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Using the Nordic Geodetic Observing System for land uplift studies

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Abstract

Geodetic observing systems have been planned and developed during the last decade. An ideal observing system consists of a network of geodetic observing stations with several techniques at the same site, publicly accessible databases, and as a product delivers data time series, combination of techniques or some other results obtained from the datasets. Globally, there is the IAG GGOS (Global Geodetic Observing System), and there are ongoing attempts to create also regional observing systems. In this paper we introduce one regional system, ~~NGOS~~ the (Nordic Geodetic Observing System) (NGOS) hosted by the Nordic Geodetic Commission (NKG).

spell out (acronym afterwards)

Data availability and accessibility are one of the major issues today. We discuss ~~on~~ in general data-related topics, and introduce a pilot database project of NGOS. As a demonstration of the use of such a database, we apply it for postglacial rebound studies in the Fennoscandian area. We compare land uplift values from three techniques, define GNSS, tide gauges and absolute gravim~~eter~~try, with the Nordic NKG2005LU land uplift model. for Fennoscandia ? The purpose is to evaluate the data obtained from different techniques and different sources and get the most reliable values for the uplift using publicly available data.

It is also important to consider the relation between geodetic observing systems and specific projects like ① DynaQlim (Upper Mantle Dynamics and Quaternary Climate in Cratonic Areas) or EPOS (European Plate Observing System). The natural aim of observing systems will be to produce data and other products needed by such multidisciplinary projects, but their needs may currently exceed the scope of an observing system. We discuss what requirements the projects pose to observing systems and their development.

① spell out before acronym

primary

1 Introduction

Permanent geodetic observing networks have been developed during the last decade to become the basic component of geodetic observing systems. The observing systems aim to provide better and more detailed information on ~~of~~ the global and regional gravity field, its temporal variation, crustal deformation, ~~and of~~ global changes in the Earth's shape, mass distribution, sea level, and the Earth orientation in the inertial frame. An ideal observing system consists of geodetic observing stations with several techniques at the same site, publicly accessible databases, and as products, data and combination of different observing techniques.

Globally, the IAG GGOS (International Association of Geodesy, Global Geodetic Observing System) is based on existing IAG Services, see (http://www.iag-aig.org/) for details and access points to the services and their products. Status and goals are described in Pearlman and Plag (2009). Parallel to the development of ~~the~~ GGOS, regional systems have been discussed and initiated. These include the European Combined Geodetic Network (ECGN) by EUREF (the IAG Commission 1 Sub-Commission 1.3.a for Europe; Ihde et al., 2004, 2005; Poutanen et al., 2013), and the Nordic Geodetic Observing System (NGOS) hosted by the Nordic Geodetic Commission (NKG, Poutanen et al., 2005, 2007).

rephrase as above

define

Observing systems produce data and other products which are typically combinations of different techniques, where the observed signals can be a mixture of several underlying physical phenomena. For example, height changes are measured by GNSS and related gravity changes by repeated gravity measurements. Mass changes are not visible in GNSS data, whereas the observed gravity change is the sum of mass and height changes. The combination of techniques can verify results of a single technique and help to quantify uncertainties between the techniques and help us to understand physical processes behind changes. (include some references here on this)

should this be geophysical processes?

There are several on-going projects which need such high-quality multi-technique data. As an example, we mention two: DynaQlim (Upper Mantle Dynamics and Quaternary Climate in Cratonic Areas, Poutanen et al., 2010) and EPOS (European Plate Observing System, http://www.epos-eu.org/). EPOS is an integrated solid Earth Sciences research infrastructure approved by the European Strategy Forum on Research Infrastructures (ESFRI) and included in the ESFRI Roadmap. DynaQlim is a regional coordination committee of the International Lithosphere Program (ILP) and ~~it has as its focus to~~ study ies ~~the~~ upper mantle dynamics, its composition and physical properties, (temperature and rheology), and Quaternary climate primarily on Fennoscandia, Northern Canada and Antarctica.

is there a better reference to EPOS?

Specific data needs of ~~in~~ such projects may exceed the scope of an observing system and this raises the ~~an~~ issue to discuss and develop the products of the ~~an~~ observing system. As an example of such dialogue, a joint meeting of GGOS and DynaQlim was organized in 2009 in Espoo, Finland (Gross and Poutanen, 2009). One of the goals was to discuss what specific data or products DynaQlim may expect from GGOS and what possibilities GGOS has to fulfill such requirements. An obvious shortcoming of GGOS is the density of the observing network. It is too sparse for regional studies, and there is a need for denser regional observing networks.

One of the major geodynamic processes acting ~~phenomena~~ in ~~the~~ Fennoscandia and Northern Canada is the land uplift caused by ~~the~~ Glacial Isostatic Adjustment (GIA). GIA is the response of the solid Earth to the time-varying load due to the waxing and waning of Northern Hemisphere glaciers and the varying sea level up to 130 m in about 100 000 yr cycles. rephrase * Taking into account the mass change between oceans and glaciers and upper mantle viscoelastic flow, there is a total of 5×10^{19} kg mass transportation during the glaciation cycle (almost 10^{-5} of the mass of the Earth; e.g. van Dam et al., 2008; Poutanen and Ivins, 2010).

The GIA signal, however, is contaminated by non-GIA-induced mass changes and crustal deformation. Separating GIA-induced contributions from other sources is not straightforward and using ~~Using~~ data from a geodetic observing system with multiple techniques can help in this task. However, the global network of GGOS is not sufficient to observe

* glaciers, causing sea levels to vary by up to 130 m in cycles of ~100 000 years.

GIA in detail because in the Fennoscandian rebound area there are only half a dozen GGOS stations. In Northern Canada, the number of stations is even smaller.

An improvement is to include permanent stations of a regional network. In Fennoscandia, there exists ~~is~~ the NGOS network, which contains the Nordic geodetic GPS/GNSS stations operated by the national mapping authorities. Many of these are also regularly visited by absolute gravimeters. A step further is the EPOS which is planned to be an open access infrastructure serving as primary source of data and tools for researchers in geosciences (http://www.epos-eu.org/).

define

rephrase

It is important to test the capability of current observing systems and regional networks, databases and other sources of information in GIA-related studies. The EUREF Technical Working Group decided in 2011 to propose a pilot project within ECGN (Poutanen et al., 2013). The project is meant to demonstrate the ideas and usefulness of a regional observing system in utilizing existing networks and databases. The ECGN network consists mostly of EPN (Euref Permanent GNSS Network) stations, which especially in Fennoscandia are too sparse for detailed studies of regional crustal deformation.

capitalize

A suitable network for such studies already exists in ~~the~~ Fennoscandian ~~area~~ as a result of the NKG NGOS task force in 2004–2010 (Poutanen et al., 2005, 2007). One of the authors of this paper (MP) proposed such a project for NKG and the NKG Presidium accepted it in 2012 under the name NCGN (Nordic Combined Geodetic Network). rephrase - is it really relevant?

As a part of the NCGN project, we have collected information of geodetic stations in the Fennoscandian and Baltic areas into a database using mostly the station list of NGOS. ~~The work was carried out as a part of Master's Thesis~~ (Kairus, 2012) ~~supervised at the Finnish Geodetic Institute~~. We describe the data in Sect. 2, comparison of different techniques and discussion of results are presented in Sect. 3, and Sect. 4 is left for conclusions.

NGOS stations?

2 Selection of data and previously published studies

The existing station list of NGOS (Poutanen et al., 2005) was taken as the starting point. We created an interface which contains metadata for those stations and links to different geodetic databases. The interface can be found on the NKG web pages (http://www.nkg.fi → NKG Data Banks). The station list database is also available as a clickable map interface (Fig. 1). For each station a page with station information and links to relevant databases was created (Fig. 2). The links include GNSS databases (IGS, EPN and SONEL), gravity databases (GGP, BGI), tide gauge databases (PSMSL and SONEL) and databases of VLBI, SLR and DORIS of respective IAG/GGOS services. In addition to data, links to relevant research papers are given.

define + reference

To demonstrate and study the usefulness of the database ~~in research~~ to study ~~of~~ GIA induced land uplift, we have chosen 12 stations. They are all located at ~~on~~ the coast~~s~~, have permanent GNSS stations with absolute gravity measurements and ~~they~~ are in the vicinity of a tide gauge. The locations are shown in Fig. 1 with blue dots.

There have been numerous campaigns and observations in ~~the~~ Fennoscandia for ~~the~~ land uplift studies using different techniques together and separately. Land uplift data from several previously published sources are collected here but there are several nuisances which are not properly handled. For example, tide gauge heights are orthometric, whereas GNSS refer to the ellipsoidal heights. Different techniques refer to different points, for example GNSS height refers either to the antenna or a benchmark on the ground whereas gravity is measured on a different point. Local ties are incomplete at most stations. A step forward was taken in the First Science Week of NKG in Reykjavik, March 2013 where the NKG database was decided to be developed and taken in use by the Working Groups of the NKG.

where it was decided to develop.. ..

2.1 GNSS data

~~The~~ GNSS measures three-dimensional coordinates, providing the station height above the ellipsoid. The time series and land uplift rates derived from the BIFORST

rephrase GNSS measures? → we derive!

GPS studies have the densest spatial coverage of all techniques at the moment. The stations have been operational since mid 90's, thus offering time series of almost 20 yr. There are several studies published, the first one by Johansson et al. (2002). Next generation of uplift rates were published in Lidberg et al. (2007), and the latest update in Lidberg et al. (2010). Uplift rates from GNSS time series can be seen in the first part of Table 1. We have chosen the results of Lidberg et al. (2010) (in gray in Table 1) for the comparison because the time series are the longest (maximum 10.2 yr) and the spatial coverage (with 85 stations) is the largest. GNSS processing software have developed markedly, making it possible to recompute satellite orbits in a unified reference frame and, in turn, giving a more consistent solution over the years. These are also in favor of choosing the latest solution. The error estimate of the uplift value based on the GNSS time series depends on the length of time series. For stations with long time series, the error estimate is 0.2 mm yr^{-1}, whereas for other stations the error is approximately 0.5 mm yr^{-1} (Lidberg et al., 2010). → in the presence of temporal correlations the error reduces much slower!

there is nothing grey in Tab. 1.

not entirely true

2.2 Absolute gravity data

Gravity changes provide information on mass changes related to the land uplift. The gravity change can be converted to height change by using a simple ratio, limited by theoretically computed bounds, and derived from observations,

$$\dot{g}/\dot{h} = -0.17\,\mu\mathrm{Gal\,mm}^{-1} \tag{1}$$

where $\dot{g}$ is the gravity change and $\dot{h}$ is the height change (e.g. Ekman and Mäkinen, 1996). There have been several campaigns with numerous absolute and relative gravimeters during the last decades in the Fennoscandian area. For this study, we have chosen the latest newest published absolute gravity values from Pettersen (2011), Gitlein (2010) and Breili (2009). The values (in µGal yr^{-1}) are shown in the second part of Table 1. For Tables 2 and 3 these values are converted to mm yr^{-1} using Eq. (1). The error of the absolute gravity measurements has been estimated to be ±0.3 µGal yr^{-1}

~~Reference? by all these teams?~~

(Timmen et al., 2011) for one instrument over five years. This corresponds to an error of ±1.8 mm yr^{-1} in the uplift value.

How representative is this error for all the AG time series?

2.3 Tide gauge data

Tide gauges measure the sea level relative to land and provide the longest continuous geodetic time series in the Fennoscandia. The water column scale records start already in 1774 in Stockholm and there are several tide gauges in the area dating back to the end of 19th century. There are several sources for the tide gauge data; we have used tide gauge trends derived in Woodworth and Player (2004), Peltier (1998, 2004) and Ekman (1998).

The trends of the Permanent Service for Mean Sea Level (PSMSL, Woodworth and Player, 2004) are the apparent mean sea level secular trends derived from PSMSL data with all available observations for each station. GIA-RSL (Glacial Isostatic Adjustment corrected Relative Sea Level trends) is the apparent sea level trends predicted from Peltier's GIA model (Peltier, 1998, 2004). The third set of trends is the values from Ekman (1998), which combine leveling and tide gauge data to define the sea level rise. We choose the PSMSL secular trends for the present comparison (Table 1), because they are not affected by other techniques (e.g. GIA model or fitting of data).

There are three different cases of uplift values which can be observed. From the GNSS time series one obtain the absolute uplift, height change of the crust relative to the mass centre of the Earth (origin of the global reference frame). With a tide gauge, one observes the apparent uplift value, i.e. change of the sea level relative to the shoreline. The relative uplift is the difference of the apparent uplift rates between two tide gauges. The apparent uplift differs from the absolute uplift due to the global eustatic sea level rise, rise of the geoid, as well as steric effects (salinity and density changes due to the thermal expansion). The relation between these is (Mäkinen et al., 2005)

$$\dot{h} = \dot{H}_\mathrm{a} + \dot{H}_\mathrm{e} + \dot{N} + \dot{H}_\mathrm{s} \tag{2}$$

where $\dot{h}$ is the absolute uplift rate, $\dot{H}_a$ is the apparent uplift, $\dot{H}_e$ eustatic rise of the sea level, $\dot{N}$ is the rise of the geoid, and $\dot{H}_s$ denotes ~~possible changes~~ ~~is~~ in steric effects. The last one is often neglected.

In Tables 2 and 3, the tide gauge values are corrected for the eustatic sea level rise using two different estimates, respectively; see the next chapter for discussion. The uncertainty estimate of the tide gauge trends is the lowest of the compared techniques, with a value of 0.2 mm yr^{-1} (Ekman, 1998), since the time series are the longest.

Why use Ekman for this when PSMSL gives also values?

2.4 NKG2005LU model

The NKG2005LU land uplift model (Vestøl, 2005, Ågren and Svensson, 2007), which was initiated and computed in the NKG working group for height determination, is used widely in the Nordic countries for practical applications. The observations used for the model stem mainly from two sources. Tide gauge and leveling values are taken from Ekman (1996) and GNSS values are from Lidberg (2004) and Lidberg et al. (2007). These data have been used to interpolate and extrapolate a continuous surface for land uplift. For areas where observational data are sparse or missing, the GIA model values from Lambeck et al. (1998) have been used. This includes especially the Karelian area.

indicate on Fig 1

3 Comparison and discussion

The land uplift values obtained from the individual techniques for the chosen 12 stations are given in Tables 2 and 3. Tide gauge and NKG2005LU values refer to the apparent sea level change and thus need to be converted to absolute uplift rate using a fixed value for the eustatic sea level rise in Eq. (2). The geoid rise due to the uplift is about 6 % of the uplift value near the center of the uplift maximum (Ekman and Mäkinen, 1996). We used this value in Eq. (2) for the geoid rise. The steric effects were ignored because they cannot be estimated and they are presumably small.

We give two sets of trend estimates which we computed assuming two different values for the sea level rise. In Table 2, the sea level rise has been taken to be 1.32 mm yr^{-1}, which is the value used in the NKG2005LU model (Vestøl, 2005). For Table 3, we have estimated the sea level rise by computing the mean absolute sea level value from our dataset (see Eq. 3). The mean and standard deviation of the trend estimates at each station have also been computed.

The results in Table 2 show the well-known pattern of high uplift rates at the Gulf of Bothnia (Vaasa, Skellefteå, Kramfors) with gradually falling values towards the edges of the rebound area. The NKG2005LU model shows quite low values for the Norwegian sites compared to the latest GNSS solution. This is most likely due to the fact that in the model the older version of BIFROST solutions (Lidberg et al., 2007) were used and these old values include only Swedish and Finnish sites. The standard deviations for the stations range from 0.6 (Skellefteå) ~~and~~ to 1.7 mm yr^{-1} (Bodø), indicating more stable land uplift trends on the Baltic Sea, while more variability is seen on the Atlantic coast and Danish straits. The mean of the standard deviations is 1.1 mm yr^{-1}. The values of Table 2 are depicted in Fig. 3.

The contemporary global sea level rise is known to be about 3 mm yr^{-1} (e.g. Cazenave and Llovel, 2010) which is considerably more than the value used in the NKG2005LU model. The lower value was based on the mean sea level rise in the Baltic Sea 1891–1990 (Vestøl, 2005). For Table 3, a new value of the sea level rise was computed as a mean of the chosen stations,

$$\dot{H}_e = \frac{1}{n}\sum_{i=1}^{n}\left\{\left(\dot{h}_i \times 0.94\right) - \dot{H}_{a,i}\right\} \qquad (3)$$

where $\dot{H}_e$ is the mean sea level rise, $\dot{h}_i$ is the absolute land uplift value from GNSS, $\dot{H}_{a,i}$ is the apparent sea level change from tide gauge data (Table 1) and n is the number of stations. The value 0.94 scales the GNSS derived uplift value for the 6 % geoid rise (Ekman and Mäkinen, 1996). We obtain the value for $\dot{H}_e = 3.03 \pm 1.04$ mm yr^{-1}, which agrees coincides with the contemporary sea level rise values from satellite altimetry (e.g. Cazenave and Llovel, 2010).

Table 3 shows the values of land uplift using the value for sea level rise computed above. The standard deviations vary from 0.3 to 1.8. The mean of the standard deviations diminishes from 1.16 $\mathrm{mm\,yr^{-1}}$ to 0.99 $\mathrm{mm\,yr^{-1}}$, which is not surprising, since a mean value computed with this dataset was used. The values of Table 3 are depicted in Fig. 4.

Comparison of techniques is challenging since they measure height relative to different reference levels and conversions are needed to bring all measurements to the same system. Stations with multiple techniques can be used to study the differences and similarities of the measurement techniques, since different techniques are affected by different geophysical processes phenomena, e.g. GNSS observes ellipsoidal height change, a gravimeter observes gravity change due to the height change and redistribution of masses, and tide gauge data are affected by the sea level change and local uplift.

We made a comparison using the values of ten selected stations in Table 3. The first item is to find a plausible estimate for the sea level rise because it is required needed to transform the tide gauge values into same reference level as the GNSS data. The value strongly depends on the time span of our time series. The global sea level rise is currently accelerating and thus the selection of the time series length used to estimate the rise may play an important role. If the trend of sea level is computed for the same period of time when GNSS has been operable (last 20 yr), the values differ markedly from the values of the whole tide gauge record. There might also be large spatial differences, since, e.g., the melt waters from glaciers are not distributed equally around the Earth (Tamisiea et al., 2001).

The global sea level rise of the last century was about 1 $\mathrm{mm\,yr^{-1}}$ (Church et al., 2001). Similar values were obtained for the Baltic Sea (Johansson et al., 2003) but the question remains whether the same global sea level rise value can be used for the Norwegian coast as for the Baltic. The Baltic Sea is a semi-closed basin where the effect of the North Atlantic Oscillation (NAO) (e.g. Johansson et al., 2003, 2004) and the effect of the meridional wind (Johansson et al., 2012) is noticeable. The strength

of prevailing westerly winds will push less or more water through the Danish straits, thus giving rise up to decadal variation of the sea level rise in the Baltic, following the general trend of the NAO index. In general, the Baltic sea follows the sea level rise of the North Sea and Northern Atlantic, but decadal anomalies can exist as discussed in (Johansson et al., 2003). rephrase

In the NKG2005LU model, (Vestøl, 2005) used the value 1.32 $\mathrm{mm\,yr^{-1}}$ for the sea level rise, which was the best estimate for the Baltic Sea in 1891–1990 (the value used in Table 2). From satellite altimetry the sea level rise of the last decade is about 3 $\mathrm{mm\,yr^{-1}}$ (Cazenave and Llovel 2010, Church and White 2011, Johansson et al., 2012). Using the values in Table 1 and Eq. (3) we computed the sea level rise based on the ten stations in our example. The value, 3 $\mathrm{mm\,yr^{-1}}$ coincides well with the global value given by (Cazenave and Llovel, 2010). This value is used in Table 3.

The absolute gravity measurements are very sensitive to environmental changes (nearby sea, groundwater, etc.). In many cases, the AG time series may contain only a few observations. Therefore, the difference in the trend estimate from either short or long time series can be significant and any anomalous observation may affect the trend. This can be seen in the case of Onsala and Copenhagen, where changes in the sea level of Danish straits affect the measurements noticeably (Müller et al., 2010; Timmen et al., 2011).

In Table 3 all standard deviations are greater than 1 are coming from cases where the gravity-based values are deviating from the three other techniques. We computed also the case where the AG observations were neglected (last two columns in Table 3). As one can see, the standard deviation diminished significantly, from the mean value of 0.99 to 0.60. More data are needed to make a final conclusion in general on the usefulness and reliability of the AG time series.

In data processing, problems may also stem from the use of different theoretical models. For example, for both GNSS and gravity computations, the solid Earth tide and ocean tidal loading are taken into account. Differences in these models' reference frames have been shown to produce spurious signals in GNSS computation (Fu et al., 2012). Also different handling of the solid earth tide in these two specific cases may produce a latitude-dependent bias (Poutanen et al., 1996).

Another theoretical aspect is that the gravity values were transformed using the ratio $-0.17\,\mu\text{Gal}\,\text{mm}^{-1}$. This value has been argued in the literature (Wahr et al., 1995; Ekman and Mäkinen, 1996; Mäkinen et al., 2005; Gitlein, 2010). It is a modest approximation, but not necessarily the optimum one. When more gravity data are processed and values also from the sinking subsiding areas are used, the accuracy of the ratio will most likely improve (Mäkinen et al., 2006).

In this study, we have shown that data comparisons are needed to exploit the full potential of the geodetic networks. To fully utilize the potential of different techniques and measurements and to avoid problems with different models chosen for data handling, all data should be processed for the same time period and using the same models.

One concern with this type of review study is that the user has no control over the observations or data reduction. The authors of the published results have chosen the best observations and models for their study. Thus, the values need to be taken as they are and trust that differences in data selection and processing do not distort the comparison markedly. In order to make comparisons possible and reliable researchers should document what they have done in detail. Such information can nowadays be easily embedded into appendixes or other electronically saved background information. Such information should be available in the database.

4 Conclusions

During the last decade, geodesists have proposed and developed regional and global observing systems with several observing techniques at the same site, databases, and combination of different observing techniques. In Nordic countries, the proposed observing system NGOS, organized by the NKG, includes stations in the Nordic countries and Baltic States up to Iceland and Greenland. The first goal of this study was to create a simple database offering access to the network stations and the related data.

This was realized by collecting available information and providing an interface with metadata and relevant links to the users.

The second goal was to demonstrate the use of the database in geodetic studies. Here we carried out land uplift studies using a set of coastal geodetic stations and compiled uplift values obtained by three techniques: GNSS, TG, AG. The results were then compared to the NKG2005LU land uplift model to estimate values for the present day uplift. We conclude that the best compatibility is obtained between continuously measuring techniques, i.e. continuous GNSS and tide gauges. The outcomes of techniques are difficult to compare because they measure different phenomena and their reference levels are not the same. More work is needed to solve for this issue.

Integrity and reliability are essential when combining multi-technique data. These include standardized techniques to process the original observations, unified models, and accessible original data and background information. Geodetic observing systems are on a way towards the goal.

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for

Table 1. Trend estimates of all techniques and ~~different~~ sources for the selected sites (see Fig. 1). AG = absolute gravity, TG = tide gauge. In *italic* are the values chosen for each station for the comparison. Model is the NKG2005LU uplift model.

Station	GNSS ($mm\,yr^{-1}$)			AG ($\mu Gal\,yr^{-1}$)			TG ($mm\,yr^{-1}$)			Model ($mm\,yr^{-1}$)
	Lidberg 2010	Lidberg 2007	Johansson 2002	Gitlein 2010	Pettersen 2011	Breili 2009	PSMSL	GIA-RSL	Ekman 1998	Vestøl 2005
Metsähovi	*5.21*	4.26	5.4	*−0.88*	−0.5		*−2.08*	−2.02	−2.28	*2.59*
Vaasa	*9.28*	8.62	10.7	*−1.22*	−2.2		*−7.11*	−8.66	−7.62	*7.19*
Skellefteå	*10.95*	9.61	10.7	*−1.88*	−1.8		*−8.25*	−9.63	−8.75	*7.84*
Kramfors	*10.11*	9.24	10	*−1.44*			*−6.38*	−8.01	−7.57	*7.6*
Mårtsbo	*8.86*	6.74	7.3	*−1.56*	−1.2		*−5.94*	−6.52	−5.9	*5.63*
Copenhagen	*1.26*	−0.24		*0.19*			*0.6*	−0.26	0.24	*−0.39*
Onsala	*4.05*	2.66	−0.4	0.5	*−0.8*		*0.32*	−1.85	−1.99	*0.84*
Oslo	*6.51*	5.78				*−0.6*	*−3.75*	−4.33	−4.1	*2.86*
Stavanger	*2.9*	1.18			−0.1	*−0.2*	*0.37*	−1.14	0.19	*−0.39*
Ålesund	*3.72*					*−0.4*	*0.82*	−0.85		*0.22*
Bodø	*6.39*					*−0.5*	*−1.23*	−1.56		*2.15*
Tromsø	*4.15*	2.3	4		−0.2	*−0.5*	*−0.02*	−1.16	−3.06	*0.95*

(uses

uplift trends for

Table 2. Comparison of different techniques ~~using~~ the eustatic sea level rise of 1.32 $mm\,yr^{-1}$). AG is absolute gravity (converted using Eq. 1), TG is tide gauge and Model is the NKG2005LU uplift model values converted to the absolute uplift values using Eq. (2). Mean is the mean value of four techniques and Stdev is the standard deviation.

SD

Station	GNSS	AG	TG	Model	Mean	Stdev
Metsähovi	5.21	5.18	3.62	4.16	4.54	0.79
Vaasa	9.28	7.18	8.97	9.05	8.62	0.97
Skellefteå	10.95	11.06	10.18	9.74	10.48	0.63
Kramfors	10.11	8.47	8.19	9.49	9.07	0.89
Mårtsbo	8.86	9.18	7.72	7.39	8.29	0.86
Copenhagen	1.26	−1.12	0.77	0.99	0.47	1.08
Onsala	4.05	4.71	1.06	2.30	3.03	1.66
Oslo	6.51	3.53	5.39	4.45	4.97	1.28
Stavanger	2.90	1.18	1.01	0.99	1.52	0.92
Ålesund	3.72	2.35	0.53	1.64	2.06	1.34
Bodø	6.39	2.94	2.71	3.69	3.93	1.69
Tromsø	4.15	2.94	1.43	2.41	2.73	1.13

SD is an internationally known abbrev. for standard deviation see Tab 2.

Table 3. Comparison of different techniques using the eustatic sea level rise of 3.03 mm yr^{-1}. AG is absolute gravity (converted using Eq. 1), TG is tide gauge and Model is the NKG2005LU uplift model values converted to the absolute uplift values using Eq. (2). Mean is the mean value of four techniques and Stdev is the standard deviation. Mean2 and Stdev2 are computed without the absolute gravity values (see text).

Station	GNSS	AG	TG	Model	Mean	Stdev	Mean2	Stdev2
Metsähovi	5.21	5.18	5.44	5.98	5.45	0.37	5.54	0.40
Vaasa	9.28	7.18	10.79	10.87	9.53	1.73	10.31	0.90
Skellefteå	10.95	11.06	12.00	11.56	11.39	0.48	11.50	0.53
Kramfors	10.11	8.47	10.01	11.31	9.97	1.16	10.48	0.72
Mårtsbo	8.86	9.18	9.54	9.21	9.20	0.28	9.21	0.34
Copenhagen	1.26	−1.12	2.59	2.81	1.38	1.80	2.22	0.84
Onsala	4.05	4.71	2.88	4.12	3.94	0.76	3.68	0.69
Oslo	6.51	3.53	7.21	6.27	5.88	1.62	6.66	0.49
Stavanger	2.90	1.18	2.83	2.81	2.43	0.83	2.85	0.05
Ålesund	3.72	2.35	2.35	3.46	2.97	0.72	3.18	0.73
Bodø	6.39	2.94	4.53	5.51	4.84	1.48	5.48	0.93
Tromsø	4.15	2.94	3.24	4.23	3.64	0.65	3.88	0.55

NGOS

Fig. 1. The stations in the database. The blue dots show the stations chosen for the comparison (see below). Map: Google.

→ ridicole Karelian area

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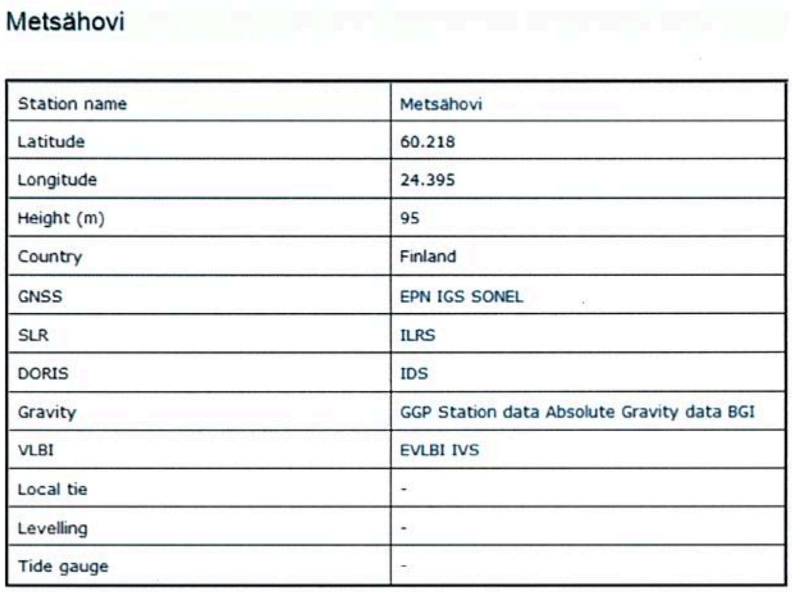

Metsähovi

Station name	Metsähovi
Latitude	60.218
Longitude	24.395
Height (m)	95
Country	Finland
GNSS	EPN IGS SONEL
SLR	ILRS
DORIS	IDS
Gravity	GGP Station data Absolute Gravity data BGI
VLBI	EVLBI IVS
Local tie	-
Levelling	-
Tide gauge	-

Fig. 2. Database entry for station Metsähovi, containing station coordinates, and links to various databases with observations from Metsähovi.

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Using the Nordic Geodetic Observing System for land uplift studies

M. Nordman et al.

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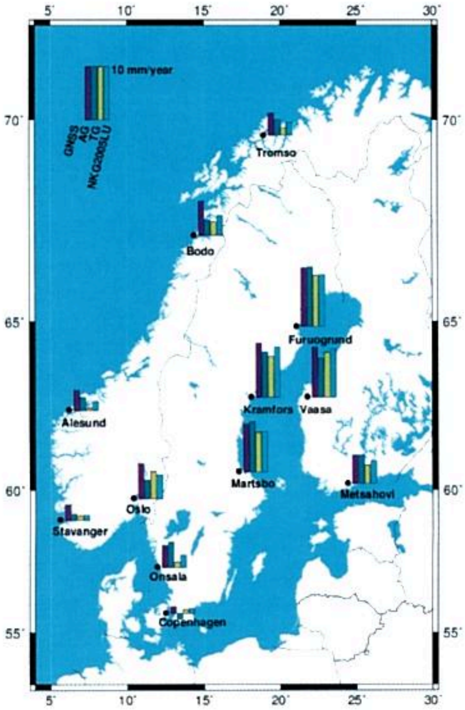

Fig. 3. Land uplift values with the sea level rise estimate of 1.32 mm yr^{-1} (Table 2).

→ could be better → GNSS and AG do not depend on sea level!

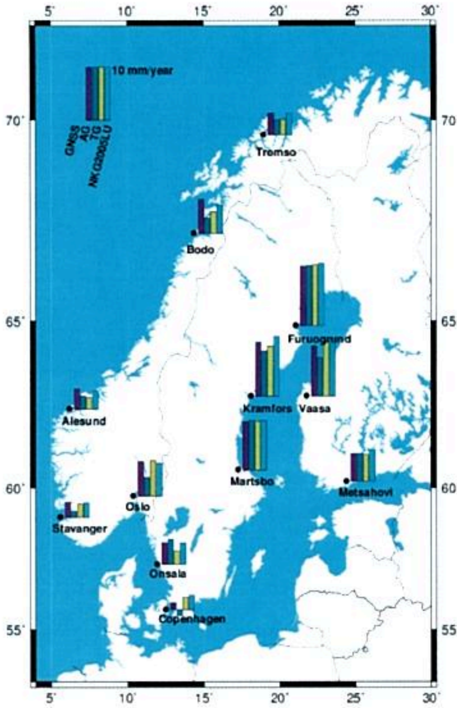

Fig. 4. Land uplift values with sea level rise estimate of 3.03 mm yr^{-1} (Table 3).

See Fig 3.