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REVIEW ARTICLE

Sea level changes monitoring using GNSS technology – a review of recent efforts

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Sea level is traditionally observed with tide gauges (TG). These measurements are relative to the Earth's crust. To improve the understanding of sea level changes it is necessary to perform measurements with respect to the Earth's center of mass. This can be done with satellite techniques.

Global Navigation Satellite System (GNSS) is a tool that can solves several hundred kilometers vectors with centimeter level of accuracy and can measure point height changes relative to the reference ellipsoid WGS84 which is centred at the actual center of mass of the Earth. Although in the past two decades GNSS were used in almost every field of geodetic measurements, it is still almost not in use in the field of sea level monitoring. Attempts of using GNSS equipped buoys for the determination of precise sea level (at centimeter level) were successful and suggest that GNSS is capable of replacing the conventional tide gauges.

A review of recent efforts made on observing sea level variations using data from a GNSS receivers were presented here. Furthermore, presented review resulted in a conclusion that the use of a GNSS based Tide Gauge (GNSSTG) system for the determination of sea level changes is possible, and that its accuracy level (averaged) is equal to a float based tide gauge. More than that, an absolute change of sea level should be easier to be determined using GNSSTG system

Key words: sea level, tide gauges, GNSS

INTRODUCTION

The Earth's climate is continuously changing. Variations in climate can be caused by variations in solar forcing or natural variations in greenhouse gas concentrations or volcanic eruptions. However, latest observations from various components of the Earth's climate system show that the climate is changing also due to anthropogenic activities (SLANGEN 2012; SOLOMEN *et al.*, 2007). Greenhouse gas concentrations have been increasing due to fossil fuel combustion, causing an strengthened greenhouse effect and, as a result, the global mean (air and ocean) temperature are rising. An important consequence of this is that glaciers and ice sheets are shrinking and global mean sea level is rising.

In addition to other important oceanic research (e.g. DADIĆ *et al.,* 2006; ORLIĆ *et al.,* 2007), measurements of sea level, are crucial for increasing our understanding of the processes that cause sea-level change.

Sea levels have been measured for many hundreds of years. Early measurements consisted mainly of the heights and times of tide only (e.g. WOODWORTH, 1999; WÖPPELMANN *et al.*, 2008). However, only after the first automatic tide gauge was developed, it became possible to record the full tidal curve. This innovation led to important developments in studies of tides, storm surges and mean or extreme sea levels (WOODWORTH *et al*., 2009).

To determine sea-level changes before 1700, when instrumental measurements started, there are several types of sea-level indicators that can be used. These indicators can be of geological, biological or archaeological nature. A review of these indicators measurements can be found e.g. in BINTANJA & VAN DE WAL (2008), CHAPPELL & SHACKLETON (1986), DE BOER *et al.* (2011), VORREN & MOE (1986).

The first instrumental records of sea level start in the 1700's, when tide gauges were install in Amsterdam, Stockholm, Kronstadt and Liverpool. These tide gauges were only rocks or wooden rods in the ocean (Fig. 1).

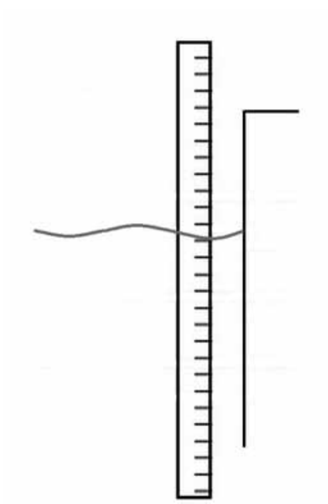

Fig. 1. First tide gauge construction

The first automatic tide gauge was mounted at Sheerness in the Thames estuary and it became possible to record the full tidal curve. The method was adopted at many other worldwide sites and even today the technology remains a practical one. In the second half of the 20th century, a number of other methods were developed for measuring sea level changes, e.g.: the measurement of sub-surface pressure or the time of flight of an acoustic or radar pulse between a transducer and the sea surface (IOC, 2004, 2006).

The number of sea-level measurements increased when satellite altimetry was introduced. The project starting in 1992 with the launch of the TOPEX/Poseidon radar altimeter satellite and this enabled to increase the spatial resolution and coverage of sea-level measurements. In 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite and, complementary to GRACE, the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite in 2009 were launched.

At present-day sea-level change is determined mostly consider both in situ -tide gauge- as well as remote sensing measurements. Data are available for over 1750 tide gauge stations worldwide. In 1933 the Permanent Service for Mean Sea Level (PSMSL) was established and operates under the auspices of the International Council for Science (Fig. 2). The advantage of the tide gauge measurements is that they provide relatively long time series. On the other hand, the spatial coverage of the satellite altimetry missions is much higher. Using remote sensing measurements eliminates the problem that tide gauges are mainly biased towards coastal areas in the northern hemisphere.

For this reason 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 & WOODWORTH, 2004).

At is well known, tide gauges measure the sea level relative to a benchmark. This provides the additional problem with the tide gauges - the vertical movements. Movements of the benchmarks and thus movements of tide gauges have been conventionally observed by levelling. Because levelling is done very rarely (once a

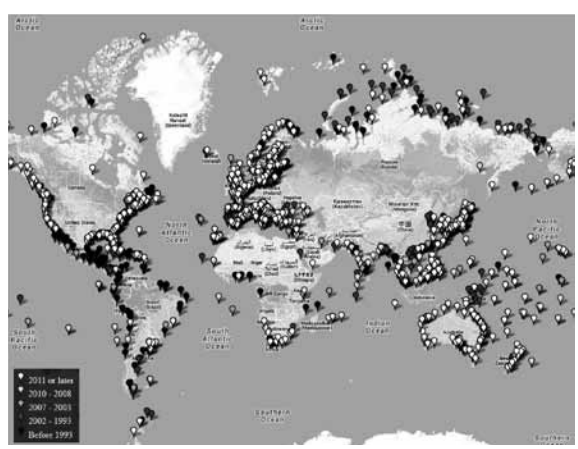

Fig. 2. PSMSL Data Stations (source: PSMSL web-site)

year or even less frequently), it is not very fast or accurate method. To solve this problem GNSS technology can be used. GNSS offers better temporal coverage and continuous tracking in real time. Additionally, the benchmark stability data collection and analysis can be automated.

Some drawback is fact that while determination of the horizontal point's position using GNSS techniques, according to the requirements for different groups of the precision, generally is not difficult, the accurate determination of heights causes some problems. This is due both, the high accuracy requirements for height appointment as well as specification of GNSS measurements – it is assumed, on average, that the vertical coordinate is determined about 50% less accurate than the horizontal coordinates. Some analyzes of the accuracy of GNSS measurements can be found e.g. in CEFALO & GATTI (2000), DAWIDOWICZ & ŚWIĄTEK (2008), DAWIDOWICZ & KRZAN (2013). Additionally, there are periodic and random temporal variations in the vertical component, which may limit the resolving power. These variations have been studied for example in MAO *et al.* (1999), WILLIAMS *et al.* (2004). The second method to used satellite technology in sea-level monitoring is to place GNSS buoys and finds the compatibility of their data with the orthodox tide gauges data (YANG & LO, 2000).

Finally it should be noted that sea-level changes can be measured in absolute or relative mode. Figure 3 shows the two reference frames that are used in sea-level research. On the left is the absolute sea-level change, which measures the sea-surface height change with respect to the Earth's centre of mass. These changes are measured by altimetry satellites. On the right side is the relative sea-level change, which is the difference between the ocean surface and the ocean "floor". This sea level is measured by tide gauges. To obtain relative sea-level change from satellite altimetry, the measurements must be corrected for vertical surface displacement. These corrections can be obtained using GNSS measurements.

Along with the developments in tide gauge technology and the use of satellite technology to

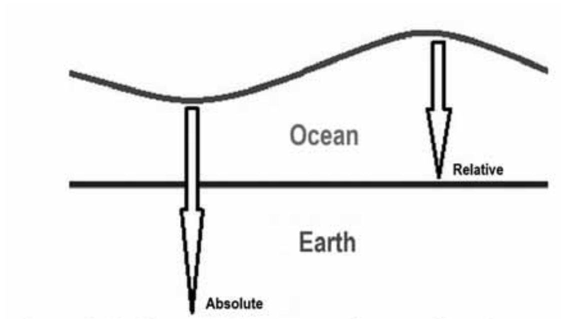

Fig. 3. Reference frames used in sea-level research

continuous tracking in real time sea-level changes, corresponding progress has taken place in techniques for the transmission of the sea level data to centers. The availability of near real-time sea level information enables the utilization of the data by a wide range of new users. The most important example is still flood warning (FLATHER, 2000).

The aim of this paper was to present a review of recent efforts made on observing sea level variations using data from a GNSS receivers. GNSS technology was shortly described and some examples of ways how it was applied to sea-level monitoring were also attached. Presented results show that the GNSS based Tide Gauge system can be very useful for the determination of sea level changes.

GNSS technology

Satellite Navigation is a method employing a Global Navigation Satellite System to accurately determine position and time anywhere on the Earth.

The importance of artificial satellites in geodesy becomes evident from a number of reasons. First of all satellites can be used as high orbiting targets, which are visible over large distances. Analogously as in the classical concepts of trigonometric networks, the satellites may be regarded as "fixed" control points within global three-dimensional network. Additionally satellites can be considered to be a probe in the gravity field of Earth. Observing the orbital motion and the variation of the parameters describing the orbit, conclusions about the forces acting can be derived. Summarizing, the main advantage of satellite observations, when compared with classical techniques, is that the results refer to the planet Earth as a whole, and that they have a global character by nature. Among the first spectacular results obtained using satellites measurements were a more accurate value of Earth's flattening, and the proof that the figure of Earth is non-symmetrical with respect to the equatorial plane (SEEBER, 2003).

GNSS generally provide two techniques: absolute or differential (relative) positioning. Absolute positioning involves the use of only a single receiver to collect data from multiple satellites in order to determine the station's location. It is not sufficiently accurate for precise surveying or hydrographic positioning uses. In order to obtain higher accuracies, GNSS can be used in a differential (relative) positioning mode. Differential or relative positioning requires at least two receivers set up at two stations (usually one is known) to collect satellite data simultaneously in order to determine coordinate differences. This technique is based on spatial correlation of systematic errors between receivers to estimate or reduce their effects.

Lately precise absolute positioning, known as Precise Point Positioning (PPP), was developed (KOUBA & HÉROUX, 2001; KRZAN *et al.*, 2013; ZUMBERGE *et al.*, 1997). PPP is a combination of the absolute positioning concept and differential positioning techniques. It is based on the processing of observations from a single GNSS receiver and employs a number of corrections.

An absence of differentiation of observations necessitates using precise satellite orbits and clock corrections in the post-processing of results as well as modelling iono- and tropospheric refractions, solid earth and ocean tides, antenna phase-center offsets and variations, carrier-phase wind-up, relativistic effects, etc. (MIREAULT *et al.*, 2012). The impact of these factors is determined from continuous satellite observations by different GNSS services (e.g. solid earth and ocean tides) or by laboratory tests (antenna phase-center offsets and variations, carrier-phase wind-up). The ambiguity of phase measurements is also a certain barrier. As a standard, the PPP technique employs a float-type solution, which requires long observations (over 20 minutes) to achieve a precision of several centimeters.

GNSS measurements can also be divided in dependence on the state in which the receiver is on static and kinematic. The static method is used when GNSS is used to find the position of a fixed site, and that position is treated as constant.

The main technique for positioning moving objects with GNSS, both in post-processing, and in real time, is the kinematic method. It uses the geometric strength of simultaneous observations of several satellites made with a receiver, to determine the instantaneous position of any moving object. Since high accuracy can be obtained in this way with GNSS, this approach is universally used today.

Sea level monitoring using GNSS – sample results

Sea level monitoring is an important part not only of geodesy but also, and perhaps first of all, of oceanography and climate investigation. The sea level can be observed from the coasts by tide gauges or from space using different artificial satellites. Tide gauges are spatially limited, but they provide the longest sea level time series. Satellite data are better spatially distributed but their time series are much shorter. Fortunately the shorter and longer time periods methods can be combined (e.g. CHURCH *et al.*, 2004; HOLGATE & WOODWORTH, 2004; WHITE *et al.*, 2005).

From the perspective of geodesy, sea level should be connected to the ellipsoidal height system for several reasons. One of them is as assessing the absolute change of mean sea level (MSL). Generally two methods are found to relate sea level with ellipsoidal heights. The more accepted one is to establish a continuous permanent GNSS station (CGNSS) near the tide gauges and conduct high precision leveling between the station and the tide gauges bench marks (TGBM) repeatedly. The second method is to place GNSS buoys and finds the dependence of their data with the traditional TG's data. Recently a GNSS-based tide gauges are proposed as the third method.

Using satellite technique for the study of sea level changes can be considered in many aspects. Only some of them, the most important, are presented below.

Controlling movements of the TGBM and thus movements of TG

Tide gauges measure the sea level relative to a fixed, land-based benchmark. The problem with the tide gauges, besides their spatial limitations, is their potential vertical movements. Processes that can cause the land movement include plate tectonics, glacial isostatic adjustment and anthropogenic factors that contribute predominantly to subsidence. So it is important to determine whether or not the land upon which the tide gauge is located is moving, i.e. is the sea level rising or the land falling (Fig. 4).

Movements of TGBM and thus movements of TG have been conventionally observed by levelling. These "relative" tide gauge measurements are, however, a combination of the actual change in mean sea level and the vertical movement of the land upon which the tide gauge is located. However the vertical land motion at a tide gauge site can be as large as the sea level change (WOODWORTH, 2006). Additionally, sea level trends obtained from tide gauge records are only adjusted for glacial isostatic adjustment since other vertical land motion components are not known (HOUSTON & DEAN, 2011). Many researchers have highlighted the nature of various land movements factors that can affect estimates of sea level change derived from tide gauge measurements (e.g. CHURCH et al., 2004; LAMBECK, 2002).

Benchmark stability can be monitored also with GNSS (Fig. 5). GNSS 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).

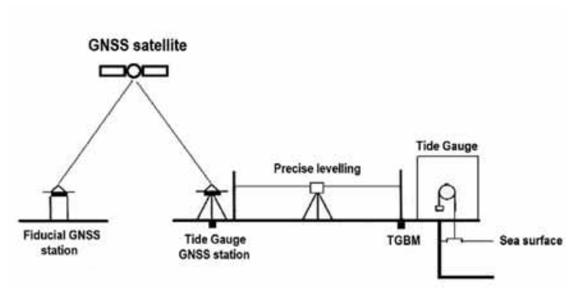

Fig. 5.TGBM stability monitoring using GNSS

The establishment of a long-term stable global reference frame is important for studying sea level. GNSS stations connected to the tide gauge benchmarks provide the necessary technique. The ideal tool for providing accurate and continuous measurements of land movement at tide gauge locations are GNSS Continuously Operating Reference Stations (CORS) (TERVO *et al.*, 2007). Recent studies have shown that GNSS is able to provide vertical land motion monitoring

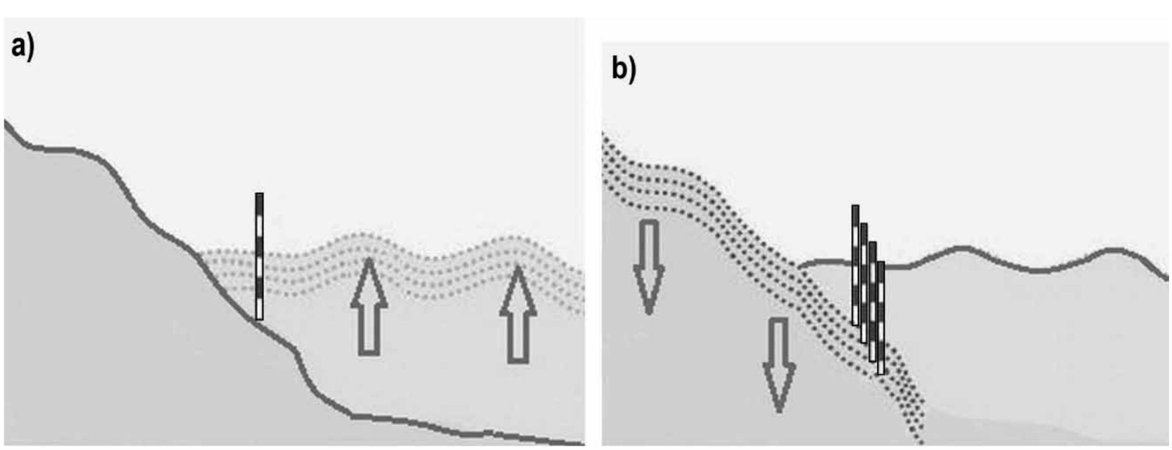

Fig. 4.TG potential vertical movements problem: a) the sea level rising, b) the land falling

Table 1. Land movement monitoring using traditional methods and GNSS CORS (based on: JANSSEN et al., 2013)

Issue	Terrestrial Methods	GNSS CORS Techniques
Monitoring	episodic/sporadic	continuous
Reference Frame	local	global
Land Motion	relative	absolute
Data	internal, validated in-house	shared, validated by others
Precision	generally fixed	improving with time/algorithms
Accuracy	survey specific	homogeneous across all sites
Data Archiving	manual & centralised	electronic & distributed
Labour	intensive	automated
Intent & Outcome	defined/limited	multi-user/infrastructure
Alarms	n/a	near-real time (variable thresholds)

with an accuracy of better than 1 mm/yr. So it is a perfect tool to improve the estimation of sea level rates both regionally (e.g. BINGLEY *et al.*, 2001; BUBLE *et al.*, 2010) and globally (e.g. WÖPPELMANN *et al.*, 2009; BOUIN & WÖPPELMANN, 2010).

Compared to traditional monitoring methods, the use of GNSS technology offers significant improvements in the measurement of land movements at tide gauges. A brief comparison of these two approaches is provided in Table 1.

In order to achieve the required accuracy, GNSS processing is required to carefully take into account numerous factors causing the Earth's crust to deform periodically. These factors include ocean tide, atmospheric pressure and solid earth tide displacements. All of them have to be considered within a stable reference frame over the time period considered (SANCHEZ & BOSCH, 2009). Correcting GNSS observations for non-tidal ocean loading displacement in order to increase the quality of the results has also been recommended (WILLIAMS & PENNA, 2011).

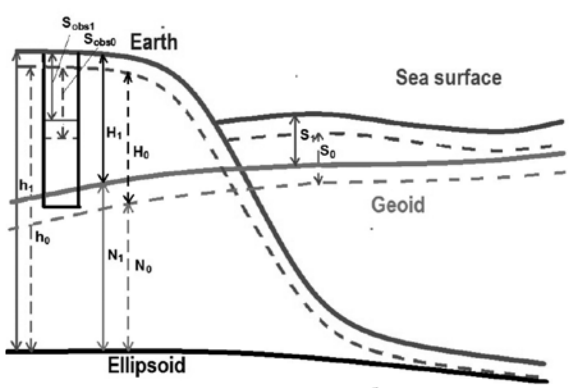

Fig. 6. Calculating of absolute sea level change (based on: TERVO et al., 2007)

An example of calculating absolute sea level change, i.e. the change relative to the mass centre of the Earth, can be found in TERVO *et al.* (2007). In this approach absolute sea level change is computed using time series from tide gauges and permanent GNSS stations. From levelling the orthometric height *H* was obtained and from GNSS the ellipsoidal height *h* (Fig. 6).

The geoid undulation *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 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

$$\Delta H = H_1 - H_0 \quad (1)$$

or from ellipsoidal heights using geoid height

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

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

$$S_{obs} = H - S, \quad (3)$$

so the observed sea level change is

$$S_{obs1} - S_{obs2} = (H_1 - S_1) - (H_0 - S_0) = (H_1 - H_0) - (S_1 - S_0) \quad (4)$$

$$\Delta S_{obs} = \Delta H - \Delta S. \quad (5)$$

The absolute sea level change becomes

$$\Delta S = \Delta H - \Delta S_{obs} \quad (6)$$

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

$$\Delta S = \Delta h - \Delta N - \Delta S_{obs}. \quad (7)$$

The observed sea level change contains components which must be modeled, e.g. crustal deformation, sea surface topography changes and geoid changes.

Using this method the absolute sea level rates were calculated for the Baltic Sea. The rate was found to be between 0.1 - 2.9 mm/year, average being 1.6 mm/year. These results agree with the global rate, though the scatter and uncertainty of the trend were large. Generally it was shown that GNSS may be used for controlling the stability of the tide gauges with a sub-mm accuracy when the baseline is very short. Disadvantage of the short baseline is that the reference receiver may move together with the tide gauge benchmark receiver if there are local deformations. This can be avoided by locating the reference point further away from the tide gauge. In this case the GNSS-related errors, which can be up to several mm over a baseline of 10 km limit the accuracy obtained.

For the needs of controlling movements of the TGBM and thus movements of TG in 2001 the IGS Tide Gauge Benchmark Monitoring Pilot Project (TIGA) was established. The main objective of TIGA is the processing and reprocessing of GNSS data of stations at or near TG in order to provide homogeneous and high-quality estimates of the vertical motion. A second objective is the establishment, maintenance and expansion of existing network of GNSS stations at TG's. TIGA aims to solve issues related to the accuracy and reliability of the GNSS height component at tide gauge sites. Several scientific issues are benefiting of the results of TIGA, e.g., satellite altimetry calibrations (e.g., MITCHUM, 2000), global isostatic adjustments and separation between crustal movement and sea level changes (e.g., BAKER *et al.*, 1997; NEREM *et al.*, 2001; TEFERLE *et al.*, 2006) or other GNSS related studies (e.g., SCHMID *et al.*, 2007).

GNSS buoys methods

Actually the most commonly used techniques to monitor sea level are tide gauges and satellite altimetry (WILLIS *et al.*, 2010). However, tide gauges are crust-fixed instruments resulting in measuring only relative sea level. Satellite altimetry in coastal regions, on the other hand, is inaccurate because of unreliable geophysical corrections and noisy returned radar waveforms (LEE *et al.*, 2010). Additionally high-frequency sea level variations cannot be sufficiently detected from tide gauges measurements or weekly sampled satellite altimetry data. Observations from the GNSS buoys have the potential to mitigate the drawbacks of these techniques.

Buoys equipped with GNSS receivers can been used to measure water levels, atmospheric parameter and other physical conditions in sea, for the purposes of navigation, tide correction, the altimeter range calibration, ocean environment and pollution monitoring, flood control, and fisheries (KEY *et al.*, 1998; MOORE *et al.*, 2000; ROCKEN *et al.*, 1990).

They can also be used to the transfer of tidal datums. With rising sea levels and an increasing demand for coastal properties, cadastral surveyors and engineers need to be able to readily define cadastral boundaries both reliably and accurately. Some of the problems associated with different aspects of cadastral can be found e.g. in PARZYCH (2011), BIEDA & PARZYCH (2012). The use of GNSS buoys has the following advantages for tidal datums transfer (MARSHALL & DENYS, 2008):

- efficient datum connections between the GNSS buoy and benchmark,
- relatively easy data collection,
- existing GNSS equipment can be used,

GNSS buoys can be deployed in close proximity to the shore and do not have to be attached to an existing tide gauge instrument.

GNSS buoys have demonstrated to be an effective and economical technique to monitor sea level variations (CARDELLACH *et al.*, 2000), calibrate satellite altimetry measurements (e.g. CHENG *et al.*, 2010) and to other (CHENG *et al.*, 2008; CHENG *et al.*, 2009; DEL COGALIANO *et al.*, 2007; FRAPPART *et al.*, 2006). At the beginning GNSS buoys were tested in DGNSS mode. The use of DGNSS assumes that both ends of a baseline have similar and highly correlated conditions in ionospheric, tropospheric and other error sources. This allows a DGNSS to reduce such errors significantly. As the length of a baseline increases, the errors sources are different at the ends of a baseline and previous assumption for reducing errors becomes invalid. Therefore, the positioning accuracy of a buoy was limited by the baseline length. Fortunately precise point positioning (PPP) technique was developed and has allowed solving this problem (ZUMBERGE *et al.*, 1997).

It has been demonstrated that centimeter level positioning precision can be achieved for static points on land with the PPP techniques, which is comparable in quality with the conventional differential mode. Decimeter level Kinematic PPP has also been developed in precise orbit determination or meteorological study in low earth orbit (LEO) spacecrafts such as TOPEX/POSEIDON and CHAMP mission. In natural way the kinematic PPP technique was adopted for GNSS buoys to measure the sea level.

Using a GNSS buoy to measure water levels offers many advantages over traditional techniques with its ability to determine heights relative to an absolute reference frame. While large scale GNSS buoys have been used for long-term datum determination (e.g. ARROYO-SAUREZ *et al.*, 2005), there has been research involving light-weight buoys for short-term tidal datum transfers.

Since early designs in the late 1980's (e.g. KELECY *et al.*, 1994) GNSS buoys technology has rapidly progressed in design and applications. Generally research has involved three types of buoys (Table 2):

- lightweight wave rider, which must be tethered and operated from a boat,
- autonomous lightweight wave rider, con-

Table 2. The characteristic of different GNSS buoy types (based on: MARSHALL & DENYS, 2008)

GNSS buoy type	Lightweight wave rider (antenna only)	Autonomous lightweight wave rider	Autonomous, large scale
Description	- used a life preserver as the floatation source, - houses the GNSS antenna only, - operated from a boat, - antenna offset from the mean water level is small (5–25cm).	- used a life preserver as the floatation source, - houses the GNSS receiver, antenna and battery, - can be operate autonomously, either: anchored, drifting or tethered.	- large buoy that houses the GNSS system in addition to power generator and data communications, - can be operate autonomously for significant durations, - antenna reference point is typically 5-7 m above the mean water level.
Advantages	- economical and simple to construct, - easily portable with their small size, - no need to monitor and correct for the buoy's tilt, - low center of mass.	- as beside, - autonomous operation up to 5 days.	- can be operate long time in rough sea conditions, - additional sensors can be integrated into the buoy, e.g. meteorological instruments.
Disadvantages	- logistical support is required, - lack of the required strength, - operation restricted in rough sea conditions, - short operational duration.	- as beside, - hampered logistics, - operation time is still limited to short to medium terms.	- high cost, - not easily portable, - can be difficult to measure and correct for buoy's tilt influencing the antenna's position above the water level, - reliability issues with power and communications.
Application Examples	- absolute altimeter calibration, - tidal datum transfer, - high frequency wave analysis.	- as beside, - verifying and calibrating tide gauges.	- tsunami monitoring, - tidal datum determination, - absolute altimeter calibration, - long term tidal monitoring.

taining all the necessary equipment within the buoy,

- autonomous, large scale buoy for use in long-term rugged environments.

The GNSS buoy's ability to measure sea surface heights should be verify. This can be due by comparing filtered GNSS heights to those from the existing tide gauge. More details can be found e.g. (MARSHALL & DENYS, 2008). This verification enabled both the precision as well as absolute and systematic biases between the two systems to be determined.

Finally it should be noted that the main design requirement for accurate sea level is accurate knowledge of the vertical distance from the sea surface to the GNSS antenna. Almost any platform can be utilized if there is a clear view for the GNSS antenna (low multi-path) and sufficient care is taken to either know or monitor the buoy orientation and motion.

GNSS buoy sea level monitoring problem has been studied by many researchers. Generally it can be concluded that sea level variations can be observed with accuracy of less than 2 cm. So it is capable of delivering similar level of accuracy, and as reliable results as traditional measurements. However there are still some problems in monitoring the variations continuously with sub-centimeter accuracy.

Obtaining such accuracy in the vertical direction is still challenging, especially for long baselines. In spite of these difficulties, there is still much room for further improvements. Therefore, we can expect future progress in this method.

Although GNSS buoy technology has been increasingly applied to many situations there has been little research investigating the use of lightweight designs for transferring tidal datums. In a study MARSHALL & DENYS (2008) GNSS buoys were deployed simultaneously at Port Chalmers and Dunedin Wharf tide gauges for four days allowing its observations to be compared against those of the gauges.

Although the obtained differences were less precise than expected (standard deviation at the 2 cm level) there was no significant bias between the two systems. The tidal datum MHWS was transferred and compared to that established from long-term tidal observations, with residuals at the 10 mm level. It can be concluded that GNSS buoys are a viable tool to transferring tidal datums. The buoys were demonstrated to be simple and cheap to construct, while also being able to utilize typical GNSS surveying equipment.

GNSS-based tide gauge stations

The sea level is traditionally observed with tide gauges that give measurements relative to the Earth's crust. To improve the understanding of sea level changes it is necessary to perform measurements with respect to the Earth's center of gravity. This can be done with satellite techniques, and thus some GNSS-based tide gauge techniques were proposed. An example is a method that makes use of both GNSS-signals that are directly received and that are reflected on the sea surface. As is well known GNSS can be used to determine the motion of the Earth's crust in relation to the center of gravity (JOHANSSON *et al.*, 2002). By observing reflected GNSS-signals from the sea surface, information of both relative and absolute sea level change can be obtained.

Additionally lately, a series of very precise satellite altimetry missions have been launched, allowing large-scale measurements of sea-level motion. To compute mean sea level variations over time using altimeter technology, there is a need to account for bias and drifts. As is know these effects can be of the same order of magnitude as the sea level signal itself. Fortunately studies have shown that altimeter bias and drifts can be corrected in a robust way if a global distribution of tide gauges is available (CHAMBERS *et al.*, 1998; MITCHUM, 1994, 2000).

As previously mentioned, tide gauge measures not only sea level but also the motion of the ground. Thus, effects such as glacial isostatic adjustment, coseismic and postseismic deformation, and land subsidence make it difficult to use tide gauges either to measure sea level directly or to calibrate altimeters. However using Global Navigation Satellite System to measure these so called local "land effects" is relatively straightforward, efforts to do so can be hampered by the lack of GNSS receivers near tide gauges. (SCHÖNE *et al*., 2009). Meanwhile LÖFGREN *et al.* (2011) suggested that a GNSS tide gauge could be used to determine both local ground motion and sea level.

Satellite techniques (e.g., GNSS) can be used to determine the motion of the Earth's crust in relation to the center of gravity (CAPRA *et al*., 1999; JOHANSSON *et al*., 2002). By observing reflected GNSS-signals from the sea surface, information of both relative and absolute sea level change can be obtained. This formed the basis of the concept of a GNSS-based tide gauge.

Using reflected GNSS signals for environmental studies was first introduced by MARTIN-NEIRA (1993). This initial concept have focused on altimetry, i.e. observing GNSS reflection signals from the ocean surface on a space-borne platform (CARDELLACH *et al*., 2004; LOWE *et al*., 2002). Much of the work has been done to observe water reflections for the purposes of validating a potential GNSS-based altimetry mission. The traditional GNSS tide gauge consists of two GNSS antennae (Fig. 7).

The zenith-pointing antenna is designed to receive the direct signal, and thus is Right-Handed Circularly Polarized (RHCP) - the same as the transmitted signal. The nadir-pointing antenna is optimized to receive the reflected signal, which becomes primarily Left-Handed Circularly Polarized (LHCP) after reflection (LARSON et al., 2012). The reflection angle of the reflected signal corresponds to the elevation of the direct signal (Fig. 7).

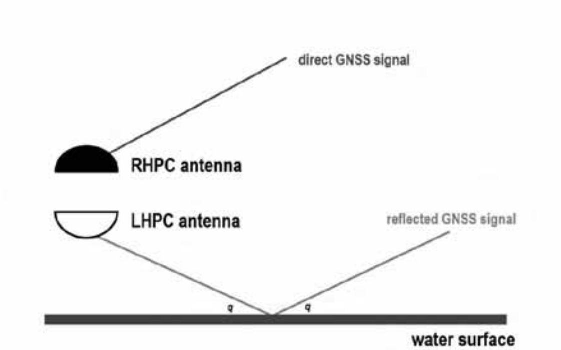

Fig. 7. Two GNSS antennas tide gauge (based on: LARSON et al., 2012)

In the traditional GNSS-based tide gauge installation (LÖFGREN *et al.,* 2010) the RHCP antenna receives the GNSS-signals directly, whereas the LHCP antenna receives the signals that are reflected from the sea surface. When the signals are reflected, they change polarization from RHCP to LHCP. The reflected signals contains an additional path delay, as compared to the directly received signals. So the LHCP antenna can be regarded as a virtual antenna located below the sea surface (Fig 8). When the sea level changes, the path delay of the reflected signal changes. For this reason the LHCP antenna will indicate to change position. This position change, which can be described as virtual, corresponds to twice the sea level change. The height of the LHCP antenna over the sea surface, can be derived from the geometry in Fig. 8, and equals:

$$\boldsymbol{h} = \frac{\frac{a+b}{sinq} - d}{2} \qquad (8)$$

where a + b = c is the additional path delay of the reflected signal, *q* is the elevation of the transmitting satellite, and d is the vertical separation between the phase centers of the RHCP and the LHCP antennas.

Multiple satellites with different elevation and azimuth angles are observed each epoch.

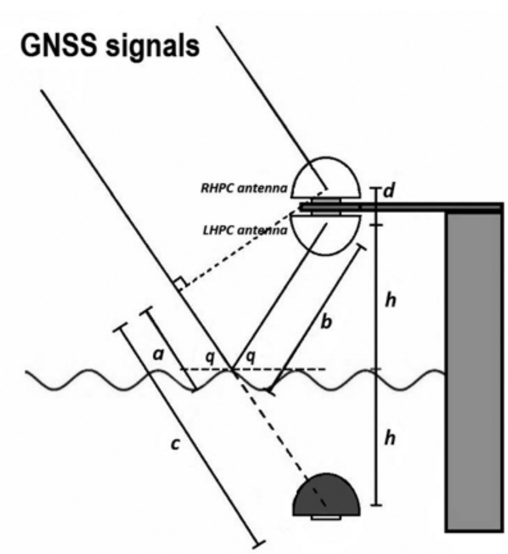

Fig. 8. The idea of sea surface height calculations using two GNSS antenna tide gauge (based on: LÖFGREN et al., 2010)

Table 3. The comparison of one and two-antenna GNSS tide gauge concepts

2 antenna concept	1 antenna concept
- carrier phase method - 2 antenna and 2 receivers - the reflected signal experience an additional path delay, which changes with changing sea surface - standard differential GNSS processing - carrier phase data	- signal-to-noise ratio method - 1 antenna and 1 receiver - the reflected signals interfere with the direct signals (multipath) causing oscillations in Signal-to-Noise Ratio (SNR) data - standard reflected height analysis - SNR data

Reflected signals reach the antenna with different angles and different directions. Thus the estimated sea level change can not be considered to originate from one specific point on the sea surface, but rather represents the change of an average sea surface formed by the reflection points. This is one of the reasons that affect the accuracy of the method.

Because it is a very short baseline, simple GNSS analysis software can be used to estimate h (LÖFGREN *et al.*, 2011). Various methods can been used to extract sea level heights from the raw GNSS observations, e.g., (CARDELLACH *et al.*, 2004; DUNNE *et al.*, 2005; SOULAT *et al.*, 2004; LÖFGREN *et al.*, 2011). Generally in each of mentioned previous GNSS tide gauge studies, the researchers have designed their experimental equipment (specifically the LHCP antenna) with the objective of observing reflected signals.

Two GNSS antenna tide gauge station has a drawback: the RHCP antenna is also sensitive to sea surface reflections. Although the purpose of the zenith-directed RHCP antenna is to maximize the direct signal and suppress reflected signals, it does not completely reject reflected signals energy. Studies on correction these reflections (known as multipath) in the GNSS literature extends from the late 1980's to the present (PARK *et al.*, 2004; BILICH *et al.*, 2008).

Based on the analysis of reflected signals one GNSS antenna tide gauge concept was formulated (see e.g. TREUHAFT *et al.*, 2001). Most of these efforts focus on the assumption that multipath is repeatable and can be modeled as a specular reflection (Fig. 9). The distance of the reflecting, planar surface (h) from the RHCP antenna phase center can be determined from the interference pattern caused by the direct and reflected signals. These multipath interference patterns can be observed in the pseudorange, carrier phase, and Signal-to-Noise Ratio (SNR) data. BENTON & MITCHELL (2011) used a similar approach to examine sea surface reflections with SNR data. They found reflection frequencies that agreed to first order with expected values. Some comparison of one and two-antenna GNSS tide gauge method is presented in Table 3.

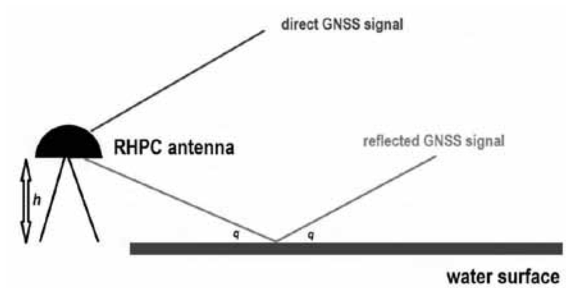

Fig. 9. One GNSS antennas tide gauge concept (based on: LARSON et al., 2012)

A test installation at the Onsala Space Observatory (LÖFGREN *et al.,* 2010) shows that the reflected GNSS-signals have only about 3 dB less signal-to-noise ratio than the directly received GNSS-signals. A comparison of relative sea level observations from the GNSS based tide gauge to traditional tide gauges gives an RMS agreement on the order of 4 cm.

The accuracy of this type of sea level surface measurements is worse than using GNSS buoys because the estimated sea level change represents the change of an average sea surface formed by the reflection points. Despite this the GNSS-based tide gauge installation shows that it is possible to receive GNSS-signals reflected in the sea surface and obtain reliable results.

The one antenna concept (LARSON et al., 2012) demonstrated that such systems are capable of determining sea level with a precision of 5 cm. This is a degraded performance relative to the geodetic analysis of the two antenna/receiver GNSS tide gauge system (LÖFGREN *et al*., 2011).

The primary advantage of any GNSS tide gauge is that it allows simultaneous determination of sea level and position with respect to the International Terrestrial Reference Frame system (e.g. as provided by its latest realization ITRF2008, ALTAMIMI *et al*., 2011). In addition to other advantages it can be particularly useful in areas with land surface motion where the usefulness of traditional tide gauges is restricted.

CONCLUSIONS

There are many applications of GNSS in tide gauge monitoring. Among the most important ones is the possibility to calculate movements of absolute sea level rise. Combining tide gauges and GNSS stations world wide would give a significant contribution to the sea level monitoring.

DGNSS sea level measurements can provide absolute sea level measurements over length and time scales that are impossible to achieve with satellite altimetry. It could play very important role in regional oceanographic experiments such as mapping coastal sea level variations due to tides, currents or fronts. In inactive waters, DGNSS can also be used for mapping the marine geoid. It has been shown by various experimenters that DGNSS can provide accurate absolute sea level positioning from a wide variety of buoy designs over relatively short baselines.

That accuracy is better than 2 cm. With this 1-2 cm accuracy, GNSS can be used for observations of the seasonal and intraseasonal variation. Although sea level variations can be observed with accuracy better than 2 cm, there are some problems in monitoring the variations continuously with sub-centimeter accuracy. Obtaining such accuracy in the vertical direction is still challenging, especially for long baselines. To be routinely useful for oceanographic research, accuracy over longer baselines needs to be improved. Processing of sea level and wave statistics needs to become more routine for many applications. There is a lot of progress that needs to be made before DGNSS can be a routine part of oceanographic measurements but the future looks bright and we are looking forward to great progress over the next decade.

Although GNSS-based tide gauge stations have a lower accuracy than the GNSS buoys methods can not be underestimate their importance for sea level measurements. The GNSS tide gauge has better performance in high wind conditions and allows simultaneous and permanent determination of sea level and position with respect to the International Terrestrial Reference Frame system. They might become extremely useful as a campaign instrument for researchers having an interest in monitoring water levels, even in tectonically active regions and could be used in altimeter validation/calibration experiments. Because they do not need to be located in the water, they are simple to install and operate and can be easily moved.

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Praćenje mijenjanja razine mora pomoću GNSS tehnologije - pregled nedavnih pokušaja

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SAŽETAK

Razina mora se tradicionalno promatra s mareografima (TG). Ova mjerenja se odnose na Zemljinu koru. Kako biste poboljšali razumijevanje promjena razine mora potrebno je izvršiti mjerenja s obzirom na središte Zemlje mase. Takva mjerenja se provode pomoću sateliteskih tehnika (metoda).

Globalni navigacijski satelitski sustav (GNSS) je alat koji može izmjeriti nekoliko stotina kilometara vektora s razinom točnosti do u centimetar, te može izmjeriti visinu točke promjene u odnosu na referentnog elipsoida WGS84 koji je usmjeren na stvarni centar Zemljine mase. Iako se u posljednja dva desetljeća GNSS upotrebljava u gotovo svakom području geodetskih mjerenja, ipak još uvijek gotovo da nije u uporabi u području praćenja razine mora. Pokušaji primjene plutača opremljenih GNSS-om za određivanje precizne razine mora (na razini centimetara) bili su uspješni, a ukazuju na to da GNSS može zamijeniti konvencionalne mareografe. Pregled posljednjih promatranja promjena razine mora u kojima se koriste podaci iz GNSS prijemnika su prikazane u ovom radu.

Nadalje, predstavljeni pregled u ovom radu rezultirao je zaključkom da se korištenje GNSS temelji na mareografskom (GNSSTG) sustavu za određivanje promjena razine mora, a da je njegova točnost razine (u prosjeku) jednaka plutajućem plovku mareografa. Štoviše, apsolutna promjena visine trebala bi se lakše moći odrediti pomoću GNSSTG sustava.

Ključne riječi: razina mora, mareografi, Globalni navigacijski satelitski sustav - GNSS