Tide gauge monitoring using GPS

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Abstract. In this work we have studied accuracy of GPS for tide gauge stability monitoring as well as possibilities for observing the absolute sea level rise of the Baltic Sea with GPS and tide gauge time series. Our determination give the average sea level rise for the long, up to 120 years, time series 1.9 ± 1.0 mm/year, and when corrected for the geoid rise, 1.6 ± 1.0 mm/ year. Rates of recent years are even eight times higher. The possibility to detect minor changes in tide gauge benchmark height with GPS may be limited by GPS-related errors, which can be up to several mm even in a 10 km baseline.

Keywords: Sea level rise, land uplift, Baltic Sea, GPS, tide gauge, stability monitoring

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1 Introduction

Sea level monitoring is an important part of oceanography and climate investigation. Information of the sea level can be used for forecasts of climate change and marine resources as well as for natural hazard mitigation and improvement of use and protection of coastal areas.

The sea level can be observed from the coasts by tide gauges or from space with different satellite borne radars. Tide gauges are spatially limited, while they are of limited number and situated on the coasts, but they provide the longest continuous sea level time series. Satellite data are spatially more evenly distributed but they can be temporally limited and their time series are much shorter. Both data are needed to complete each other. There are several studies combining the methods for shorter and longer time periods (e.g. Church et al. 2004, White et al., 2005, Holgate and Woodworth, 2004).

Tide gauges measure the sea level relative to a benchmark. The problem with the tide gauges, besides their spatial limitations, is their vertical movements. Movements of these benchmarks and thus movements of tide gauges and the ground around them have been conventionally observed by levelling. Because levelling is done mostly once a year, or even less frequently, it is not very fast or accurate method if sudden movements happen.

Benchmark stability can be monitored also with GPS. GPS offers better temporal coverage, ultimately continuous tracking in real time, and the data collection and analysis can be automated. However, there are periodic and random temporal variations, especially in the vertical component, which may limit the resolving power. These variations have been studied for example in Mao et al. (1999) and Williams et al. (2004). The major component of land movements in Fennoscandia is the postglacial rebound, which has been studied also earlier with GPS (see e.g. Johansson et al., 2002).

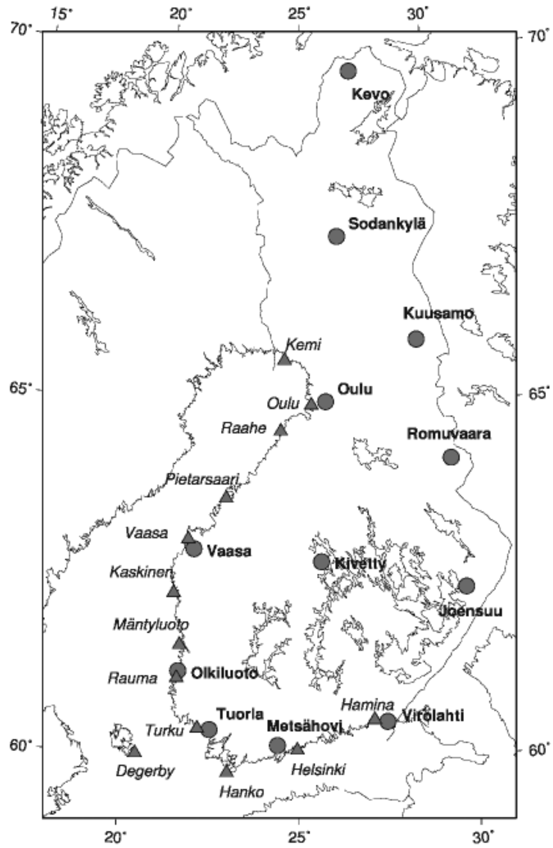

Fig. 1. The GPS stations of Finnish permanent GPS network FinnRef are marked with spots and the Finnish tide gauges with triangles.

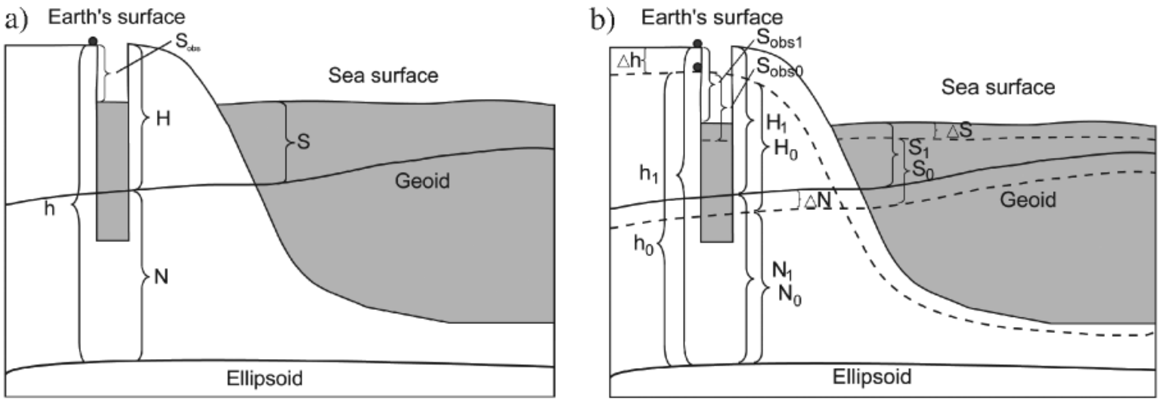

Fig. 2. Reference surfaces and heights (a) and their changes (b). S_{obs} is the observed sea level height, S is the absolute sea level height, H is the orthometric height of a benchmark, h is the height above the ellipsoid, N is the geoidal height. Subscripts 0 and 1 in b) denote epochs 0 and 1. Vertical changes are not in scale.

2 Sea level change

We have calculated absolute sea level change rates for the Baltic Sea using time series from Finnish tide gauges and Finnish permanent GPS stations (Figure 1), (Tervo, 2004, Poutanen *et al.*, 2004). We chose six tide gauge – GPS station pairs that were less than 30 km from each other. We also assumed that the Finnish bedrock is stable enough for the GPS land uplift rates to be valid also for the closest tide gauge. By combining these two series we get the absolute sea level rise, i.e. the change relative to the mass centre of the Earth.

The GPS data was achieved from the Finnish permanent GPS network, FinnRef, and the tide gauge data was provided by the Finnish Institute of Marine Research (K. Kahma, private communication, 2004).

Tide gauges measure the sea level relative to a benchmark; this is the observed sea level height S_{obs}. The height of the benchmark, and thus the ground in the vicinity of the tide gauge, can be observed either by levelling or with GPS.

Levelling gives the orthometric height H and GPS the ellipsoidal height h (Figure 2a). The height of the geoid N is the difference between orthometric and ellipsoidal heights ($N = h - H$). The absolute sea level height S is the difference between the orthometric height and the observed sea level height.

The surfaces change in time (Figure 2b) and changes in their heights can be observed. The deformation of the crust ΔH between epochs 0 and 1 can be calculated from orthometric heights

$$\Delta H = H_1 - H_0 \tag{1}$$

or from ellipsoidal heights using geoid height

$$\Delta H = (h_1 - h_0) - (N_1 - N_0) = \Delta h - \Delta N . \tag{2}$$

The observed sea level height is the height between the benchmark and the sea level

$$S_{obs} = H - S , \tag{3}$$

so the observed sea level change is

$$\begin{aligned} S_{obs1} - S_{obs2} &= (H_1 - S_1) - (H_0 - S_0) \\ &= (H_1 - H_0) - (S_1 - S_0) \end{aligned} \tag{4}$$

$$\Delta S_{obs} = \Delta H - \Delta S . \tag{5}$$

The absolute sea level change becomes

$$\Delta S = \Delta H - \Delta S_{obs} \tag{6}$$

and combining this with Eq. (2) gives the equation to be used with ellipsoidal heights

$$\Delta S = \Delta h - \Delta N - \Delta S_{obs} . \tag{7}$$

The observed sea level change contains components of crustal deformation, sea surface topography changes and geoid changes. The crustal deformation can be calculated from GPS observations assuming the long-term stability of the reference frame. This requirement is not yet fully achieved in sub-cm level in the current ITRF realisations, or the frames used in GPS satellite orbit computations.

The geoid rise values were calculated using the uplift rates from GPS time series and an empirical relation between the land uplift and geoid rise in Fennoscandia. The relation was derived by Ekman and Mäkinen, (1996) using repeated precise levellings, tide gauge records and gravity data. They obtained the geoid rise to be 6% of the land uplift.

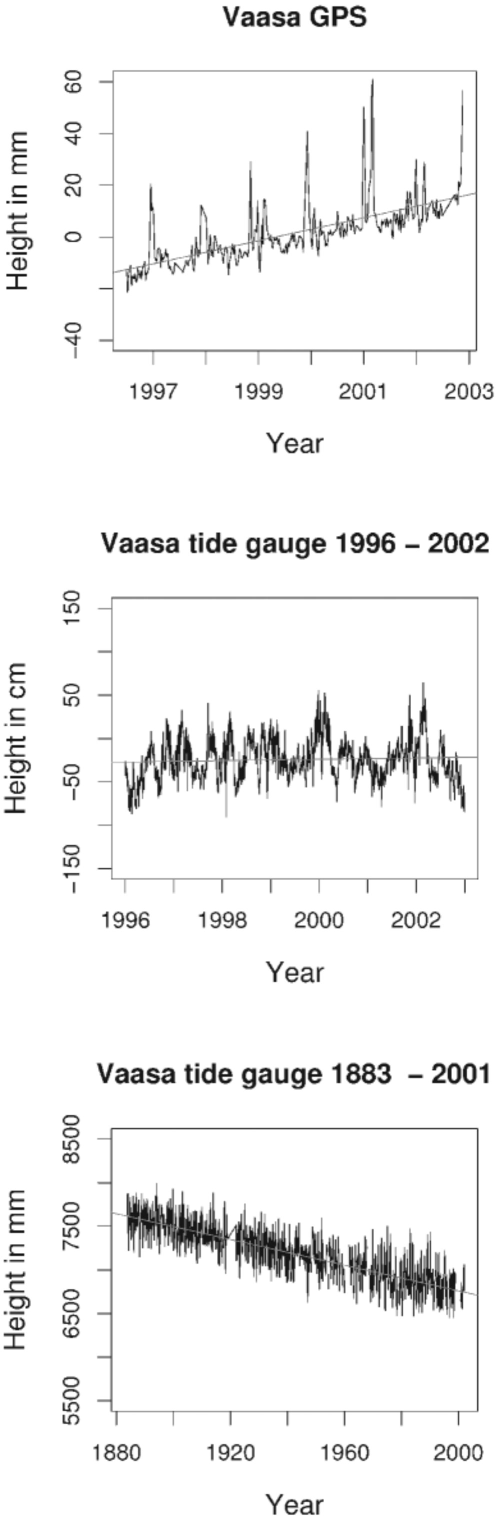

Fig. 3. Time series for Vaasa GPS station and for Vaasa tide gauge. Note, that the scale of the GPS time series is 10 cm and the scales of the tide gauge time series are 3 m. Spikes in GPS time series are due to the snow on the antenna radome in winter time.

Table 1. The absolute sea level rise rates of the Finnish tide gauges (mm/yr). 'Long time series' is the longest existing time series for each tide gauge and the ' Short ' covers years 1996-2002. 'With uplift' values are corrected for the land uplift and 'With geoid' also for the geoid rise derived from a model.

	Long time series			Short time series	
	Length (yr)	With Uplift	With geoid	With uplift	With Geoid
Helsinki	123	2.2	1.9	16.3	16.0
Hamina	74	1.4	1.2	15.5	15.3
Turku	80	2.6	2.3	16.5	16.1
Rauma	69	3.3	2.9	17.0	16.6
Vaasa	119	1.6	1.1	16.7	16.2
Oulu	112	0.5	0.1	14.5	14.1

To obtain the absolute sea level change rates for the Baltic Sea, we calculated ΔS using Eq. (7). In Figure 3 one can see examples of the GPS and tide gauge time series used in the calculation. The GPS time series are relative to the Metsähovi GPS station. Land uplift rates agree well with the previous results, e.g. Mäkinen *et al.*, 2003.

The tide gauge time series are given for two different time periods, the shorter being years 1996-2002 and the longer one the longest time series existing for each tide gauge. In Vaasa (63° 06' N; 21° 34' E, Fig. 3) the tide gauge observations have started in year 1883. The trends for the six tide gauges corrected with land uplift from GPS can be seen in Table 1 (Tervo, 2004).

To compute the absolute rates in sea level change, one should use as long tide gauge time series as possible. The average of the long time series gives for the sea level rise 1.9 ± 1.0 mm/year (varying between 0.5 – 3.3 mm/year), and when corrected for the geoid rise, 1.6 ± 1.0 mm/year (varying between 0.1 – 2.9 mm/year). Globally the sea level rise is observed to be 1 – 2 mm/year (Church and Gregory, 2001, Church et al., 2004). There are also regional differences in the sea level rise rates, as Church et al. (2004) present in their study. Our results for the Baltic Sea agree with the previous studies but the scatter is too large to make any further conclusions.

One can see the change in observed rates in the short time series. It means that the sea level rise in the Baltic Sea is now different than what it has been before the year 1990. Possible explanations are discussed in (Johansson *et al.*, 2003), but the reason for the change is not yet satisfactory explained.

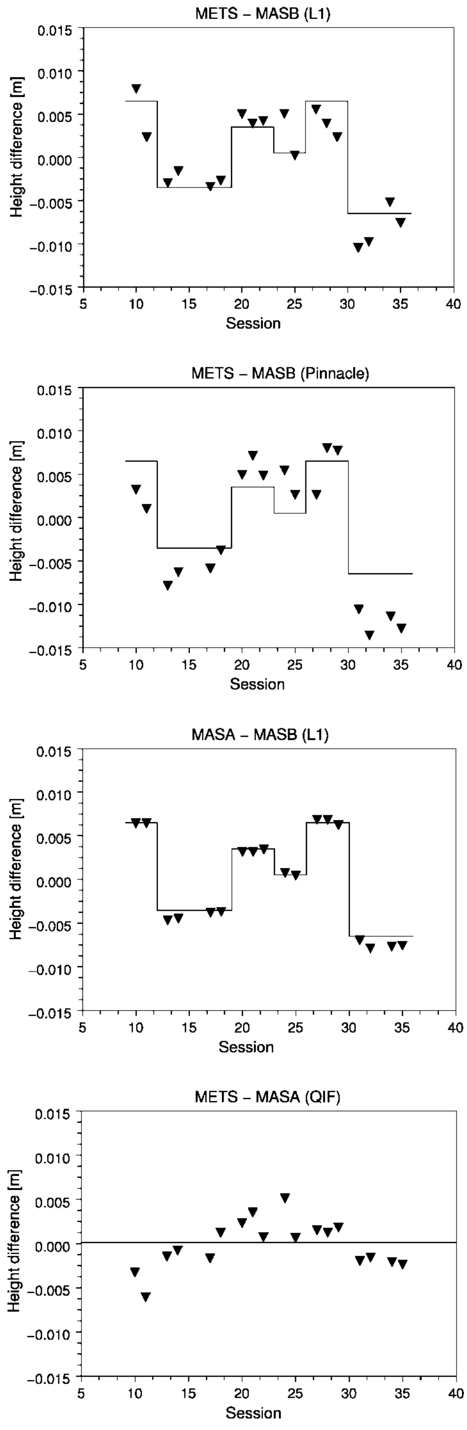

Figure 4. Results of the GPS test. Two top rows: Vectors METS-MASB computed with two softwares. Solid line is the actual change in height between METS and MASB. Third figure: Observed height change using only the 3 m vector MASA-MASB. Bottom: Observed drift METS-MASA. There has been no actual change in height between these stations. There is more than 5 mm change during the period of one month.

3 Stability and accuracy of the GPS solution

To simulate the accuracy of a footprint GPS installation to detect minor vertical movements, we made a test where two identical antennas were 3 m from each other, and a reference station was about 10 km away. In a footprint technique, the stability of a marker is controlled with a network of reference stations 10 – 15 km from the site. In our test we moved one test antenna in vertical direction, and the second one was unmoved during the test.

The GPS data were processed with two different softwares (Pinnacle and Bernese) to find out the difference in results between different softwares, and to confirm that observed features are not artefacts from the data processing. In both cases a standard troposphere and PCV models were used. We made a total of 18 sessions, 24 h each, in January – February 2004. The reference station is called METS, the fixed test antenna is MASA and the moving antenna is MASB.

In Fig. 4. we have three different solutions for MASB, two computed from METS (about 10 km vector) with two different softwares, and one using the 3 m baseline MASA – MASB. In the figures, the "ground truth", i.e. the known vertical shift of MASB, is shown with a solid line. Height of MASB was changed 5 – 15 mm during the test.

Sudden changes of a few mm in height are hardly visible in some cases in our GPS solution when the 10 km vector METS – MASB is used. However, if we process the data of the 3 m vector, 0.2 mm changes may become visible. It means that even with the footprint technique sudden sub-cm shifts may remain undetectable in episodic measurements.

In continuous measurements the change will become visible in long time series, but even in that case, periodic changes may degrade the resolving power (Poutanen *et al.*, 2005).

Most notable thing is the observed drift in height METS – MASA. Both antennas were fixed, and we have tried to exclude external reasons for the drift. METS is an IGS station, and data are used also for our permanent network analysis.

The same pattern in METS – MASA is visible in the results of two independent softwares, thus excluding the software based reason. There are several possible cause for the drift, including environmental effects (like snow) and crustal loading, as discussed in Poutanen *et al.*, 2005. This data set does not allow us to make any detailed conlusions but longer time series are needed to analyse the temporal variation in this vector.

The same drift is visible also in METS – MASB vector. If we compute separately METS – MASA and METS – MASB and from these the height difference MASA – MASB, the agreement with the ground truth becomes better than directly from the vector METS – MASB.

4 Conclusion

There are many applications of GPS in tide gauge monitoring. Among the most important ones is the possibility to calculate rates of absolute sea level rise. Combining tide gauges and GPS stations world wide would give a significant contribution to the sea level monitoring, giving it a well-defined reference frame.

We calculated absolute sea level rates for the Baltic Sea using GPS and tide gauge time series. The rate was found to be between 0.1 – 2.9 mm/year, average being 1.6 mm/year. The results agree with the global rate, though the scatter and uncertainty of the trend are large. Recent rates differ significantly, but these can be addressed to local temporal variation and they do not represent the long-term trend. This stresses the importance of uninterrupted long-term tide gauge time series.

We have shown that GPS may be used for controlling the stability of the tide with a sub-mm accuracy when the baseline is very short. Disadvantage of the short baseline is that the reference antenna may move together with the tide gauge benchmark antenna if there are local deformations. This is avoided by locating the reference antenna further away from the tide gauge. In this case the GPS-related errors, which can be up to several mm over a baseline of 10 km limit the accuracy obtained. One should find a suitable combination between the desired accuracy and the distance between the reference antenna and tide gauge.

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