Ocean Engineering 118 (2016) 165–172

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

# Study of post-processed GNSS measurements for tidal analysis in the Belgian North Sea

Cornelis Stal [a,b,*], Hans Poppe [c], Annelies Vandenbulcke [a], Alain De Wulf [a]

[a] Department of Geography, Ghent University, Ghent, Belgium
[b] Department of Real Estate and Land Surveying, Ghent University College, Ghent, Belgium
[c] Flemish Hydrography, Maritime and Coastal Services, Ostend, Belgium

ARTICLE INFO

*Article history:*
Received 7 October 2015
Received in revised form
4 March 2016
Accepted 13 April 2016
Available online 19 April 2016

*Keywords:*
GNSS
Buoy
Tide
Post-processing

ABSTRACT

In this paper, the use of a tidal buoy, equipped with a GNSS, is assessed. The prediction of the tide in the North Sea area is performed by a network of coastal tidal gauges. Long term measurements by these gauges are used to derive tidal constituents and the construction of tidal prediction tables for each separate measurement location. To estimate the tide between these locations, an interpolation is required. However, the quality of this calculation is heavily reduced for offshore predictions. The aim of this research is to deal with this challenge by the deployment of GNSS-buoys on full sea. The focus is on the data processing and the analysis of meteorological influences on the data quality. In this context, a strong correlation between meteorological parameters and the ability to calculate a fixed position will be demonstrated. Based on the results of two separated measurement campaigns, it is stated that the developed data acquisition technique results in highly accurate elevation measurement.



## 1. Introduction

Networks of tidal gauges are mainly situated along the coast, with fixed measurement instruments on quay walls or dykes. These systems are maintained by governmental organizations and allow real-time tidal elevations determination, as well as the estimation of tidal tables. On an international scale, different countries world-wide have connected their tidal observations to monitor climate change and sea level rise (Woodworth and Player, 2003). The systems are frequently positioned in important harbor basins and the corresponding tidal tables are based on complex predictive modeling for that specific location. In order to derive the tidal amplitude at full sea, a spatio-temporal extrapolation of the data from different tidal stations of multi-dimensional hydrodynamic modeling is performed (Walters, 1987). The resulting predictions and real-time estimations are not fully reliable when the resulting values are solely based on onshore measurements, since tidal movements at full sea have a different behavior than in near-shore areas. Therefore, long term offshore water level measurements are performed and correlated with measurements from tidal stations. The ratio between the two calculated principal lunar semi-diurnal constituent or $M_2$ tidal components and the phase shift between the two locations are used to derive the tide for each location at full sea for a given time. The success of this co-called $M_2$-method is based on the fact that 92% of the tide is explained by the $M_2$ constituent. The actual tidal predictions are based on hydrodynamic models, where the entire North Sea is considered as a basin, rather than the sole Belgian Continental Shelf. In both cases, the resulting values are related with the local equipotential of the geoid. Therefore, the Flemish Hydrography aims at the optimization of a tidal buoy, which has been deployed at full sea for measurements related to the ellipsoid. Consequently, the main motivation for this research is to improve the performance of the currently used $M_2$ model and to allow high quality tidal estimations at locations at sea where no continuous tide gauge system is available. In contrast with current tidal systems, where measurements are related to a geoid model, this research also aims at gaining elevation measurements directly related to a reference ellipsoid (Fotopoulos et al., 2003). Measurement techniques directly resulting in ellipsoidal heights are not necessarily preferred above techniques resulting in geoidal heights, but an accurate model of the geoid at the Belgian Continental Shelf is lacking. Besides, satellite RaDAR data, from platforms like JASON-2 (Masters et al., 2012), have a low temporal resolution and are more suitable for mean sea level monitoring, rather than tidal modeling. Therefore, the use of kinematic Global Navigation Satellite System (GNSS) measurements are performed and processed. GNSS has been used in various research projects on tidal measurements using multipath-based phase delay using two oppositely

* Corresponding author at: Department of Geography, Ghent University, Ghent, Belgium
*E-mail address:* cornelis.stal@ugent.be (C. Stal).

http://dx.doi.org/10.1016/j.oceaneng.2016.04.014
0029-8018/

positioned antennas (Löfgren and Haas, 2014) or the comparison of onshore and offshore kinematic Precise Point Positioning (PPP) (Chen et al., 2004). Furthermore, it has been shown that GNSS on tidal buoys may result in sub-decimeter accuracies (Chen et al., 2014).

This research paper elaborates on the accuracy of different post-processing procedures for raw GNSS data. Based on the analysis of these procedures and their corresponding parameters, the significance of each parameter and the influence of its value on the quality will be assessed. This allows the formulation of series of recommendations for the post-processing of GNSS data measured by a wave rider tide buoy, as used by the Flemish Hydrography. The discussion is based on two case studies, where the buoy was deployed in the Belgian North Sea for three months (June until August) in 2013 and in 2014 (near Bol van Heist and Wandelaar respectively). The results of the GNSS processing of these first North Sea data are validated by a comparative analysis with additional data from June until August, 2014. In comparison with the previously mentioned research papers, the data for this research cover a much longer time span. This opportunity allows the inclusion of meteorological influences on the resulting data.

After a brief theoretical discussion on the background of the tide and GNSS, the study area and data are elaborated. Special attention is given to the construction of a complete data set for the processing (regarding reference data, satellite ephemeris and clock information) and to the processing of these data using the open-source program RTKLib (Chambers and Schröter, 2011) (Section 2). The primary objectives of this paper are:

- To define the most optimal parameter set for post-processing GNSS data. This set will be generated by a thorough comparative analysis of all available parameters (Section 3.1);
- To automate the post-processing of large recording files using the most optimal parameters (Section 3.2);
- To derive a tidal model for the post-processed GNSS data. This procedure is performed by implementing least-square harmonic analysis and Fourier series development. Depending on the application and used methodology, the tidal constituents are rather or not assumed to be known. An important tool for the extraction of tidal constituents is the t_tide Matlab library (Pawlowicz, Beardsley, & Lentz, 2002) (Section 4.1);
- To discuss the influence of meteorological parameters on the quality of the GNSS data (Section 4.2).

The tidal estimation and elaboration on meteorological parameters is supported by a comparative study of the resulting post-processed data with GNSS-based data using PPP (El-Mowafy, 2009) and augmented GNSS (Roscoe Hudson and Sharp, 2001), but also with an independent data set measured by a nearby RaDAR tide gauge as. RaDAR-based data are currently used reference data by coastal managers in Belgium.

Based on the conclusions of this research, it becomes clear that GNSS buoys are suitable for supplying tidal information at full sea. In the near future, it is foreseen to derive a model for the equipotential surface, facilitating a smooth connection between the current bathymetric and terrestrial model. It is expected that an operational tidal prediction model solely based on a GNSS buoy is not optimal, since only limited time windows are recorded. Nevertheless, the harmonic analysis of these time series allows the determination of tidal constituents with their corresponding magnitudes and phases.

## 2. Study area and data description

### 2.1. Study area

The idea of this project is to allow the coverage the entire Belgian Continental Shelf with GNSS-based tide buoys. For this preliminary study, the data collection took place around the sandbar Westhinder and Bol van Heist, which are situated approximately 30 km north of the port of Nieuwpoort and 6 km north of the port of Zeebrugge respectively (Fig. 1). At these locations, permanent measurement stations are installed (MP7, [51° 23′ 18″N, 2° 26′ 16″E], Fig. 2, left MOW3, [51° 23′ 31″N, 3° 11′ 51″E], Fig. 2, right) as part of a larger Monitoring Network Flemish Banks (MNVB, www.meetnetvlaamsebanken.be).

At these and other stations, various meteorological parameters are measured with fixed intervals, like the wind speed, air pressure, wave height, etc. An overview of the parameters used for this research is presented in Table 1. For the sake of completeness, the delivered wave parameters are characterized as $H_{mean}$ and $H_{sign}$,

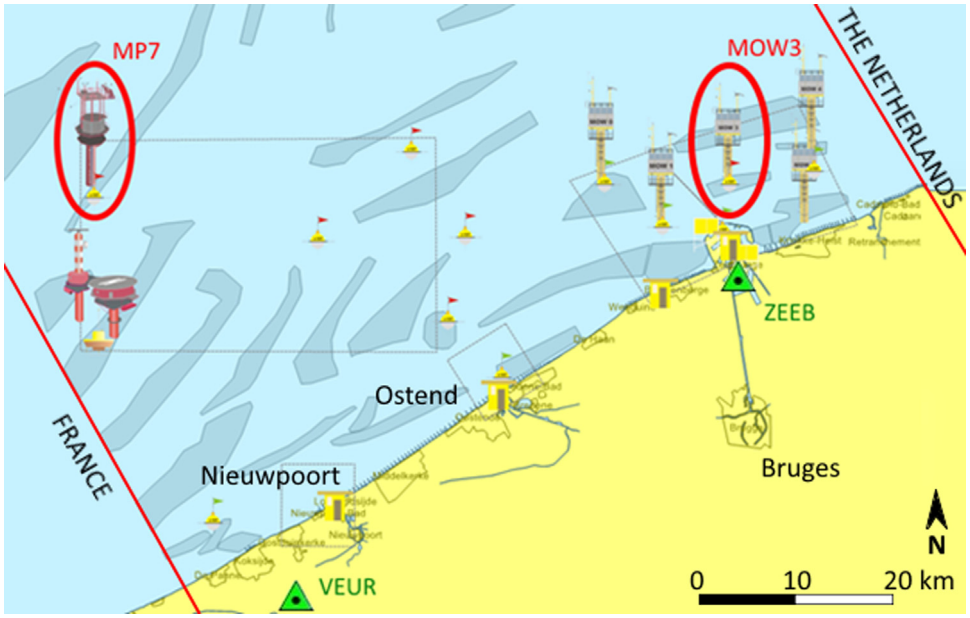


**Fig. 1.** Configuration of the measurement network "Vlaamse Banken", as well as the used CORS antennas as green triangles.