Title: Towards the automation of sand dune detection in the bathymetry.

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ABSTRACT: Underwater sand dunes are complex features of the seafloor. They are the consequences of coupled phenomena: bedload transport, sediment properties, seabed morphology and hydrodynamics. The advances in the echo sounder (MultiBeam EchoSounder) and positioning (GPS) technologies of the past two decades revealed how diverse these structures are in terms of shape, spatial organization, dimensions, sedimentary properties, locations, etc. In order to cope with the large volume of bathymetric data available, the development of new tools allowing to quantitatively describe their morphology and dynamics seems necessary. The automation of the process will mainly enable to objectively characterize the sand dunes and banks. With this goal of dune characterization, the first step consists in detecting the dunes in the bathymetry. As a preliminary approach, we propose a detection technique inspired from geomorphometry.

1. INTRODUCTION

Underwater dunes and banks have been discovered on continental shelves as well as in rivers all around the world. They have the particularity of being dynamic features capable of distorting or migrating.

These dunes have become an actively researched subject for several reasons. First, their dynamic nature makes them worth of attention especially when it comes to human activities at sea. For instance, they constitute a risk to navigation safety; can cause damage to offshore structures (pipelines, communication cables, wind farms, etc.). In addition, it is the source of environmental concerns (aggregate extraction, biodiversity or coastal protection).

Dunes are the visible part of a complex system linking seabed morphology to sediment dynamics and hydrodynamics. Two main complementary research axes exist on dunes. The first focuses on the understanding and modelling of these not well-understood physical mechanisms(Németh et al., 2002; Besio et al., 2004). The other axis aims at describing qualitatively and quantitatively the underwater dunes and banks. From these studies, few dune classifications have emerged as well as methods providing descriptive parameters (wavelength, height or length) on dune fields (Lisimenka, 2013; Dorst, 2004).

In this context, the purpose of our work is to design an automatic algorithm to delineate dunes in the bathymetry. Parameters could, then, be derived from the extracted dunes to analyze their morphology and dynamics. The algorithm should make as few assumptions as possible and take into account the dune specificities.

In this paper, a new method, inspired from geomorphometry, is presented. The preliminary results are encouraging, even though, the current algorithm is, yet, too heuristical.

2. DATA

To realize this study, data are key point. Indeed, when comes the validation phase, the used datasets should be representative of diversity of dunes shape and dynamics. Such data were made available to us by SHOM (the French Hydrographic office) and the FPS Economy (Belgium Economy ministry) continental shelf service. Although both offices collect data on dunes, they have clearly distinctive objectives. In this regard, they are complementary.

The aim of the Belgian is to monitor the impact of aggregate extraction on the sediment stocks. Consequently, a limited number of areas have been surveyed regularly (few times per year) and for about fifteen years. These data are shallow water (few tens of meters deep). Added to the use of cutting-edge acquisition equipment, the collected data are ideal to study the dune dynamics. However, the complex spatial organization of dunes makes their extraction very challenging. In fact, dunes are often on banks and depict rhythmic or fingerprint-like patterns. Furthermore, megaripples can superimpose on top of the dunes.

The French available datasets were acquired on the continental shelf off the coast of Brittany, France.
Lines were run across the continental shelf during campaigns spaced by at least one year. Different vessels and equipment were used for these campaigns. Ultimately, the aim is to survey the entire continental shelf. The French data can sparsely contain dunes. Furthermore, the dunes are very likely to be partially described as survey lines are not overlapping. The depth ranges from a couple of meters to about two hundred meters deep. Thus, the data accuracy is not consistent through the entire dataset.
Yet, the covered area being very wide, very miscellaneous dunes were discovered. The most interesting regions were fully surveyed but only a couple of times. Hence, these data are very useful to understand how diverse dunes can be.

For both databases, acquisition equipment was changed from one survey to another having an impact of the data quality. This must be considered as it necessarily influences the quality of the dune extraction and, consequently, the descriptive parameters estimation.

3. GEOMORPHOMETRY

Techniques have been designed to semi-automatically or even automatically characterize dune morphology. Generally, they rely on the fact that dunes are quasi periodic structures.
They either adjust a model with a periodic component to the bathymetry or frequently analyze the bathymetry with 2D Fourier Transform or Wavelet Transform. From these analyses, parameters (e.g. dune height or wavelength) can reliably be teased out.
We made the choice to design a method inspired from geomorphometry in order to avoid making assumptions such as the dune periodicity. Indeed, are sometimes isolated or having very unique shapes (e.g. barchan dunes) and our algorithm should be able to identify dunes indifferently.
Geomorphometry has been used to delineate landforms of the landscape. It is based on the estimation of attributes quantitatively describing the land surface. In our case, these attributes are derived from the depth. Classically used attributes are the slope, the aspect, and the curvatures.

The methods exploiting these attributes to detect land elements can be divided in several categories:

(1) Object-based algorithms
(2) Algorithms based on disparity lines
(3) Drainage basin –based algorithms
(4) Region growing algorithms

Such methods have been developed to detect features such as mountains, drumlins, volcanoes(Graff, 1992; Grosse et al., 2012; d'Oleire-Oltmanns et al., 2013). Most of the time, they use a DTM (Digital Terrain Model) as representation of the land surface.
The first category demands to identify a list of attributes that are homogeneous within each structure to be extracted. It does not seem suited to our case as no attribute is homogeneous on an entire dune.

The algorithms based on disparity lines have the opposite approach to the feature detection. In fact, it focuses on the identification of the feature boundaries. Boundaries are seen as loci of disparity.
For strongly asymmetric dunes, the foot of the Stoss side tends to be smooth. Hence, the transition continuity between the seafloor and the dune is continuous. This type of algorithms is suited to the extraction of features whose presence briskly modifies the land surface. The algorithm capacity to detect disparity lines also depends on the data resolution/ level of smoothness.

For dune detection, the drainage divides obtaining from a third category algorithm potential includes

the dune crests. Nevertheless, the algorithm results highly depend on the noise/smoothness of the input DTM. The risk is the under or over segmentation of the land surface. In the first case, dune crests could be omitted and, in the second, a selection among the drainage divides would need to be made. Furthermore, drainage divides would have to be merged to form the dune crests. Then, the transition from a crest to a dune is not trivial. All this demands to tune numerous parameters in order to avoid the under or over segmentation and construct crests.
Considering the disparities in the quality and resolution of the available data and the diversity of dune shape, such an approach appeared inappropriate to our objectives.

A region growing technique is composed of two steps. First, one searches for notable loci in the data. They are called the seed regions. Then, the seed regions are extended to the connected cells in accordance with a chosen criterion. This is the type of approaches we chose to develop.

4. THE ALGORITHM

The choice of a region growing was made since, intuitively, the crests are remarkable structural lines of the seafloor. They are lines characterized by the high sharpness of the seafloor. In addition, they can be differentiated from the other sharp structures of the seafloor such as rock heads by their length. Henceforth, crests are used as seed regions.

Among the available geomorphometric attributes, curvature is the one capable of highlighting the sharpness of the surface at dune crests.
At each point of a surface, there is infinity of curvatures. The intersection of the surface with a plane defines a curve. The curvature enables to quantify the speed of change of the curve direction.
For an analytical surface, the curvatures can be calculated from the first and second derivatives.
Consequently, at each cell of the input DTM, a bivariate quadratic function was fitted in the least squares sense over a N x N centered neighborhood (N being an arbitrary selected odd number).

The curvatures calculated in a plane containing the normal to the surface are named normal curvatures. Two of them are called the principal curvatures and correspond to the minimum and maximum of the normal curvatures at the calculation point. Their main advantage is that their calculation is independent from the first degree coefficients of the quadratic function. Hence, the curvatures allow making the distinction between being flat and having a zero slope. Crest lines correspond to high maximum curvature values, though the slope, there, is commonly close to zero.

The seed regions are created by gathering connected DTM cells where the maximum curvature is higher than a user-defined threshold in regions. More than crest lines, the seed regions are more influence regions of the true crests.
The regions that are too small to be dune crests are deleted.
Then, the seed regions are iteratively extended to connected cells where the slope is higher than a chosen threshold. The idea is that the Lee and Stoss sides of a dune are relatively steep regions near a crest.

5. RESULTS AND PERSPECTIVES

The algorithm was tested on dune fields in order to analyze in which conditions it succeeds or fails to extract dunes and why. It was able to extract correctly most of the dunes. Dunes were detected either the French or Belgian data, though that have different characteristics. The higher the dune is and the sharper the crest is, the more satisfactorily the dune is extracted.
In addition, isolated dunes are simpler to detect splitting and merging dunes belonging to dense dune fields or banks. The results show that a region growing algorithm has the potential to tackle the dune extraction problem. Furthermore, it enables understanding where the difficulties in the dune extraction can raise from.

For correct results to be obtained, it demands to adjust by a trial-error process the curvature and slope thresholds as well as the neighborhood size. In fact, they are not intuitive heuristics. The curvature threshold has a large impact on the detected crest regions. There is no optimal value since an increase of its value can prevent the detection of features not sharp enough for being crests but, also, can cause the split of crests in few crest regions. On the contrary, close dune crests are merged in one seed region when the threshold is too low. In the same manner, the slope threshold influences the under or over growth of the crest regions leading to abnormally large or small dunes. Dunes are so different that the use of common threshold values to all of them is not realistic. For instance, the slope threshold cannot be the same on the Lee and Stoss sides of an asymmetric dune. By consequent, the detection of the crest lines and the growth step need to be thought differently.

The neighborhood size impacts the smoothness of the estimated curvature and slope maps. If too large, the attributes map ranges tend to decrease and the detection gets more difficult. And, if too small, the input data noise can induce false detection. This leads to another issue: the data uncertainty. Ultimately, it would be interesting to be able to quantify the uncertainty on the detection dune and to compare it with the dunes dimensions.

To conclude, the algorithm parameters (e.g. thresholds) definition must be more data-driven and less user-defined and their number should be kept low. The user-defined thresholds have to be intuitive (nothing like a curvature threshold). The problem of automatic dune extraction is very challenging as each dune/dunefield is unique and lay in a different environment (seafloor, rocks, wrecks, etc.). In addition, these structures are represented by noisy measurements.
The ongoing work aims at studying deeper data-driven algorithms for crest detection. A promising approach based on these mathematically well-defined algorithms is currently under development.

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