

Development towards continuous dynamic vertical reference for maritime and offshore engineering by applying geodetic and machine learning strategies

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The absence of a consistent, high-resolution dynamic vertical reference limits the accurate quantification of hydrodynamic processes across marine environments, thereby constraining engineering applications that depend on reliable vertical referencing. To overcome this challenge this study develops a method for real-time continuous dynamic vertical reference for quantifying hydrodynamic processes with respect to a high-resolution and accurate marine geoid model. In particular, we show that this can now be realised through dynamic topography (DT), which is defined as the instantaneous sea surface height (SSH) deviation from the marine geoid ($DT = SSH - \text{geoid}$) and represents one of the most useful parameters of marine dynamics.

The Baltic Sea countries have been fortunate to have access to a wide range of marine data products, including that of a high-resolution marine geoid and hydrodynamic models that enable allow further capabilities to be explored in terms of sea-level accuracy and validation. It should be noted that in regions with high-quality and dense coverage of gravity data, a 5 cm marine geoid modelling accuracy is achievable. With an accurate geoid model, the DT values can now be estimated, e.g., from a suitable hydrodynamic model with a decimetre-level accuracy. This corresponds to the strictest requirement for vertical accuracy at cargo handling in ports, dredging, maritime engineering, hydrography and under-keel clearance (UKC) management. This DT accuracy range also creates pre-conditions for identifying realistic sea level variations and circulation patterns of oceanic currents, seamlessly from the coastline toward the offshore over large basins.

Accordingly, this study proposes a geodetic-oceanographic methodology for determining DT that synergises different sea-level data sources by utilization of the marine geoid. The methodology applied utilised mathematical, statistical and machine learning strategies to obtain a spatio-temporally continuous dynamic topography of the Baltic Sea level.

Various maritime and offshore applications require short-term and realistic sea-level forecasts for hours to days in advance due to strict safety regulations. Thus sea-level forecasting using DT is examined using machine learning approaches such as Convolutional and Recurrent Neural Network, achieving a DT modelling accuracy within 5 cm. This shows that deep learning approaches can match the accuracy of traditional data-assimilation-based forecasting methods without requiring real-time data assimilation.

We demonstrate how improved dynamic topography estimation, together with uncertainty quantification, enhances under-keel clearance determination and delivers economic benefits for maritime operations. Accomplishing this demanding accuracy requirement creates a marine dynamic vertical reference frame, which enables allows novel opportunities for marine digital twins, navigation, oceanographic processes, and marine forecasting abilities.