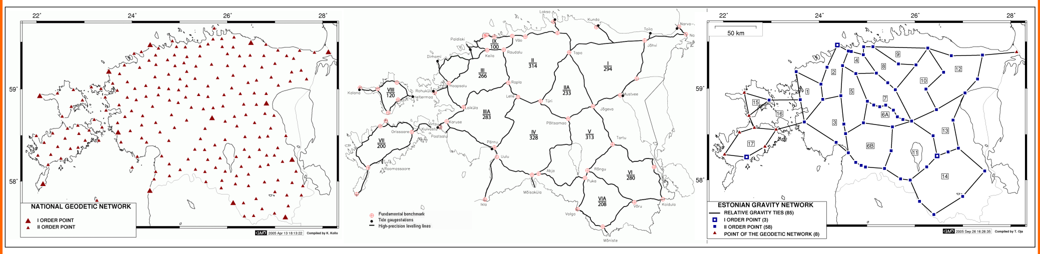


Figure 2. Estonian geodetic (GPS) network (left), levelling network (middle) and gravity network (right) (www.maaamet.ee)

How to keep the networks updated? Solutions:

- repeated measurements over a period of time (expensive and time-consuming)
- corrections from the maps of crustal movements (many maps available)
- use predictions of physical earth models (how well constrained?)

In Estonia, geological and sea level data, repeated levellings and gravity measurements are available to study vertical crustal movements and isostatic processes inside the Earth. Also one permanent GPS station is operating since 1996 for estimating 3D crustal deformations.

The most uplift maps for the region have been compiled on the basis of sea-level data records and precise repeated levellings (Vallner *et al.* 1988, Randjärv 1993, Ekman 1996, Kakkuri 1997, Torim 1998 etc.). Predicted rebound rates (radial velocities) based on the physical Earth models have been presented by Lambeck et al. (1998) and by Milne et al. (2001; see also BIFROST project homepage).

Geological sea-level records have also been studied and preliminary uplift rates deduced for Estonia and surrounding areas (eg. Saarse *et al.* 2003).

Aim

In this work I estimate secular gravity change on the basis of precise gravimetric data measured on the gravity network of Estonia. Near 70% of the relative gravity ties (see Fig. 2 right) have been measured 5-6 times in 1971/72, 1977, 1979/80, 1985-87 and in 1992-2004. Currently we have collected and inserted about 2500 observations into a digital database and that work will be continued. Later on I compare the observed rates of gravity change with rebound rates obtained by geodetic methods and also predicted by the Earth models.

Method

Several corrections to observed gravity data:

A) tidal correction applying tidal potential development and local parameters (gravity factor, phase lag)
B) atmospheric correction using local air pressure
C) free air correction
D) correction for polar motion

Gravity network adjustment:

New observation model with gravity change parameter $\dot g$ is introduced to the gravity network adjustment

$$y(t) = g^{T_0} + \boxed{\dot g^{T_0}(t - T_0)} + a + \sum_{p=1}^{r} D_p (t - t_0)^p + \sum_{k=1}^{m} Y_k z^k + \sum_{l=1}^{n} A_l \sin(2\pi t / T_l + \varphi_l) \qquad (1)$$

where
$y(t)$ – corrected reading of the gravimeter (mGal) at the observation time t,
g, $\dot g$ – gravity value at the epoch T_0 and it's rate of change (µGal per year, 1 µGal = 10 nm/s²).

All observations are cast into the system of linear equations and solved by least-squares method:

$$A\mathbf{x} = \mathbf{b} \quad \Rightarrow \quad A^T A\mathbf{x} = A^T\mathbf{b} \quad \Rightarrow \quad \mathbf{x} = (A^T A)^{-1} A^T\mathbf{b} \qquad (2)$$

where $\mathbf{x}$ is vector of unknown parameters (includes $\dot g_i$).
Error estimations are obtained from covariance matrix

$$\sigma_x^2 = \sigma_0^2 (A^T A)^{-1} = \sigma_0^2 Q_{xx} \qquad (3)$$

Results. Part I: Observed gravity change

The observed rates of secular gravity change (network solution with measurement data from 1977 and from 1992-2004) and surfaces of the change are presented in fig.3. Error estimations of observed rates stay between ±1.7 and ±3.3 µGal/yr.

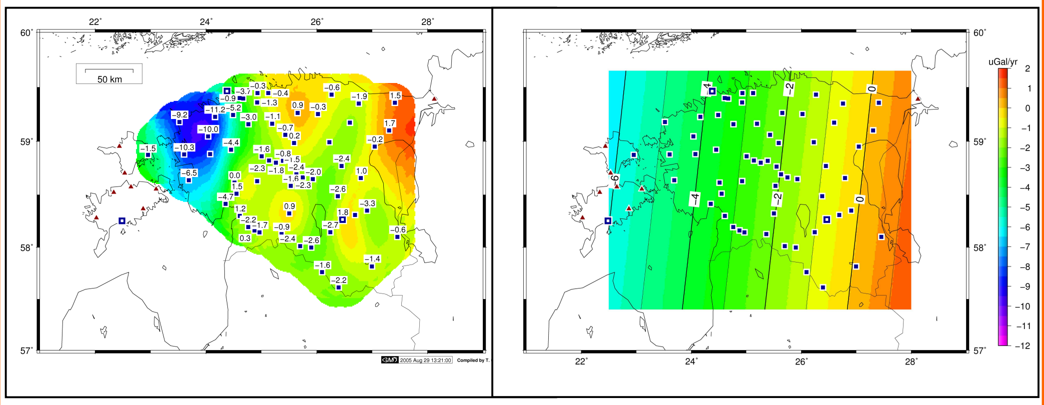


Figure 3. Observed rates of secular gravity change (left) and fitted linear surface (right)

Results. Part II: Gravity change and PGR

Gravity change is closely related to PGR because of the land uplift and mass redistribution inside the Earth. The contribution of both effects is efficiently described by the ratio $\dot g / \dot h$ (see Ekman and Mäkinen 1996) where $\dot h$ is absolute crustal uplift (mm/yr) relative to the Earth's centre of mass (radial velocity).

To interpolate uplift rates for the gravity points I select several published uplift maps (Randjärv 1993, Ekman 1996, Kakkuri 1997, Torim 1998) and predictions of two PGR models (Lambeck et al. 1998 and Milne et al. 2001). Apparent uplift rates were converted to absolute rates with formula

$$\dot h = \dot H_a + H_e + \dot N \qquad (5)$$

where
$\dot h$ is absolute and $\dot H_a$ apparent uplift,
H_e eustatic rise of mean sea level (in this work +1.1 mm/yr),
$\dot N$ uplift of geoid (about 6% of $\dot H_a$).

	Torim (1998)	Randjärv (1993)	Ekman (1996)	Kakkuri (1997)	Lambeck et al. (1998)	Milne et al. (2001)
Average	**-0.8**	**-1.7**	**-0.8**	**-2.1**	**-0.8**	**-1.1**
RMS	**1.0**	**4.5**	**1.0**	**7.3**	**1.0**	**1.4**
Min	**-2.9**	**-32.2**	**-3.0**	**-40.3**	**-3.6**	**-4.7**
Max	**1.3**	**2.2**	**1.3**	**14.4**	**1.0**	**1.8**
Range	**4.2**	**34.4**	**4.3**	**54.7**	**4.6**	**6.5**

Table 1. Statistics of the ratio $\dot g / \dot h$ (µGal/mm)

I found that interpolated uplift values from various sources differ more than ±1 mm/yr.

Based on observed gravity changes and various estimates of absolute uplift rates I compute the ratios $\dot g / \dot h$ for the points of Estonian gravity network (see table 1 and fig. 4).

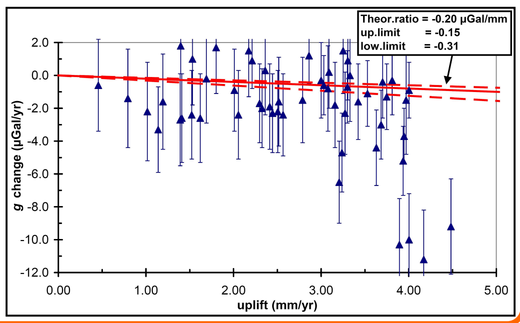


*Figure 4. Gravity change vs. uplift. Uplift rates interpolated from the map of Torim (1998). Red solid line describes ratio **–0.2 µGal/mm** introduced by Ekman and Mäkinen (1996). Dotted lines show upper and lower bounds of the ratio predicted by theoretical models.*

Conclusions

Main results:

- Observed rates of secular gravity change in Estonia between -11.2 and 1.8 µGal/yr with average error ± 2.5 (1-sigma)
- Fitted linear surface of the gravity change correlates with the pattern of uplift
- The gravity changes combined with various estimates of uplift give ratios between -3...+1.5 µgal/mm
- Estimated ratios are mainly outside from the theoretical bounds ⇒ noisy gravity data but also disagreement between observed/predicted uplift rates
- Observed gravity changes have better agreement with uplift rates introduced by Ekman (1996), Torim (1998), Lambeck et al. (1998) and Milne et al. (2001)

Discussion:

- The improvement of computational methods and software for gravity data process
- More gravity data (from 1971/72, 1979/80 and 1985-87) into digital database
- Repeated and new absolute gravity measurements in the gravity network to constrain network solution
- New consistent uplift maps and constrained regional PGR models on the basis of repeated observations and time series of geodetic and sea level data in eastern Europe

Acknowledgements

Isobases of Torim's (1998) and Randjärv's (1993) maps were digitized by J. Klaus and T. Kall (Klaus 2004). A grid of Ekman's map (1996) was digitized by B-G Reit and J. Mäkinen, Lambeck's map (1998) by M. Karjalainen, P-A Olsson and J. Mäkinen, Kakkuri's map (1997) by M. Poutanen.

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