DETECTION AND DESCRIPTION OF SAND DUNES USING A GEOMORPHOMETRIC APPROACH

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1 INTRODUCTION

As mankind seeks to explore the oceans, our understanding of the marine environment and its mechanisms keeps enhancing. Along the way, remarkable seabed features such as marine sand dunes and banks were discovered on continental shelves all over the world[1–5].

These marine sand dunes and banks have started arousing interest for multiple reasons. Sometimes located in shallow waters, these giant mobile features constitute a danger for human activities at sea. Dunes crossing shipping routes or navigational channels pose a risk for navigational safety. It is to bear in mind dunes can be over 10 m high, few km long and move by several tens of meters a year. In addition, these dunes can damage communication cables and pipelines laid on the seafloor with problems of free spanning. Furthermore, marine renewable energies are an emerging field that could prove crucial in the next decades. Yet, it demands the setting up of marine current turbines or windfarms that could turn out to be in dunes way. In many countries, they represent a readily accessible source of aggregate. Besides, they also play a key role in terms of coastal protection or biodiversity.

These dunes and banks exhibit diverse shapes, granulometry, dimensions, spatial organizations or migratory behaviors[1,3,4,6–8]. All these aspects made these special features worth being considered. All this diversity comes from the tight balance between the hydrodynamics, the sedimentary dynamics and the dune dynamics. Indeed, they all have an impact on one another. Scientists have decided to look closely at these particular seabed structures with different approaches.

Some authors try to model these interactions and to understand the processes controlling this whole complex system. This modelisation requires various data types or information such as currents, granulometry or bathymetric data[9–11]. The recent advances in echosounding technologies, especially with the new MultiBeam EchoSounder (MBES) systems, permit collecting soundings in increased amounts and precision. Henceforth, studies focusing on the detailed description of dunes[1,3,4,6] and the estimation of their morphological[12–17] and dynamical[18,19] characteristics flourish.

From our point of view, dunes must be seen as bedforms belonging to a larger ensemble, the dune field. This vision suggests being able to identify these specific bedforms, in other words, one must distinguish the dunes from their surroundings. The only known way for detecting dunes in the bathymetry is to manually digitize them. Yet, like for other bed/landforms, a human operator can encounter difficulties when trying to draw dune boundaries. That is why the only dune part that is generally digitized with relative confidence is the crest line. Besides, the manually-extracted morphologic characteristics are too simple (width, height) and imprecise. So, this technique is not satisfactory because it is a tedious, subjective and not repeatable chore.

Here, our purpose is to present a procedure capable of detecting these particular seabed features as an alternative to the manual detection. This assumes the new technique to be semi-automated or even fully-automated. In the first section of this paper, one will review algorithms of two types: The first gathers algorithms designed for analyzing sand dunes from morphological and dynamical points of view. The others are techniques developed for extracting specific features of the seabed/land surface. The second section will be devoted to the introduction of our algorithm and its principles as well as the presentation of first results. The final section will bring conclusions about the algorithm and its potential limitations.

2 STATE OF THE ART

2.1 Dune Characterization Methods

For all the previously-mentioned reasons, the marine sand dunes and banks have become a major concern. Most of the time, visual and manual processes are applied to quantify their morphology and dynamics. This raises the issue of how it could be done more efficiently, especially when the amount of discovered dunes never stops growing. In order to keep the pace, methods were designed to automatically analyse dune fields and determine their principal properties. These methods can be divided into two distinct categories: (1) techniques based on a frequency analysis of the seabed; (2) techniques based on the fitting of a model to the bathymetry.

The first category methods begin with the division of the Digital Elevation Model (DEM) into rectangular regions. Next, 2D Fast Fourier[12,14] or Wavelet[10,13] transforms are applied to the sub-regions. The absence/presence of sand dunes in a region with one or more preferential orientations is visible in the diagram of power spectral density. This is reflected in the spectrum by the presence of isolated peaks. Further manipulation (such as a power law fitting[12]) are sometimes made in order to better identify these peaks. Besides, these peaks are valuable source of information since they enable evaluating parameters such as the dune orientation, their height, the wavelength or the orientation uncertainty. Wavelet analysis are slightly different as it requires choosing a function (filter) family[10]. These functions derive from a mother function that was dilated, translated and rotated. Such techniques are capable of saying whether or not a bedform is complex, multi-scaled. Where the seabed results of the superimposition of signals with diverse sizes, it can be detected by the method and the orientation of these patterns can even be obtained.

To simplify things, the second category algorithms aim at locally fitting a mathematical model to the bathymetry. The interpretation of its coefficients in terms of dune parameters is straightforward. The fitted model is basically a sinusoidal wave with variants (e.g. sinusoidal wave + planar slope[15], plane progressive wave[16], Gabor filter[17]). In the end, the main dune parameters (dune height, wavelength, orientation) can be extracted from the model.

Both categories perfectly achieve the tasks they were meant to. Yet, some of the implicitly made assumptions are not satisfactory. With these approaches, dunes appear like evenly-spaced bedforms with constant height and orientation at a sub-region scale. Unfortunately, these hypotheses are not systematically true. Moreover, the seabed often contains other specific features (e.g. rocks, wrecks, steep slopes, etc.). These features necessarily bias the dune analysis regardless of the chosen techniques. Furthermore, the described algorithms only provide a general picture of how the seabed locally looks. Actually, the calculated parameters are values averaged over a certain region. This means one has no information about morphological particularities down to the dune scale, the number of dunes, their relative positions or if a dune overlaps few regions. The only way we could think of allowing to get to such a detailed level was to isolate dunes from the rest of the seabed. Though no algorithm able to perform this work was to be found in the literature, morphometry-oriented methods already exist to identify specific landforms or objects in a terrain.

2.2 Specific Landform Extraction Methods

To delineate specific features of the terrain is not an easy task and the advances in computer technology made the development of automated faster segmentation techniques feasible. The proposed techniques can be divided into three main approaches to our problem. The first approach corresponds to the said “graph-based” methods aspiring to detect the feature boundaries. Basically, the concept is to identify the morphological discontinuities and singularities (e.g. peaks, ridges, slope breaks, inflection points or lines, etc.) by analyzing the values of altitude and its derived attributes (slope, aspect, curvatures, etc.). For instance, algorithms for the extraction of drainage networks and the associated catchment areas are typical of this method type. Such algorithms have already been designed to detect specific landform other than dunes and this is the case for volcanoes[20]. Their delineation relies on the fact the edifice base almost systematically coincide with areas of gently slope and maximum of concavity.

The second type of techniques is composed of “clustering” algorithms and especially of the so called “OBIA” (Object-Based Image Analysis) algorithms. These techniques gave promising results and differ from the usual clustering methods. Actually, they take into account the closeness of pixels in both the attribute and geographical spaces. The core concept is to merge neighboring pixels or objects iteratively so that the newly-formed objects comply with internal homogeneity and shape criteria. The aim is to maximize the intra-object homogeneity and the inter-object heterogeneity. The homogeneity enables measuring how alike objects in terms of morphometric parameter values. Drumlins are interesting glacial landforms often clustered that has been widely-studied. An OBIA-based approach to detect a drumlin field has been described in the literature[21]. The drumlins are convex structures exhibiting an elliptic and elongated shape. These drumlins morphological characteristics were translated into attribute homogeneity and shape criteria.

The last imagined way for identifying specific features at the Earth’s surface inspires from region growing techniques. The starting point is to locate the “seed” points. In the domain of geomorphometry, seed points are particular, singular points or lines (e.g. ridge and valley lines, peaks, pits, and altitude and its derived fields discontinuities). Regions are initialized from these singular structures. Then, the regions are iteratively grown by assimilating the connected cells meeting a morphometric parameters-related criterion. Graff[22] describes such a technique to delimit the extent of mountains. First, one looks for ridge points and, then, grows the regions to their limits. Prior to the growing step, the mount boundaries were defined by displaying the slope attribute and determining the slope value matching the best the natural mount limits.

Though they show intrinsic differences in their vision of the problem, these major categories have each proven to be successful and so worth of interest in our attempt for identifying dunes. Despite the fact dunes differs from the above-mentioned features in many regards, all these techniques present flaws and advantages that could be combined to end up with a dunefield adapted algorithm.

3 PROPOSED ALGORITHM

3.1 Applicability of the above-mentioned techniques to the dunefield case

As it has been shown, there is not a unique way for extracting seafloor features. But, these techniques offer miscellaneous possibilities and were developed to answer a common expectation in different environments. This part is devoted to understanding to what extent they can be suitable for our study case: dunes.

Despite their impressive dimensions, marine sand dunes do not constitute brutal and pronounced discontinuities in the bathymetry. In fact, their vertical extent is much smaller than the horizontal making the depth variations look gentle from crest to toe. At the dune scale, the dune toes seem to be concave parts of the seafloor. However, when trying to precisely locate them, the seafloor appears to be an almost horizontal planar slope. All of it makes risky the definitions of dune boundaries and, consequently, the application of graph-oriented techniques.

In order to use an OBIA-inspired method, one should be able to identify a set of geomorphometric parameters that are constant over an entire dune. Unfortunately, no parameters comply with the homogeneity criterion. Unlike the drumlins, dunes are neither totally convex nor concave or even flat. The slope is nearly zero at the crest and toes and varies in between according to the dune type. In other words, an OBIA-oriented approach is not adequate in the context of the present paper.

A dune can always be decomposed into a crest and two sides. The crest is an area of locally extreme convexity. This is typically the sort of surface irregularities studied in geomorphometry. They constitute potential seed areas to initiate a region growing process. Despite the considerable diversity in the dune shape, their sides are always sloping. Henceforth, the slope parameter is likely to be suitable for the growing step. In a first approach, the choice of a region growing algorithm is deemed more judicious. Now, how this can be transposed to dunes is to examine.

3.2 The Basic Principles

In order to tackle the initial problem of dune identification, a geomorphometry-oriented viewpoint has been adopted. Before going into technical considerations, the principal steps of the algorithm are presented on Figure 1.A.

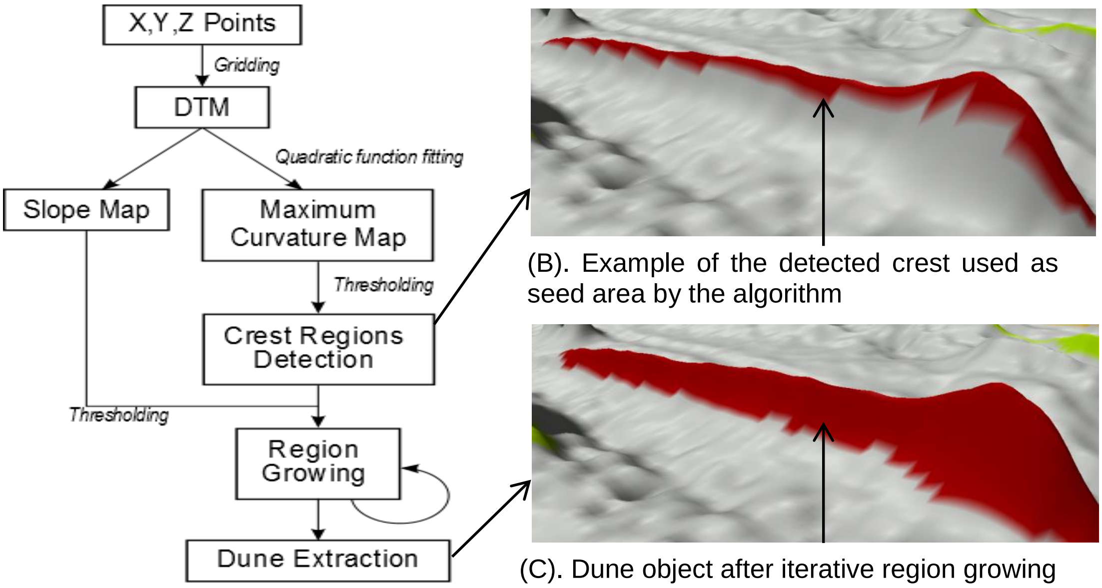

Figure 1: Principal steps of the algorithm (A) and application to a dune: (B) detected crest; (C) Dune after the region growing step.

Firstly, bathymetric data was collected on the area of interest. This data, starting point of our work, can be available in two main structures: (1) a DTM; (2) a set of (x,y,z) points called "soundings". In the second case, the soundings are gridded before the algorithm is allowed moving on to the next step. Then, a number of depth-derived morphometric parameters are estimated. It is done by determining the best bathymetry-fitting least-squares quadratic function[23] (Eq. 1) over a moving window with a user-defined size. The obtained slope and maximum curvature maps are retained as they prove useful in the following. These two parameters are calculated from the quadratic polynomial coefficients (Eq .2 and 3).

$$Z=ax^2+by^2+cxy+dx+ey+f \qquad \text{(Eq. 1)}$$

$$Slope=\sqrt{d^2+e^2} \qquad \text{(Eq. 2)}$$

$$max\_curvature= -a-b+\sqrt{(a-b)^2+c^2} \qquad \text{(Eq. 3)}$$

Curvature measures quantify the local surface shape. The basic curvatures can directly be calculated from the polynomial coefficients and give a measure of concavity/convexity in a predefined direction. These curvatures go by pairs describing the surface concavity in perpendicular directions. More sophisticated curvature measures exist and often derive from the basic ones[24].In the context of the paper, the most highly-remarkable part is the crest that is a convex structure surrounded by sloping sides. This can easily be used as seed areas to initiate the growing process. Besides, the structures we are interested in are imposing in terms of length (at least a few hundred meters) and it makes them hard to confound with other convex features. In crest areas, the d and e coefficients are close to zero making most curvatures be close to zero too. On the contrary, maximum curvature can exclusively be estimated from the second-order coefficients (see Eq. 3). Hence, it was selected to highlight and then extract the crest regions (positive curvature values).

Next, a threshold is manually-adjusted in order to figure out what cells (high positive curvature values) potentially belong to dune crests (Figure 1.B). These 8-connected cells are grouped and labelled to form potential regions of crest. The smallest regions are filtered out being assessed too small to be crests. The following stage is the expansion of the “dune seeds”. It suggests identifying the cells located on dune sides. Dunes exhibit a tremendous variety of shapes and especially of their flanks. Yet, these flanks are invariantly sloping areas, so it means the slope attribute is appropriate to detect them. The detected dune crests are successively expanded to the adjacent cells showing a slope value higher than a chosen threshold. This stage is iterated until the remaining adjacent cells either have too small slope values or belong to other dunes. In the end, one gets a map of individually-delineated dunes (e.g. Figure 1.C) that can lead to a detailed analysis of the dune morphological properties.

3.3 Application

3.3.1 Data

In order to validate the algorithm, bathymetric data was acquired about 150 kilometers off the coast of Brittany, France. The study area extends over a 15 x 6.5 km rectangular zone that was surveyed in mid-October, 2012 by the French vessel, “*Pourquoi Pas?”*. This survey was part of a larger survey devoted to the study of marine sand dune dynamics. The used echosounding system was a hull-mounted Reson Seabat 7111 that is a deep-water multibeam sonar. Besides, differential GPS systems (HDS 800) were used to get positioning data with submeter accuracy. Overall, more than 7,000,000 depth measurements ranging from -150 to -130 m were collected over the area.

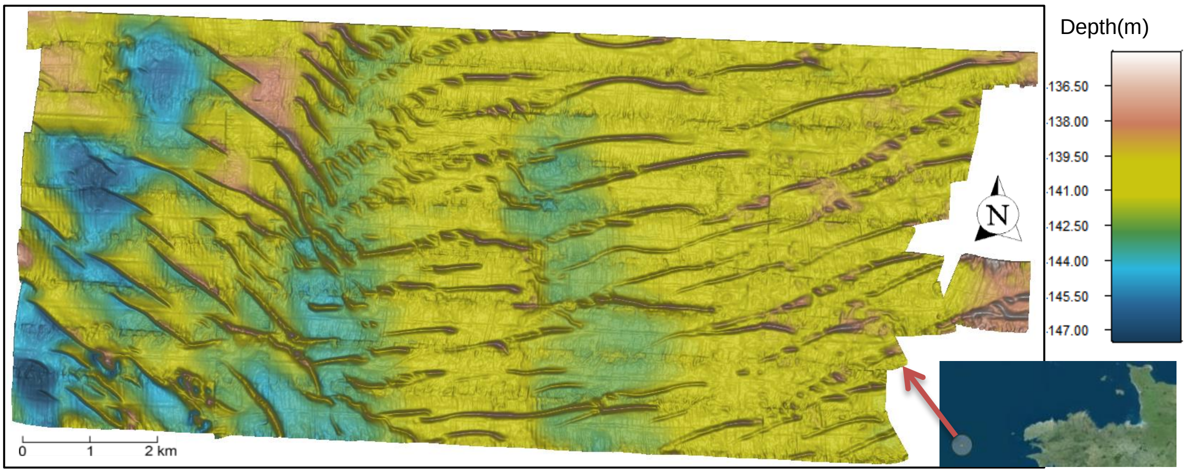

Figure 2: Top view of the shaded bathymetry in the study area

A DEM has been generated from these soundings as shown in Figure 2. The cell size was chosen thinking about limiting the number of holes in the surface as well as curbing the smoothing effect of the gridding step that complicates the feature extraction. For this dataset, the 10m cell size was deemed to be a good tradeoff.

In this zone, a dune field has been discovered. The dune number is estimated at around 250 dunes. This dunefield is singular and this is mainly due to the dune spatial organization. Even though, they are all linear dunes, they show interesting variations in their asymmetry, dimensions and orientations. In the West part of the area, the dunes are strongly asymmetrical, generally 3-5m high (up to 10m) and 500m to over two kilometers long. Their width is very hard to define since the stoss sides are gently sloping. These dunes are southwesterly-oriented. In the eastern part, the dunes are symmetrical, NW-axis oriented and it steadily changes to a N-NW orientation when moving to the

East. There, the dunes can also exceed the 2 km in length. Yet, the highest dunes barely reach 3m in height. The smallest dunes are about 150 m long and 1m high. The width goes from 70 to around 150 meters. It is worth noticing that the small dunes in the eastern side look like remains of bigger dunes that either have splintered into smaller dunes or have lost a piece of themselves in their migration. For all these reasons, this dataset appears to be complex and hence worth of interest.

3.3.2 Results and Discussions

The dataset was processed both manually and via our algorithm. A comparison between the two obtained sets of dunes is presented in Figure 3. Each automatically-extracted dune is allocated a specific ID number and color. Manually, only the crests are extracted and are displayed overlaid on top of the automatic results. Figure 3.H provides on overview of the results in the entire zone and the locations of the interest areas. Figure 3.A-G are 3D zooms on these particular areas.

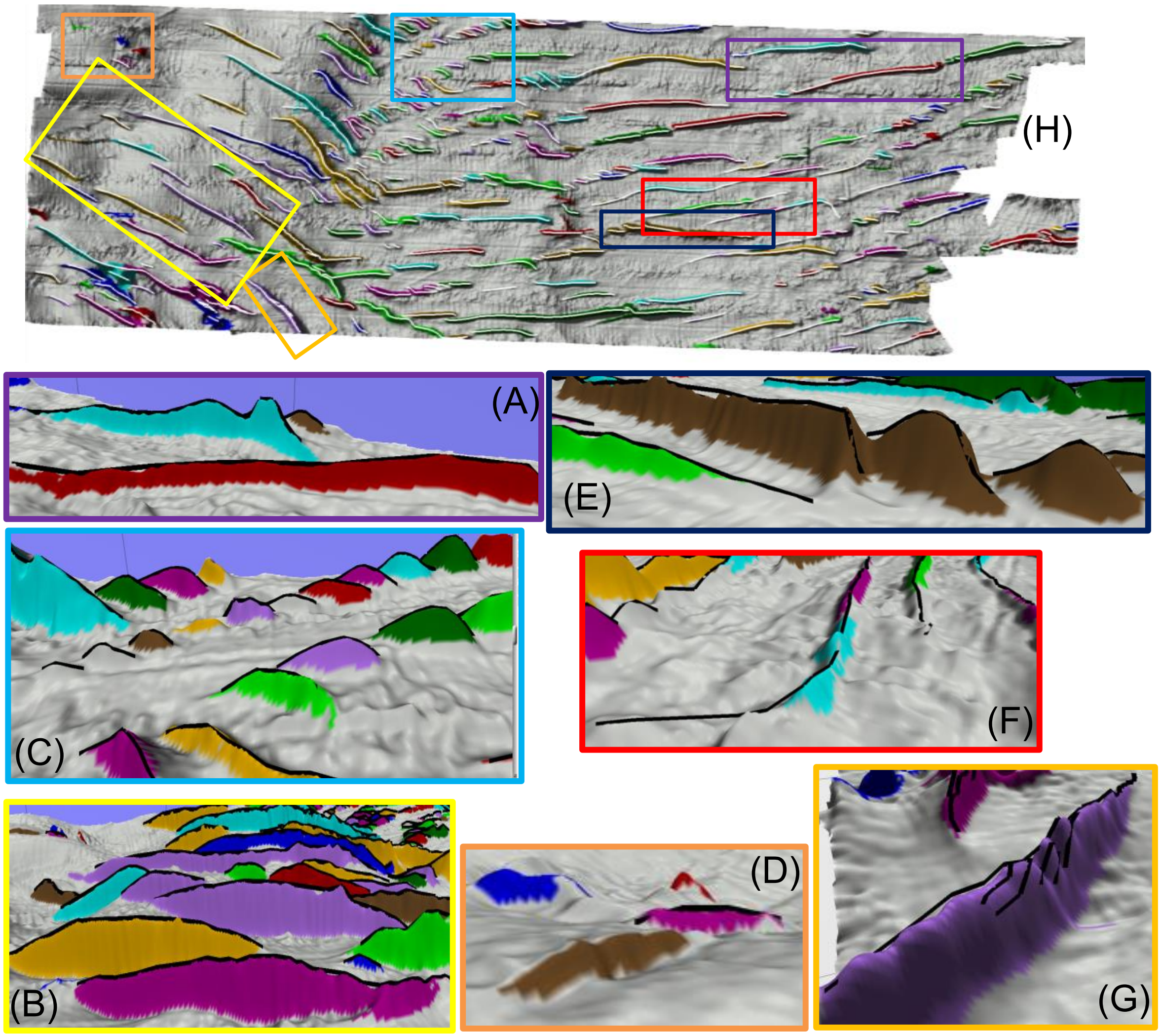

Figure 3: First (coloured areas) results compared to the manually-digitized dune crests (black polylines) in various cases. The rectangle colours in Figure 3.H enable locating the Figure 3.A-G.

The proposed method is able to detect indifferently and successfully the three main dunes types observed in this dataset: the long linear dunes (figure 3.A), the large asymmetric dunes (figure 3.B) and the small fragmented dunes (figure 3.C). Still, differences between the manual and semi-automated extractions remain and their causes need to be understood.

Occasionally, vertical shifts up to 1.5 meters occur between bathymetric swathes. After gridding, the artefacts remain and generate outcrop-like (convex) features taken to be dunes by the algorithm. It illustrated by the brown dune in Figure 3.D. Moreover, the red and blue clusters are rocks or local seabed distortions but they were wrongly-detected by the algorithm. Actually, the algorithm seeks for connected cells where the bathymetry is objectively convex and with a size sufficient to be taken as dune crests. That is why other convex features big enough can lead to misdetections.

The artefact presence prevents us from lowering the slope and curvature. Consequently, the algorithm has some difficulties in recognizing relatively small and fragmented dunes because they are almost flat and their crests are pretty sharp enough. For instance, in figure 3.C, three dunes are missed. Yet, one may notice the human processing is not perfect either as two yellow fragmented dunes were not digitized.

For reasons of local flattening, the crests of several long, rather low dunes are sometimes split into two or three convex areas. Figure 3.F shows a case where the light blue and purple dunes should be a same dune. This is due to the fact parts of the crests are assessed not to objectively be enough convex for belonging to a crest. It can also occur at dune endings as it is the case for the light green dune in figure 3.F. Figure 3.F shows another case where the human results are doubtful with the light blue crest that was extended for no apparent reason.

The opposite situation is when dunes are in straight line but so close that the bathymetry between their endings locally looks like a part of a crest. An example is provided in figure 3.E. This failure is caused by the real steepness of these dunes at their endings and their proximity. This could potentially corrected by taking into account the crest depth ups and downs in addition to the objective convexity criterion.

Although the human work enables to spot out the algorithm mistakes, the manually-digitized dune crests are a subjective reference and not mistake-free. In figure 3.G, the operator saw one main crest and additional 5 ones. Yet, not everyone would interpret this situation accordingly. When a manual approach is questionable, our algorithm provides a repeatable, predictable and objective delineation of the dunes. Furthermore, computer-assisted approach allows significantly speeding up the dune extraction process. In fact, it takes minutes for the algorithm to process the chosen dataset against hours for a human expert.

It is to note that a 3x3 neighborhood was selected to locally calculate the terrain properties. The maximum curvature threshold was set to 0.1 m^{-1} and the growing slope criterion is set to 0.2. These values were established through a trial and error process and found to be a good tradeoff between true dune omissions and the detection of artefact-caused dunes. The manual digitization has yielded to the discovery of 252 dunes against 248 with the semi-automated method (<2% error).

4 CONCLUSIONS

The semi-automated method described in this paper meets the initial expectations in terms of time saving, repeatability, and objectivity enhancement. It proves equivalent to the manual detection for this dataset as there is less than 2% error. It is to remark our algorithm extract dunes as surfaces and not polylines as done manually.

Though neither the shape diversity of dunes, nor the data artefacts constitute unsurmountable obstacles to the algorithm well-functioning, it has to be tested on other datasets. Once it would have been confronted to new scenarios (e.g. wrecks, rocky areas, dunes on banks, entangled dunes, etc.), we would start focusing on estimation of descriptive characteristics for each dune. These characteristics as well as the crest lines or boundaries can directly be derived from the detected areas and be visualized and edited if needed with any GIS software.

Furthermore, our method would surely benefit from accounting for measurement uncertainties and estimating their influence on the dune extraction and calculations of the dune morphological properties. In addition, the automation of the thresholds adjustment must be dug into. A solution could be to fix the threshold values from the maximum curvature and slope histograms.

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