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Uncertainty and bias in electronic tide-gauge records: Evidence from collocated sensors

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ABSTRACT

Understanding noise and possible bias in tide-gauge sensors is important for determining the mean sea level, its fluctuations and their climatic, geophysical and engineering implications, but not an easy task. In the past, this problem has been examined through comparison of different sensors in the laboratory, or through correlations of neighbouring sensors. In this study we identified and studied 10 cases of harbours with fully collocated sensors. Transient differences were found between collocated records. Pressure gauges were found significantly more sensitive to noise than radar-type sensors, and with higher chances of long-term transient bias. The amplitude of the observed bias is important, of the same order of magnitude with tsunami waves in the open sea and with seismic ground displacements. Only 9% of the sensors analysed were found to satisfy the 1 cm accuracy criterion imposed by the Permanent Service for Mean Sea Level (PSMSL).

1. Introduction

Tide gauges have been established in harbours since the 18th c. to provide information on the quasi-periodic tidal fluctuations of the sea level obstructing navigation. Early gauges were simple vertical metred poles fixed in quiet places of harbours. Because of their efficiency, they were also used to define the geodetic datum (zero elevation for maps) and were evolved into mechanical, continuously recording floaters. In the last 50 years, tide gauges have also been used for the study of large-scale water dynamics, as well as of various coastal, tectonic, meteorological and climatic processes (e.g. Church and White [3], Menéndez and Woodworth [11], Zerbini et al. [24], Wöppelmann and Marcos [25], Becker et al. [1]. Recently, the new generation of electronic high-rate recording tide-gauges (with a sampling rate of a few minutes to a few seconds) have been used to monitor transient effects such as tsunami waves (e.g. Fujii and Satake [4], Satake et al. [22].

Two major problems with tide-gauge data are that their number at a global scale was till recently limited (at present there are approximately 2300 operational stations worldwide; [18], and that the deterministic astronomic signal is mixed with an essentially stochastic meteorological signal; for this reason, there is no easy way to control noise and bias in their records, i.e. to understand what their uncertainty limits are [2]. As a consequence, the uncertainty in the recordings of tide-gauges has not been resolved even for the modern, electronic tide-gauges.

The advent of electronic sensors (usually accompanied with telemetry transmission of the recorded oceanographic signals) however, was a real revolution. The reduced cost and simplicity of the new instruments gave the possibility to significantly increase the number of mareographic stations at a global scale, to install tide-gauges in buoys, and hence, to collect and analyse real-time signals at various centres, e.g. the British Oceanographic Data Centre (BODC), the University of Hawaii Sea Level Centre (UHSLC) etc., and even to combine two or more tide-gauges in the same or adjacent sites. Such collocated tide-gauges give for the first time the opportunity to compare the signature of the same oceanographic effect in different sensors, and from their differences to estimate the error properties of tide-gauges. Currently, the percentage of sites with collocated sensors is of the order of a few percent of the total sites covered with tide-gauges, but with a tendency to increase. The new situation revolutionises the understanding of the uncertainty of these instruments, which so far, was only derived from measurements in laboratory conditions, usually very different from those in port or open seas environments.

In this article we examined a large number of tide-gauges at global scale, identified those which can be regarded as collocated, and analysed their differences. This approach represents the optimal way to document the uncertainties/error properties of tide-gauges from real data in different hydraulic conditions and geographic environments, and is novel. This is because so far, differences between collocated operating time gauges have clearly been noticed, but they were discarded, readily assigned to outliers, a priori assuming one sensor

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reliable. For this reason, the statistical information provided by differences in collocated sensors was ignored.

The output of this study is to identify and classify the differences between the different types of collocated sensors using raw, unfiltered data. We aim to provide information on how each sensor type behaves, which type is the most prone to bias, how big this bias can be and whether it can be related to other external factors which, if controlled, could reduce errors.

1.1. Main types and function of tide-gauges

The most common type of tide gauge is the traditional mechanical floater. The float remains on the sea surface and is connected to a system of pulleys and weights. As the float follows the sea level fluctuations, its movement is translated to actual water level on a recording paper [5]. A floater with encoder (ENC) is the type of tide gauge where the mechanism that translates the float movement to water level values is an electric current.

In the last 20 years, the mechanical sensors were replaced by electronic sensors mainly of three types (in addition to the ENC sensors mentioned above): pressure sensors, acoustic tide-gauges and radar sensors. Their basic characteristics and principles of operation are described in IOC [6] and are summarized below.

Pressure sensors (PRS) are commonly fixed below the low tide level and measure the hydrostatic pressure of a column of water above the sensor. This pressure is then converted to sea level assuming a value for the water density and atmospheric pressure at the surface of the sea. The problems of this type of tide sensors are the accurate determination of their datum and their drift (gradual change of their zero point, with a rate of 8 mm/yr; [12]) over time, mainly because of the aging of the sensor.

Acoustic sensors (AS) provide sea level values that are based on the time that an acoustic pulse transmitted by a sensor located directly above the sea level, requires to reach the sea surface and return back to the transmitter (time of flight). This signal is then converted to a distance from the sea surface. Acoustic pulses are, in the vast majority of cases, restricted within a vertical tube. This way, the sensor is less affected by changes in the temperature and pressure, factors that need to be taken into account for accurate sea level determination.

Radar sensors (RAD) are fixed above the maximum water level and measure the distance between the fixed radar and the water level below through a radio signal reflected on the water surface. Their advantage over an acoustic sensor is that they are not affected by temperature variations [6].

1.2. Previous studies on uncertainties of tide-gauges

All types of measurements are affected by measurement errors of different types, and tide-gauges are no exception. However, till recently, the understanding of their errors was nearly impossible, because tide-gauges are isolated instruments, there is no possibility to reproduce tidal effects, and no comparisons with other records (independent constrains) were possible. For example, it was found that in certain regions wrong type of lubricants were occasionally used for mechanical floaters, and saline water had the tendency to gradually reduce the viscosity of these lubricates with time. This led to gradually increased damping and attenuation of small-amplitude oscillations, hence biasing tide-gauge records. Some of these records have been discarded, but it is unknown how many others are affected, especially because no detailed metadata are available.

Industrial tests were used to derive the quality of specific types of tide-gauges, but results were limited to specific laboratory conditions [13]. In the last decades, however, efforts have been made to estimate their uncertainty in field, operational conditions. Lentz [8] studied the accuracy of tide-gauge observations for the determination of the sea level using the differences between the values obtained from 3 pairs of tide-gauges within 50 km distances. He used the root mean square of monthly mean differences between observations to establish an upper bound for the error in measurements which was found to be of the order of 1.4 cm. He attributed this to errors in establishing the datum of the tide-gauges. His study also included the comparison of data between tide-gauges and bottom pressure sensors which resulted in a similar value for the error in observations.

However, differences in the hydraulic energy along coasts are important even in nearby areas, as can be indirectly derived from significant variations of the elevation of the coastal biological zoning [21], and for this reason recordings of strictly non-collocated sensors are different, because they are influenced by unknown, different processes reflected in differences of local hydraulic energy of the sea water (mostly wave action).

Exploiting the emerging availability of collocated sensors Woodworth and Smith [23] used data collected by a radar (RAD) and a bubbler pressure gauge (BPRS) in Liverpool (UK) over a period of one year at a sampling rate of 15 min. Linear regression revealed a small scale error between the two sensors, while the root mean square of the differences between corresponding values was of the order of 1.4–1.5 cm. The radar sensor seemed to be noisier than the bubbler, but both sensors had the same accuracy of 1 cm. Although the radar sensor was deemed to be biased up to 5 cm during a storm, the authors suggest that it should be considered for future projects/applications due to ease of installation and maintenance. The authors also suggest that a value of the root mean square (RMS) of the differences below 1.4 cm would ensure that the accuracy of the sensors is better than 1 cm. The latter is the accuracy requirement for all Global Sea Level Observing System (GLOSS) sensors, the global monitoring network that provides sea level data for oceanographic and climate research. Mehra et al. [9] were also favourable towards the installation of radar sensors. Their study, based at Verem (India), was focused on two types of sensors: a radar (RAD) and a pressure (PRS) gauge. Their work highlighted the effects of atmospheric factors (atmospheric pressure, water density and rainfall) on the pressure gauge and the advantage of radar sensors over other types of sensors.

A comparative study using four different types of sensors (acoustic, pressure, and two types of radar) was conducted by Miguez et al. [12] at a port in NW Spain. They compared data sets from a 6-month period at sampling rates of 5 min, and mean hourly and daily values. They found that all sensors were providing data of acceptable accuracy but there were specific advantages and disadvantages associated with each of them. The radar sensor, for example, was not affected by bad weather conditions, but it could be easily vandalised due to lack of protection, while the acoustic and pressure sensors were biased by variations in the air pressure and salinity, respectively.

The effect of atmospheric variables on pressure gauges was the focus of the study by Mehra et al. [10] who compared the data (5-min average values) obtained by a radar (RAD) and a pressure (PRS) sensor deployed at three different locations within an area 10 km × 20 km. Each data set had a duration between 10 and 17 months. Their results revealed that the data from both types of sensors were similar if an atmospheric pressure correction was applied to the pressure sensor time series and they recommended the collection of atmospheric pressure data along with data collected by a pressure gauge for projects related to storm surges and tsunamis.

2. Methodology

Uncertainty in measurements is defined in terms of accuracy and precision [15]. Precision is a measure of the consistency of measured (usually repeated) values, and also an indicator of the repeatability of the measurements. Accuracy, on the other hand, defines a quasi-random difference between recorded values and a “true” value (systematic error, bias), but it can rarely be estimated, mostly through comparison with the output of instruments of much higher quality/