Toward Reliable Volumetric Monitoring of Sandbanks

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Abstract—**This work forms part of a study addressing volume monitoring over submarine sandbanks through a temporal sequence of DTM models computed from repeat MBES surveys. To perform reliable temporal geomorphometry, the main issue is to get an estimate of the systematic errors of each MBES survey. To this end, while supposing that the evolving shapes still exhibit some partial redundancy, this paper proposes to apply a new trend surface extractor to the first-order time difference between two successive DTMs.**

I. INTRODUCTION

Based on the five main steps commonly implemented in terrestrial geomorphometry, [1] provides an extensive review of marine geomorphometry studies. Through this review, marine geomorphometry appears as a distinct, and recently growing, discipline still in its infancy. One of its main issues arises from the complexity of interrelated physical processes involved in submarine measurements. Therefore, raw data commonly come with systematic errors, and variable noise levels. These limitations place additional stress on the availability of dedicated and *robust* tools aiming at quantitative geomorphometry. Some useful measurements and processing tools commonly available through Geographic Information Systems (GIS) while performing quantitative analyses on submarine Digital Terrain Models (DTMs) are described in [2].

Bathymetric surveys are performed primarily through on-board Multi-Beam Echo Sounders (MBES). The achievable accuracy of modern MBES measurements w.r.t. submarine geomorphology, with special emphasis on monitoring temporal seabed changes, is examined in [3]. The Special Publication No. S-44 of the International Hydrographic Organization (IHO) [4] specifies the range of the uncertainties that should be expected from hydrographic surveys carried out in an appropriate way. Since they primarily address navigation safety, these standards are conservative. Indeed, the later generation of MBES, while coupled with high accuracy positioning and inertial motion sensors, can outperform these minimum standards. However, nowadays, performing MBES surveys to build bathymetric models is still an expensive task and these native models may come with a wide spectrum of artefact level. Moreover, while addressing temporal changes, past surveys are still of high values, even if the intrinsic uncertainties of their corresponding bathymetric models are sometime unavailable or unknown. Thus, a *generic* approach able to robustly compare the bathymetric models without a priori knowledge of the data uncertainties should be a valuable tool.

This work aims at temporal monitoring of sandbank changes – *with* or without aggregate dredging. Marine sandbanks are sediment-based dynamic structures commonly observed on the continental shelf. A short survey focusing on studies addressing marine sandbank geomorphometry was recently made available in [5]. The exploration and exploitation methods of the three most important marine mineral types – including sand and gravel – are described in [6]. The main topics involved in offshore sand and gravel mining is described in [7] while [8] provides a transversal overview of research and industry practice involved in aggregate dredging.

Focusing on the monitoring of sandbanks temporal changes involve additional challenges. Their morphological spectrum is wide and depends both on sediment composition and on multiple and interrelated marine physical processes that have not been thoroughly elucidated to date. As a result, sandbanks also exhibit a wide spectrum of temporal changes – ranging from daily to annual, decadal, and more. Moreover, some monitoring zones are circumscribed to geographic areas where static seabed parts remain out-of-field, i.e., there is no reliable temporal landmark. [9] provides an overview of studies that implemented differential analysis of repeat surveys and then proposes getting volume measurements with more realistic confidence intervals while using the spatially variable uncertainty derived from MBES raw data processing algorithms.

In this challenging context, the aim of this paper is to introduce some promising new avenues while addressing reliable volume monitoring over sandbanks through a temporal sequence of DTMs issued from repeat MBES surveys. The core analysis tool is a robust trend surface extractor – potentially asymmetric. While applying it on a differential DTM, it is expected that, due to the inherent partial *redundancies* usually found between two consecutive surveys, an additive-based decomposition of each time interval into several trend surfaces could give some clues that would then help to reliably separate systematic errors from anthropogenic and/or natural changes.

II. ANALYSIS TOOL AND TEST SEQUENCE HIGHLIGHT

The core analysis tool used in this work is a shape operator $\updownarrow\mathtt{F}_{\lambda}^{m}(H)$ filtering input DTM H, fully described in [10]. It is a trend surface extractor able to robustly wipe out substructure whose extent cannot be assimilated by a cursive low-degree polynomial function locally instantiated through a fuzzy spot domain of diameter λ – hereafter denoted as the extraction scale. The degree m is currently defined within the set (0, 1, 2, 3) while using a constant, linear, quadratic, or cubic model, respectively. Its fitting behavior can be internally tuned to make use of an asymmetric or symmetric robust error norm, thus providing bottom-osculatory $\downarrow\mathtt{F}_{\lambda}^{m}$, top-osculatory $\uparrow\mathtt{F}_{\lambda}^{m}$, or neutral $|\mathtt{F}_{\lambda}^{m}$ (or, simply $\mathtt{F}_{\lambda}^{m}$) alternatives of its assimilation behavior. For the sake of simplicity, $\updownarrow F_{\lambda}^{m}$ will also denote the result of the operator. Let ${}^{*}\updownarrow\mathtt{F}_{\lambda}^{m}(H) = H - \updownarrow\mathtt{F}_{\lambda}^{m}(H)$ denote its residual DTM. For example, while performing a sandbank static analysis (Fig. 1), provided that the working scale λ is relevantly chosen w.r.t. the main dunes wave length, $\downarrow\mathtt{F}_{\lambda}^{3}$ could estimate a virtual smooth interface between fossil sand and mobile sand while still assimilating the sandbank global morphology.

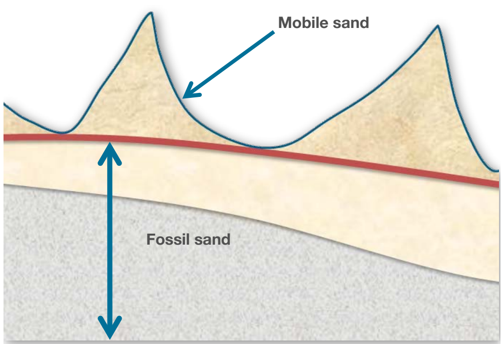

Figure 1. Morphodynamic definition of the osculatory surface as the virtual intra-sediment interface – the red curve – between the mobile sand and the fossil sand over a sandbank.

An overview of the nine models of a bathymetric time series is given in Fig. 2; their location is given Fig. 3. These models are 4x4 m DTMs. This series focuses on the monitoring zone HBMC of the Belgian sector S4c partly covering the Oosthinder bank. This zone was then subjected to intensive dredging. The raw data come from the RV Belgica MBES – a SIMRAD/EM3002D. The corresponding bottom-osculatory surface $\downarrow F_{400}^{3}$ time series is

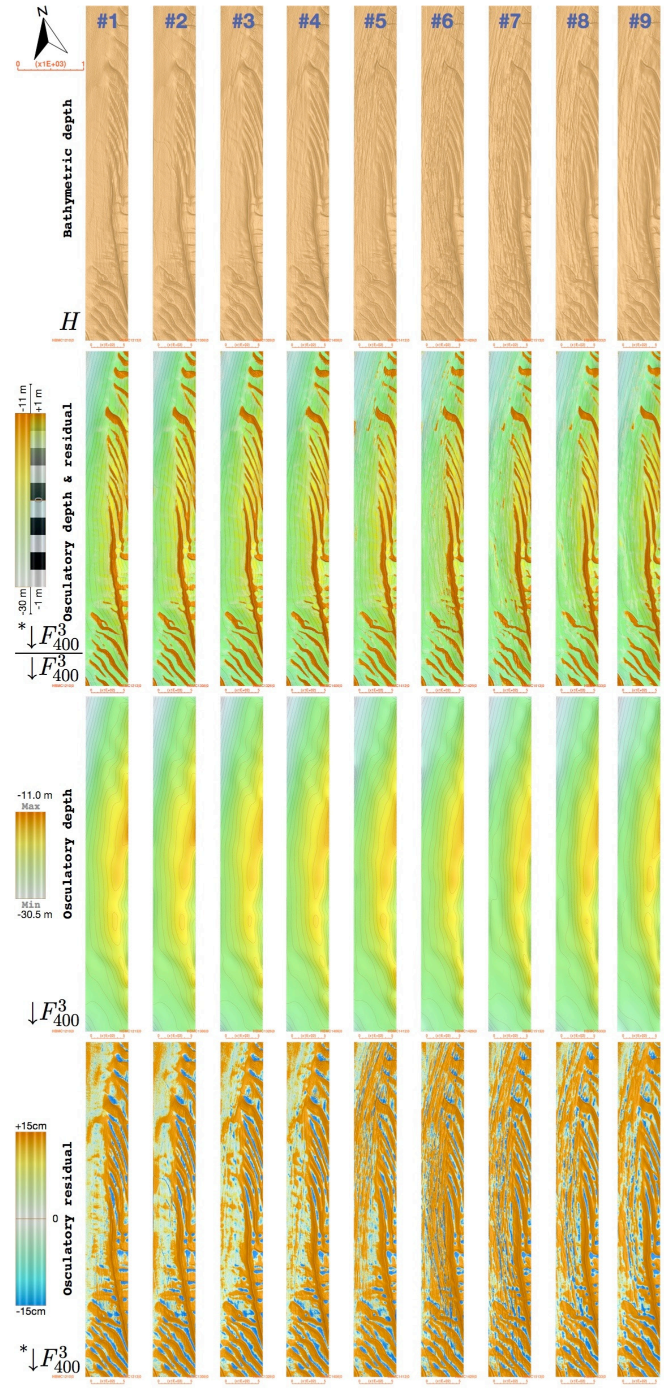

Figure 2. Nine MBES-based observations, unevenly spanning 44 months, of the monitoring zone HBMC within the Belgian extraction sector S4c. The dune network morphology is enhanced through the estimation of the nine inner osculatory surfaces extracted at scale 400 m while using a local bicubic model.

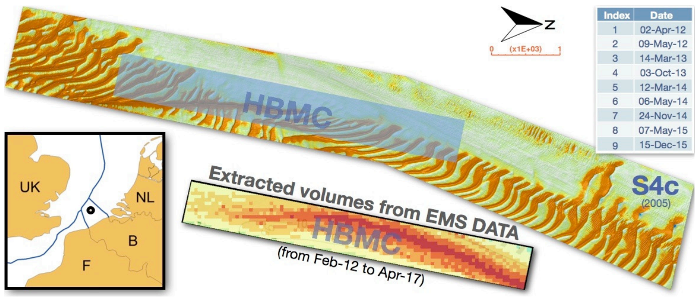

Figure 3. Geographic localization of the monitoring zone and survey dates.

used to highlight the geomorphological content – especially while mapping its residuals $^{*}\!\downarrow\! F^{3}_{400}$ on the bathymetric models through a pseudo-color palette. It is worth underlining that the bottom-osculatory models still fully assimilate the ridge of the Oosthinder bank intersected by the monitoring zone. As expected, noticeable negative residuals highlight some vortex effects near the lee side of the dunes.

The MBES-based volume change over time is the green curve drawn Fig. 4 – indeed, it is its equivalent thickness change w.r.t. to the HBMC area. The water depths range from -30 m to -10 m. Since this depth range corresponds to the Special order of the S-44 standards, the maximum admissible MBES errors should thus range from ±30 cm to ±25 cm – see dotted lines in Fig. 4. All dredging vessels are fitted with an Electronic Monitoring System (EMS). This is a black box recording, ± every 30 sec while dredging is taking place, several sensors on board the dredger – e.g., GPS position, and pumps activity levels. Once the whole EMS data of every dredger are aggregated, assuming that dredging vessels are always using their maximum capacity, an estimation of the dredged volume can be computed on a given geographic area and during a given time window. The gray curve

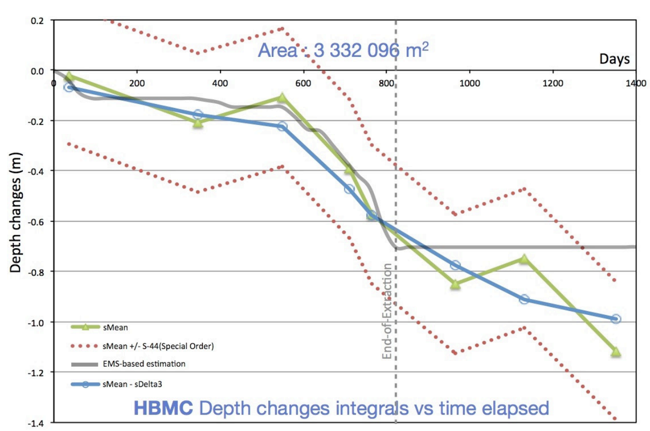

Figure 4. Comparison of the temporal evolution of the eight MBES-based volume changes measurements w.r.t. their predictions issued from the EMS system database – the time origin is the date of the first survey.

(Fig. 4) reports the corresponding EMS-based estimation for the current sequence – this EMS curve was reported in [11]. While supposing that a hypothetical natural net influx would remain negligible over a decadal time scale w.r.t. current depth accuracy, the EMS-based curve becomes a valuable reference and can thus be compared with the MBES curve. Globally, the apparent discrepancies are clearly far below the S-44 limits. However, the systematic error of the last survey seems noticeable, since the S-44 error bound should be reached by this survey.

III. Differential Volume Analysis

Let D denote an element of the first-order differential DTM sequence $D_i = H_{i+1} - H_i$. A robust decomposition of the changes over these eight time intervals by the trend surface extractor is summarized in Fig. 5. Since the global trend no longer has to assimilate the bank morphology, its elasticity level can remain very low. Conversely, a neutral setup of its error norm is now required. The decomposition selected is $D = F^1_\infty(D) + F^1_{600}(^{*}F^1_\infty(D)) + {}^{*}F^1_{600}(^{*}F^1_\infty(D))$, that is, a global (infinite scale), a semi-global (scale 600 m), and a local (residuals) trends, respectively. The results are numerically meaningful. As expected, the residual DTM mainly account for noise, dune migrations, fresh furrows created by trailer suction dredge, short-term accretion of sediments in these furrows and corresponding erosion in their neighborhood. However, the main expectation was to discover potential MBES systematic errors through the global trend component F^1_∞. Indeed, even though F^1_∞ rightly accounts for a probable MBES bias within $H_9 - H_8$, the former may still also express a partial assimilation of the large sediment valley found under dredgers corridor, e.g., $H_5 - H_4$. Since the perimeter of the monitoring zone HBMC turns out to be too tightly bounded to the dredgers mean corridor (see EMS Fig. 3), the expected shape redundancy may become excessively poor between two successive surveys, especially while it is undergoing both intensive extraction and dune large migration during the corresponding time window, e.g., $H_5 - H_4$.

Thus, ad hoc indicators must be devised to cope with the harmonization of such challenging sequences. Working through the bottom-osculatory sequence (Fig. 2) should (i) offer a better redundancy level and (ii) allow for applying a top-osculatory extractor – the latter being more immune to the influence of large extraction valleys – on its corresponding differential sequence. Let $\widehat{D}$ denote an element of the differential DTM sequence $\widehat{D}_i = \downarrow F^3_{400}(H_{i+1}) - \downarrow F^3_{400}(H_i)$. Some possible scalar indicators of the probable mean systematic errors between two surveys are then $\delta_1 = \uparrow \overline{\mathrm{F}}^0_\infty(\widehat{D})$, $\delta_2 = \uparrow \overline{\mathrm{F}}^1_\infty(\widehat{D})$, $\delta_3 = \uparrow \overline{\mathrm{F}}^{1,0}_\infty(\widehat{D})$. The last indicator is an anisotropic variant, $(m_x, m_y) = (1, 0)$, of the second, recognizing that systematic errors fluctuations are more likely orthogonal to the MBES swath direction (y-axis being first made aligned with this direction). Table 1 shows that their bias

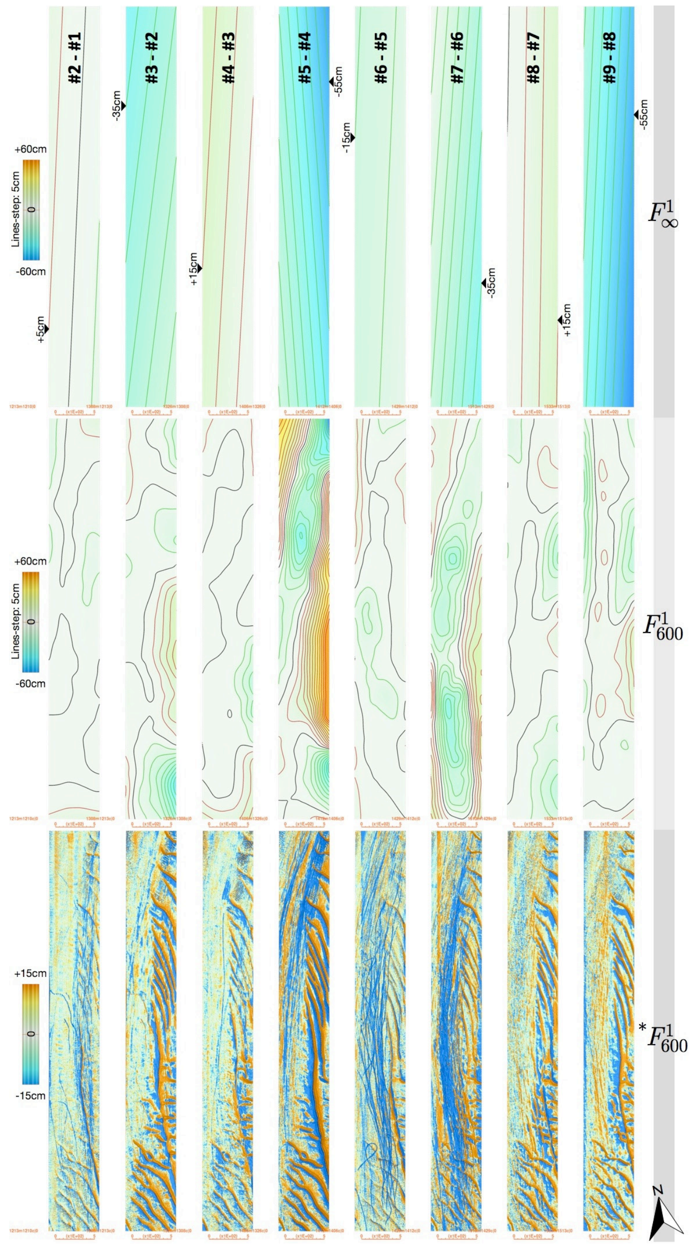

Figure 5. Robust decomposition of the eight time intervals of the sequence HBMC into three perturbation components: global, semi-global, and local.

estimations are almost equivalent. The blue curve (Fig. 4) is obtained after removal of the biases δ_3. However, it is just expressing a short-term regularization effect. Accordingly, it may still embed long-term accumulation of remaining offsets.

IV. CONCLUSION AND PERSPECTIVES

The main issue while addressing volumetric monitoring is to deal with MBES systematic errors. While operating through first-order differential DTMs, theses bias indicators allow getting a first clue about the systematic errors still embedded in the bathymetric repeat measurements. However, to perform a reliable volumetric monitoring over the whole sequence, these indicators still have to take part in an incoming *global* harmonization approach while also involving higher time order differences.

TABLE I. BIAS ESTIMATIONS

	#2 - #1	*#3 - #2*	*#4 - #3*	*#5 - #4*	*#6 - #5*	*#7 - #6*	*#8 - #7*	*#9 - #8*
δ_1 (m)	0.055	-0.053	0.147	0.004	-0.077	-0.060	0.246	-0.284
δ_2 (m)	0.044	-0.090	0.146	-0.017	-0.082	-0.077	0.241	-0.286
δ_3 (m)	0.049	-0.080	0.146	-0.032	-0.077	-0.078	0.235	-0.290

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