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The Onsala Tide Gauge Station: Experiences From the First Four Years of Operation

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Abstract A tide gauge station was installed at the Onsala Space Observatory in 2015. The official tide gauge station includes several independent senors: one radar and three pneumatic sensors (also referred to as bubblers). The radar and two bubblers are mounted in a well and one bubbler outside the well. Additional sensors such as one laser sensor and three radar sensors have been used during different time periods in order to further assess the quality of the acquired sea level data. Here we compare the four official sensors and the laser sensor which was installed in April 2016. The expected accuracy (one standard deviation) for all of these sensors is approximately 3 mm, according to the datasheet specifications. Results from the first four years of operations are used to assess and estimate the actual accuracies by means of comparisons between the sensors. We observe typical biases over time scales of months of up to 10 mm. Biases are caused by uncertainties of the reference level of the sensor, the density of the water for the bubblers, multipath effects for the radar, and nonlinearities with temperature for the laser. The observed monthly standard deviation between the sensors in the well vary between 2 mm and 6 mm, which is roughly consistent with the data sheet specifications.

Keywords Sea level · Tide gauge station

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Fig. 1: The tide gauge station at the Onsala Space Observatory.

1 Introduction

The location of the Onsala geodetic VLBI telescopes close to the coast line motivates continuous and accurate sea level observations, especially given the recent finding of an accelerating global sea level rise (Nerem et al., 2018). A tide gauge station (Fig. 1) was developed and constructed in house, with advise from the Swedish Meteorological and Hydrological Institute (SMHI). Since the end of June 2015 it is an official site in SMHI's national monitoring network of the sea level.

In Section 2 we describe the individual sensors. In Section 4 we present the sea level observations acquired so far, and in Section 4 we summarise the levelling carried out in order to connect the sea level data to the reference markers at the observatory. Finally, the conclusions are given in Section 5.

2 Sea level sensors

The official tide gauge station has several independent sensors: one radar (Fig. 2) and three pneumatic sensors

Fig. 2: The down-looking radar sensor, Campbell CS476, operating at 26 GHz, mounted at the top in the centre of the well.

Fig. 3: The pneumatic sensors, Ott CS471 of USGS type, have a compressor (green unit, left) located in the measurement hut. Each compressor is connected to a nozzle (right) via a plastic pipe. Two nozzles are used at the bottom of the well, and one nozzle is located close to the bottom outside of the well. The original black nozzles corroded rapidly in the salty water and were replaced by the ones located just above (manufactured in copper) in October 2016 (see also Fig. 5).

(Fig. 3, also called bubblers). Now in July 2019 there are also one laser (Fig. 4) and two more radar sensors installed in the well for quality assessment of the official data (Fig. 5).

The Campbell CS476 radar is our main sensor and is in the following referred to as CS476. The pneumatic sensors (bubblers) are offered with different accuracy. The type used are by the manufacturer Ott referred to be of USGS type (possibly because they fulfil requests from the United States Geological Survey). The three pneumatic sensors are in the following referred to as USGS1, USGS2, and USGS3. The bubbler USGS3, originally mounted outside the well, was taken out of operation on 17 April, 2019. This sensor is discussed further in the next section.

The laser sensor was installed 29 April 2016 (Börjesson et al., 2016). A reflector is floating in a pipe and its surface is above the actual sea level. The reflector used up to 13 September 2017 was 9 mm above the sea level. Thereafter, a new improved reflector was installed. Its reflecting surface is 11 mm above the sea level. These corrections have been taken into account when presenting the results. For more details about the laser, see Micro-Epsilon (2016).

The VEGA61 radar is similar to the sensors used in the Swedish observational network operated by SMHI.

Fig. 4: The laser sensor is mounted on the inside wall of the well. A reflecting target is floating on the sea surface inside the pipe.

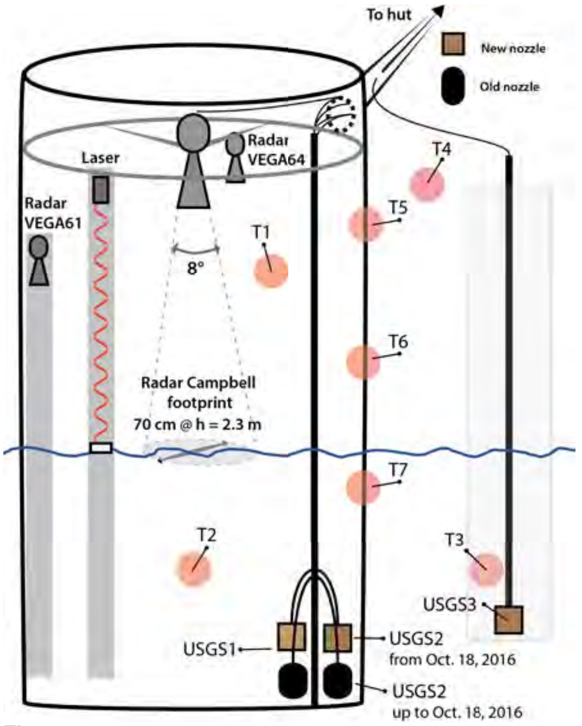

Fig. 5: Design of the tide gauge well. The official sensors are the Campbell radar CS476, mounted at the top in the centre and the three USGS bubblers. The pink circles denote temperature sensors, for the air and the water inside the well (T1 and T2) and outside of the well (T3 ad T4), and in the insulation layer of the well (T5–T7). The inner diameter of the well is 1.4 m. The insulation in the walls is 30 cm and the thickness of the outer concrete rings is 15 cm, resulting in an outer diameter of the well of 2.3 m.

The radar signal is propagating in a vertically mounted circular waveguide. It has been acquiring data since 1 December 2016.

The VEGA64 radar was installed more recently in order to investigate any possible differences due to multipath effects compared to the main sensor, the CS476 radar. The VEGA64 radar is operating in a higher frequency range, 76–80 GHz. It has a lens horn antenna which implies a more narrow beam angle. The full width half power beam width is 3.0° compared to the CS476 that has an 8° beam angle. It has acquired data from 14 September 2018.

The sketch shown in Fig. 5 gives an overall impression of the design and the approximate locations of the sensors and Fig. 6 depicts the present setup of sensors in the well. In the next section we compare the four official sensors and the laser sensor.

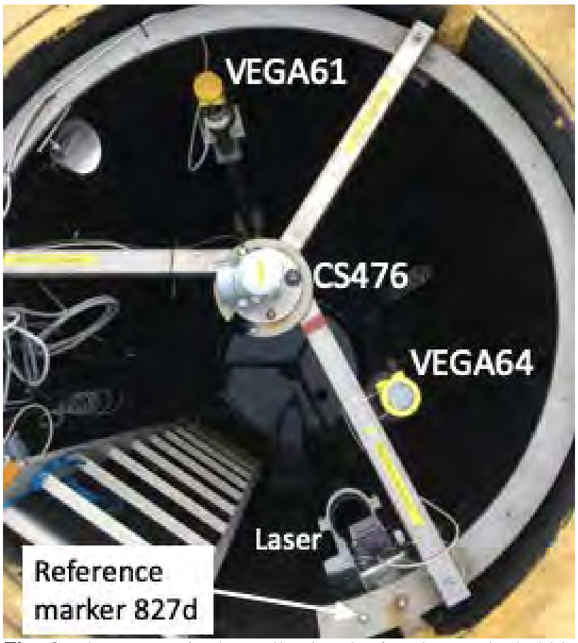

Fig. 6: The sensors in the well. The plastic tubes to the bubbler sensors goes into the water to the left just outside of the photo. The photo is taken on 23 August 2018.

Finally, it shall be mentioned that an additional tide gauge station is operated at the observatory using GNSS technology. It has been acquiring data since 2011. This station is primarily used to investigate different analysis methods in the processing of GNSS data and the results are for example compared to the official station presented in this paper. For more details on the GNSS tide gauge station and its results, see Löfgren et al. (2014); Löfgren and Haas (2014); Hobiger et al. (2014); Strandberg et al. (2016, 2017, 2019).

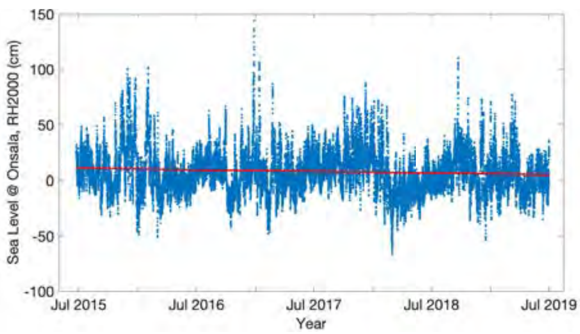

Fig. 7: The official time series, based on the CS476 radar sensor, is available from the SMHI web page. The sea level variations at Onsala are mainly caused by weather, and not by tides. The highest sea level measured so far, approximately +1.5 m, was during the storm Urd in December 2016.

3 Observational results

The official time series, based on the CS476 radar sensor, from the start in June 2015 until the end of June 2019 is shown in Fig. 7. Using these four years of data we estimate a linear trend of −1.4 cm/year (the red line in Fig. 7). The expected long term trend should be close to zero, because both the land uplift as well as the global sea level have been estimated to be slightly above 3 mm/year (BKG, 2018; Nerem et al., 2018). The negative value obtained for this time series is mainly due to the low sea levels observed during the first half of 2018. This illustrates the need for stable long time series of observations in order to assess any changes in climate related parameters. The international standard averaging period to calculate a single data point when monitoring a climate parameter is 30 years. This was decided at a meeting in Warsaw in 1935, at which the directors of most national meteorological institutes took part (Førland et al., 1992).

An example of sea level observations with the radar CS476 and the laser showing the short term variations during the month of December 2018 is presented in Fig. 8. The corresponding differences are shown in Fig. 9. For this month the bias (radar − laser) is 3.8 mm and the standard deviation of the differences is 4.3 mm.

Monthly biases and SDs between the radar and four other sensors have been calculated from samples with the temporal resolution of 1 min and are summarised in Table 1.

Table 1: Monthly biases and standard deviations between the radar sensor and the other sensors

Radar CS476 vs.	Monthly bias (mm)	Monthly standard deviation (mm)
Laser	3 – 4	2 – 5
USGS1	1 – 10	2 – 5
USGS2	1 – 9	2 – 6
USGS3	6 – 14	2 – 14

Biases are caused by uncertainties of the reference level of the sensors, plus the salinity and temperature determining the density of the water for the USGS bubblers, multipath effects for the radar, and an uncertainty of the reference level of the floating reflector for the laser. In terms of their monthly biases it is clear that the laser and radar show superior stability compared to the bubblers.

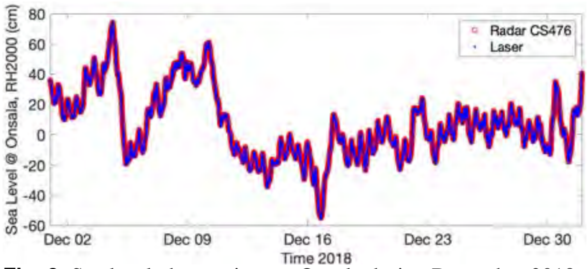

Fig. 8: Sea level observations at Onsala during December 2018.

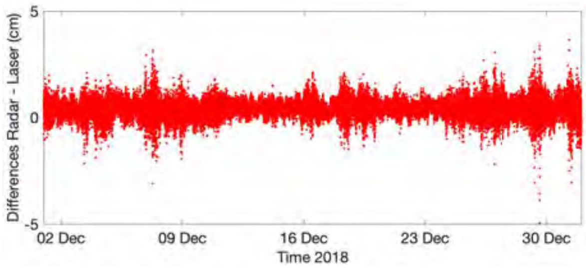

Fig. 9: Time series of the difference between the CS476 radar and the laser sensor.

The USGS3 bubbler, mounted outside the well is expected to show a larger variability given that the well acts as a low-pass filter. However, we have noted, apart from just looking at the SDs, that a systematic negative bias sporadically occurs, compared to the other sensors. We have no obvious explanation for this behaviour and as mentioned above the sensor has been taken out of operation on 17 April, 2019.

4 Vertical control

Given the importance of monitoring the sea level with the highest possible accuracy, levelling of reference markers has been carried out (at least) annually. Fig. 10 depicts the area close to the tide gauge station including the reference markers. In order to illustrate the stability of the tide gauge station the levelling results of the reference marker 827d are summarised in Table 2. This marker is the one most easily accessible, and is therefore the most frequently measured, of the markers located inside the well. We note that the standard deviation of these levelling results is 0.3 mm. The most recent levelling results were documented by Heep (2018).

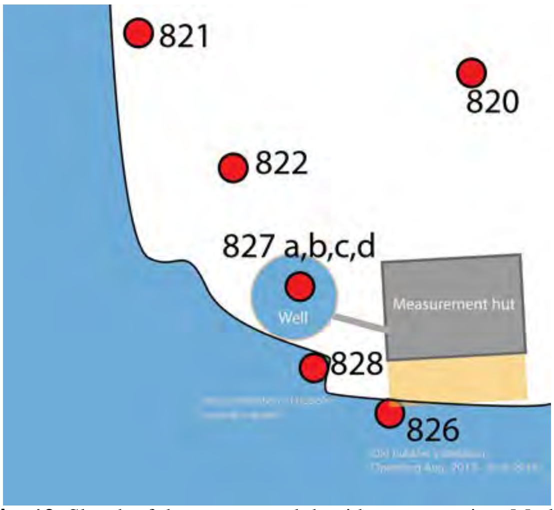

Fig. 10: Sketch of the area around the tide gauge station. Markers 820, 821, and 822 are steel markers mounted in the bedrock. Marker 826 is on the pipe protecting the plastic tube to the nozzle of an old bubbler, taken out of operation in June 2015, markers 827a, b, c, and d are on the upper side of the mount for sensors in the well, and marker 828 is on the bubbler outside the well.

Table 2: The levelling results of reference marker 827d

Date	RH2000 vertical coordinate of 827d (m)
2015-08-13	2.4875
2016-08-05	2.4868
2017-06-01	2.4871
2017-07-26	2.4874
2017-08-11	2.4872
2018-08-23	2.4875

5 Conclusions and outlook

We find that the different sensors roughly perform according to their specifications. The radar and the laser sensors appear to be more stable in terms of long term systematic errors. Therefore, future work will focus on these two sensors, plus the additional two radar sensors installed in the well. A possible development may be that the present primary sensor, the CS476 radar, is replaced by the high frequency VEGA64 radar. However, in order to take such a decision, extensive comparisons between the laser and the different radar sensors must first be carried out.

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