

Automated Dune Crestline Detection

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Abstract

TODO

1 Introduction

TODO

2 Previous Work

2.1 Dune Pattern Studies

In [6], an explanation of how dune-field patterns emerge and addresses the degree of complexity from the standpoint of self-organizing system. Dune patterns are classified into two basic categories: simple or complex. According to this paper, a simple pattern is defined as having a single pattern type. Complex patterns are said to potentially have multiple spatially superimposed pattern types. Simple patterns trend towards a better ordering, so long as the wind regime remains constant. Changes in the trend of wind pattern will cause reorientation. Complex patterns can then be interpreted as the superposition of many generations of wind regimes.

Complexity can be measured using pattern analysis, measuring parameters such as the crest length, orientation, spacing, defect density, and other properties. These properties would be very useful information to extract for the dune detection. Finding crest-lines can help us identify the patterns, extracting meaningful data such as junctions, terminations, mergers, linking, and other interesting processes explained in [6].

In later work, [21] studied the dune field pattern formations on the north polar region of Mars. These dunes are thought to be mostly inactive, with relative no movement over a period of 4 to 15 martian years. The reason this region is interesting is because there are two nearly orthogonal crestline orientations present in the region. This complex system of superposition of multiple patterns in this example showcase a set of *primary* and *secondary* crestlines which would be valuable data to automatically segment. The *primary* dunes are the largest-scale dunes, extend over the entire length of the image set, and contain many *Y* junctions, an indication of well-organized linear dunes. In contrast, *sec-*

ondary dunes are rounded, have least defined features, and are perpendicular to the main primary crestlines.

Other interesting features are the so-called *Slipfaces*. These typically appear along the *primary* crestlines, in areas of intersection with the *primary* and *secondary* crestlines. Another feature are the *Wind Ripples*. The ripples are present on the surface of most dunes with the exception of *slipfaces*. To detect these types of features, a higher resolution image is required, as those types of features are very small compared to the scale of the *primary* and *secondary* dunes. *Interdune Areas* are features specific to the area studied in [21], have a polygonal shape, and are indicative of ice.

The rest of the paper describes an in depth statistical analysis of the features to compute the flow fields and understand the geomorphic relationships which are present in the area¹.

In the most recent work, [20] study the aeolian dune-fields at different scales. Scale is an important factor to consider because aeolian dune-fields patterns can vary over a wide range of scales, both spatially and temporally. Being able to measure the change of scale over time is important in order to investigate the environmental conditions of the studied region. Aeolian dunes are developed typically in transitions from sand patches, to proto-dunes, to dunes, to dune-field patterns. Complex dune patterns are usually a juxtaposition of simple dune patterns at multiple scales. To summarize, being able to detect the crestlines and other types of features at multiple scales is invaluable.

In other related work, [5] studied the migration of submarine sand dunes. The dataset used in this paper includes digital terrain models (DTMs) retrieved from high-density multibeam echosounders (MBES) taken of submarine sand dunes along the coast of New Brunswick. In order to measure the migration of these types of dunes, the motion was measured by simply subtracting the DTMs from sequences over time. The implementation uses a simple cross-correlation to find similarities from one set to the next. From the cor-

¹The paper [21] provides a lot of interesting and valuable information which can be used to understand the application of automatic dune detection. If these features can be extracted, it would be interesting to see if we can do a similar statistical analysis based on the results presented. The next step would be to retrieve the HiRISE dataset and their data or ground truth to compare.

relation matches found, the migration vector can be computed. The migration data processing can extract the flow fields of the dunes.

2.2 Image Processing

2.2.1 Filtering

There are many common filtering approaches used in image processing and computer vision applications. In this application, satellite images of sand dunes may include various amounts of noise. In order to improve the dune detection algorithms, the goal of filtering is to filter out the noise while preserving or enhancing the necessary features such as the crest-line edges.

In [2], the bilateral filter is proposed, which allows flat noisy regions to be filtered while preserving strong edges. Bilateral filtering is a simple non-iterative algorithm for filtering out noise.

2.2.2 Illumination Normalization

Illumination normalization is a process in which the image illumination is made to be more evenly distributed across the image, to make the illumination invariant in conditions of varying lighting. This processing is most commonly used in face detection or recognition applications. In [30], a Gaussian illumination model is used to stretch the contrasts of darker areas. The process involves using a Quadtree method to divide the image into sub regions to find dark areas. The areas that meet these requirements are processed with the Gaussian illumination model to brighten them up, which evens out the illumination. Applying this normalization significantly improves performance of face recognition.

In a similar approach [8], the authors use a modified retinex algorithm to restore poorly illuminated areas of an image. According to Lambertian reflectance theory, images consist of two components, reflectance and illumination. If an image contains a set of small scale features, and large scale features, and illumination is only applied to the large-scale set, then the small scale features can be preserved. In this approach, the normalization is applied to small-scale and large-scale features independently. The Single Scale Retinex process is applied to the image to separate the reflectance (small scale) and illumination (large scale). After, images are thresholded and histogram equalization is applied, which spreads out intensity values of darker areas of the image.

In a remote sensing application, [10], illumination normalization in the gradient domain and using singular value equalization. According to the authors, the gradient domain image enhancement process can compress the dynamic range of images, increase contrast, and enhance fine details in darker regions. The goal of

singular value equalization is to make all images in a specific set to have similar mean intensity value. Some images may have a lower or higher mean intensity. By using SVE, the pixels can be processed to achieve a mean closer to the target intensity, therefore normalizing illumination across a set of images. The drawback of this method is that multiple images of the same or similar scenes are required.

2.2.3 Edge and Line Detection

The Canny edge detector is a well known and used method to retrieve important edge features from an image. In [17], enhancement to the method is proposed by analysing the responses of detection at two scales. The benefits of this technique are better localization in images with larger amounts of noise, at the cost of a slightly lower detection rate. Overall the performance of the Canny operator is improved by using multiple scales.

The Canny detector is further improved in [28] for a runway detection application for unmanned aerial vehicles. The main contribution of this paper is the use the Canny operator combined with a mean filter, and using the Hough Transform to track runways. The advantages of the mean filtering is that it filters out noise, preserves edges (better than a traditional Gaussian filter), and makes the image less fuzzy. To solve the problem of the dual threshold of the Canny operator, the proposed method is to compute the thresholds dynamically based on averages.

In [27], an improved implementation of the popular Canny edge detector is proposed. According to the authors, the traditional Canny algorithm suffers from two main problems: the gradient calculation is sensitive to noise and the use of the fixed double threshold may not be suitable for images with high gradient variability. The main flaw in the gradient calculation has to do with the inequality of the edge detection in darker versus brighter regions. For the parameter selection of the double threshold, the paper propose choosing the high and low thresholds from the computed mean and standard deviation of the gradient magnitudes.

A line detection and image enhancement has been proposed in [7], for a digital image restoration of heritage art application. The images worked with have been deteriorated over time, and contain many cracks, faint lines, and broken stroke. The goal of this is to remove unwanted edges, and enhance the desired edges. The approach is implemented in three basic steps: Initial line detection with non-maxima suppression, true line detection using anisotropic refinement, and noise reduction.

The initial step is to perform correlation convolving the image with some sort of edge detecting mask, rotated at different orientations, and retrieving the maximum response for the orientation for each pixel. The

paper claims this produces a sharper and more reliable edge map, which is then filtered using non-maxima suppression. This process preserves strong lines while removing texture lines. The image is the binarized to remove all remaining weak edges, and only allowing strong edges to remain. The smoothing is applied to the original based on the processing done, smoothing out weak edges, while not smoothing strong true edges.

In a similar approach, [23] use rotating edge detection kernels and fuse the responses from the operations. What determines what an edge is a location and a direction, as a non-edge point such as a flat area or noise, which has no specific direction. Following this principle, the response in one direction should be higher than in the other directions. For a non-edge, the responses in each of the directions are similar. Therefore computing the mean and standard deviation of each of the kernel responses can help resolve edge versus non edge pixels. The results obtained from this process shows promising results when applied to noisy images².

An interesting alternative to the classical Hough transform is presented in [11] in an application inspection or maintenance of underwater cable components. The paper discusses image processing techniques to extract linear features in cluttered and noisy images. After applying some anisotropic filtering to remote high frequency noise, edges and lines are detected on the sonar based images. To detect potential linear features, they use a Phase Congruency detector³. The Hough transform is then used to find linear features, and some criterias are determined to reject false positives and preserve true positives.

2.2.4 Edge Linking

In [31], an edge linking approach is proposed which uses local neighborhood, using geodesic distance (as opposed to the common Euclidean distance measure) between edge candidates. When calculating the direction of edge end points, typically eight directions are used, which introduces error. To address this [31] define a window size based on the maximum allowable edge gap, and fit a line to the edges, which allows a full range of directions to be accounted for. The geodesic distance measurement is not only based on Euclidean distance but also on intensity values of the image, which reportedly gives better results.

²The approach proposed in [23] has definite potential for improved edge detection applied to dune crestline detection. It also has potential for improvement of the method itself

³The Phase Congruency detector requires more research to determine what type of features can be extracted from it.

2.3 Pattern Recognition

2.3.1 Perceptual Grouping

The concept of tensor voting introduced in (REFERENCE NEEDED!!!).

In [9], a tensor voting approach is used to perform perceptual grouping on noisy data. The approach extends the standard tensor voting using Bayesian probabilities. The Bayesian framework has added benefits of reducing the learning variance of the perceptual grouping task. Another contribution of this paper is the use of a 2nd order tensor and two types of polarity vectors to handle both outlier and inlier noise. The approach also is able to process all types of geometric structures. For probabilistic tensor voting, the voting procedure uses random vector with a given standard deviation. It uses three layers of voting: sparse ball vote, sparse stick vote, and revised stick vote, where the goal is to change the positions of each token based on a random vector.

2.3.2 Watershed Segmentation

The Watershed Transform is a well known algorithm for segmenting meaningful regions from an image. The main benefit of the watershed technique as opposed to methods, such as edge-based detection, is that the watershed produces closed boundaries, which allows contours to be detected. An overview of the Watershed algorithm is presented in [19]⁴.

In [18], segmentation is achieved using the watershed transform from texture gradients. The texture gradients are retrieved using various wavelet transforms.

Similarly, in [24], an approach to texture segmentation is proposed. When applied to textures, the watershed algorithm tends to over-segment a texture into small homogeneous sub-texture regions. Therefore, a texture can be determined to be a set of texture segments. The texture sub-regions can be merged using a clustering algorithm. A wavelet transform is used to characterize the irregular shaped segment regions, which are used to cluster similar groups of sub-textures.

Another approach used in the Watershed algorithm is based on markers. The desired regions to segment can be extracted using some known feature which gets marked on the image. In [22], this concept is applied to a fingerprint pore extraction application. Marker based segmentation has been shown to be robust for segmentation problems where the objects are closed contours with boundaries being ridges. In this application, the watershed transform is applied to the gradient image of the fingerprints, and the regional minimas are computed to obtain the markers, then compute the watershed transform based on the markers.

⁴This paper still needs to be read

In [12], the watershed segmentation is applied to a breast tumor detection application.

2.4 Automated Feature Detection

In [25], a semi-automated method for extracting roads from aerial or satellite images is proposed. The purpose of this paper is to localize roads from higher resolution images, using some form of segmentation. The proposed method is semi-automated because a user must provide an initial seed point, onto which a region growing algorithm is applied to extract the road.

A level set method is applied to evolve the boundary of the road region, which can better handle noise and multiple road mergers. The boundary for the desired region is based on a speed function, which is designed based on uniformity, texture, and contrast properties. Once the regions have been extracted, the centerlines of the roads are estimated using a skeletonization procedure, with junction analysis to ensure that intersections are properly handled⁵.

In [3], linear features of internal waves are extracted using a technique called *Multiscale Retinex* (MSR) feature extraction⁶. The oceanic internal waves are typically generated from many sources such as tidal currents, ocean frontal boundaries, and other atmospheric conditions. The MSR is an image processing technique that provides consistency and dynamic range compression across an image with poor contrast. The paper discusses the use both the Wavelet Transform Modulus Maxima (WTMM) and the Canny edge detector, which turned out to have superior performance.

There has been some work done in automated dune detection. In [13], a supervised learning approach is used, training classifiers such as Support Vector Machine and Random Forests to detect dune structures on Mars. The method proposed in this paper is to classify small (40 by 40 pixels) cells in a quantized image grid. In each cell's features are computed based on the image gradients, using both phase and magnitude. In order to classify a cell as either a dune or not a dune, the features of both the cell and the cell's neighboring cells are used. The features extracted are then used to train the machine learning method, which is used to then predict if a cell is a dune.

Although this type of method has typically shown very good results, there are a few drawbacks with using supervised learning approaches. These types of methods usually require a fairly large labelled dataset which may not always be available. Anytime a dataset

⁵The skeletonization procedure used in [25] may be useful for extracting the dune crestlines and junction points from segmented dune regions.

⁶Although the problem set in [3] is different, there appears to be significant overlap and comparison between dune crestline detection and oceanic internal wave detection.

is constructed for this purpose, it is important to provide a large number of examples of different types of dunes, in order to get a robust representation of the problem set. In [13], 230 labelled images were used to train and test the method, and have a decent representation of various dune types. Another drawback of this approach is the use of cells, for which fixed-sized cells may not be scale invariant. Also, quantizing an image into larger cells will affect localization accuracy of the dunes. If the application requires higher localization accuracy, this type of supervised learning approach may not be suitable.

2.5 Automated Dune Detection

In [16], an automated extraction of dune features is proposed. In this approach, the authors claim that the Canny edge detector provided poor results, and the sobel operator generated more consistent results. The gradient magnitude of the Sobel operator is used to threshold out the weaker edges. The use of a histogram to compute the orientations of the gradients was found to have a bimodal distribution, with one of the modes being the dune edges. Dune candidates are determined based on their gradient magnitude which filter out weaker candidates unless they are near strong candidates.

3 Methodology

3.1 Dune Detection

3.1.1 Method #1: Adaptive threshold and contour detection

Adaptive Threshold Image Process: Dune crest images typically have a shaded and a light side. Depending on the conditions and image quality, the actual edge or dune crest line may not be clearly defined. Some image processing typically improves the quality and allow the extraction of the dune crest lines.

Many approaches revolve around edge detection, but because the conditions and image quality can vary, edges may not be accurately extracted. In this approach, we use a thresholding method to extract the light side of a dune. Using a fixed threshold may not be sufficient to extract the dunes since the illumination across an image is usually not uniform. An adaptive threshold can be a useful tool to threshold an image with non-uniform illumination. An example of this type of thresholding is shown in Figure 1.

Dune Crest Line Extraction: Once the image has been preprocessed, the bright regions can be extracted from the resulting binary image. As shown in figure

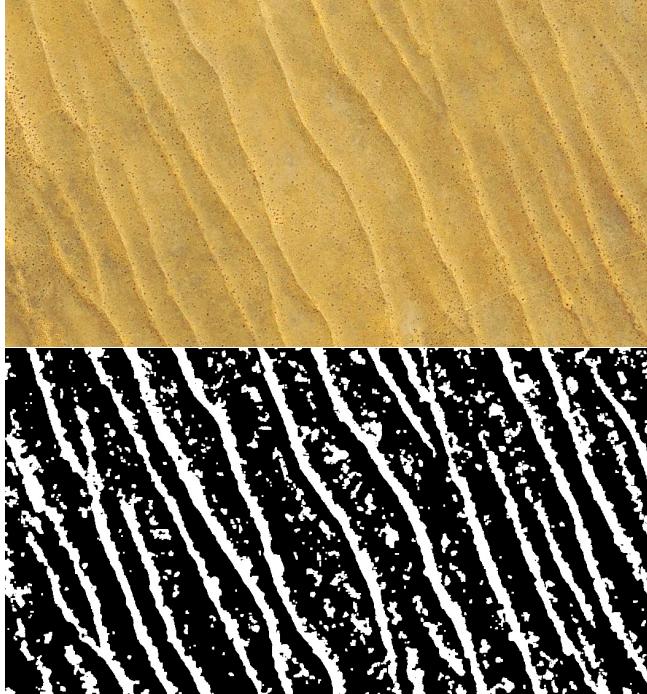


Figure 1: Example of an adaptive thresholding method applied on a dune crest image with poor illumination and contrast.

1, the bright regions shown consist of the sun illuminated side of the dunes and some noise.

From the regions, contours can be extracted, which can be filtered by size of the region. Smaller regions are considered as noise, and can be rejected from the potential dune candidates. The remaining region contours are used as potential candidates for dune crest lines. From the contours, figure 1 shows that typically one of the edges of the contour is located very nearly on the dune crest line. On the opposite side of the region is essentially the base of the dune. Figure 2 shows the results of extracting the contours from the processed image.

Because the regions tend to be noisy, the contours are therefore smoothed using a Gaussian kernel, define as:

$$G(i) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-i^2}{2\sigma^2}}$$

The Gaussian kernel is convolved on the contour, which a collection of two dimensional points (x,y). The result of this convolution is a smoother contour which can be more reliably used as a dune crest line candidate.

Typically, the dune crest lines are located on an area in the image where the derivatives are larger, or consistent along the edge of the dune. For each contour,

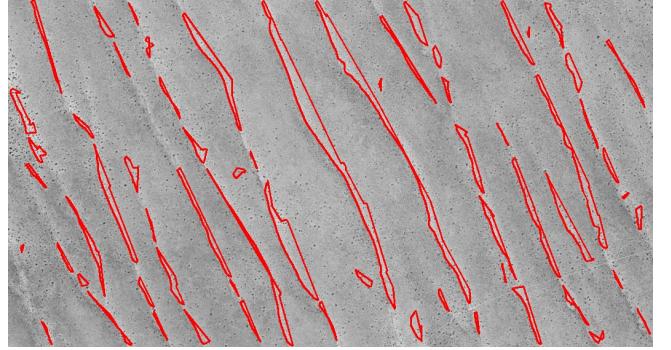


Figure 2: Contour extraction from binary processed image

the average magnitude μ of the derivative $\delta(i)$ of the image in the x and y directions is computed. Then, for each point within a contour compares its derivative with K neighbor's gradient magnitudes. Dune crest line candidate points will tend to have neighbors with similarly and consistently high gradients. To determine if a point $P(i)$ on a contour belongs on the dune crest line, we use the following criteria

$$P(i) = \begin{cases} 1 & \phi(i) \geq r \\ 0 & \text{otherwise} \end{cases}$$

where

$$\phi(i) = \frac{\sum_{k=0}^K \begin{cases} 1 & \delta(k) \geq \mu \\ 0 & \delta(k) < \mu \end{cases}}{K}$$

and $0 < r \leq 1$, which is the ratio of how many strong consistent edges to neighbors around a point i on the contour. Typically, r would be larger than 0.5, which means most of the neighbors of a point must have strong edges for a point to be considered a dune crest line candidate. The parameter r can be fine tune to allow more or less points to fit the criteria. This method will group common contour points based on gradient magnitude.

Once the dune crest line candidates on the contour have been extracted, the contour can be split into contiguous crest line segments. Some further processing can be applied to the segments, such as filtering out smaller or less significant segments (potential false positives). More work needs to be done in this area.

3.1.2 Method #2: Unsupervised Edge-based line detection

Edge Detection Image Processing: This approach is based on the gradient information detect on the image. Dune crestlines typically have relatively

large gradient magnitudes. There are a few challenges with extracting edges of the dune satellite images:

1. Images tend to be noisy and very textured, which results in many edges of varying orientations and magnitudes.
2. Many of the stronger edges may not necessarily be the crestlines themselves. Generally, dunes cast relatively large shadows which themselves produce relatively strong edges.
3. Determining the parameters and appropriate scale for the parameters of the edge detector can be sensitive and affect detection rates.

To address these concerns, the Canny edge detector is used along side some of the techniques inspired from [27] and [28]. First, in order to reduce the amount of noise in the images, both a median and Gaussian filtering is applied to the image. The reasoning for the median filter removes small speckles (which for dune images may be small bushes or other contrasting features found in the images) while preserving major edge gradients. The Gaussian filter will then smooth out the gradient magnitudes and even out the image.

Another important pre-processing step is to apply histogram equalization (REFERENCE NEEDED) to the image. Histogram equalization is important because it stretches the contrast which is crucial to feature extraction in dune-field images, which tend to have poor contrast. This in turns also helps in the extraction of edges, and improves determination of the dominant gradient orientation.

Once the image has been pre-processed, the Canny edge detector is used to recover the potential crestline candidates. To overcome the parameter selection of the high and low threshold, the mean gradient μ and standard deviation σ is computed over the entire image. The high and low thresholds are determined as follows:

$$T_{high} = \mu + q \cdot \sigma$$

$$T_{low} = \frac{T_{high}}{2}$$

where q is so factor which can be determined based on the problem set. This makes the threshold parameter less sensitive to fixed threshold problems. The result of the Canny edge detector after filtering are displayed in figure 3.

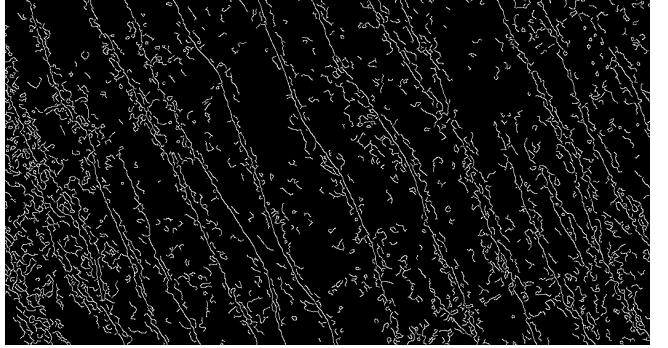


Figure 3: Canny edge detector after median and Gaussian filtering of the Kalahari dune image.

Unsupervised Crestline Detection from Detected Edges

Many of the edges provided in the edge detection step are noise, shadows, and non crestline textures. Crestlines all have one feature in common: all of their gradient have relatively similar orientations. Dune crests typically appear to have larger gradient magnitudes relative to other noisy edges or texture (but this may not always be the case). **To help solve this issue, as mentionned above, using histogram equalization can help normalize edges and improves calculation of the dominant orientation of the edges.**

Similarly, because of the position at which the sun, edges generated from the shadows of the dunes will also have similar orientations within themselves. Given these properties, there should be a clear deliniation between crestline edges, and non-crestline edges.

Using KMeans: Resolving these differences by grouping similar edges together can be achieved by clustering the gradients. There have been many approaches to clustering (REFERENCES NEEDED HERE??), but the most common is the K-Means algorithm. The benefits of using a clustering algorithm is that it is unsupervised, so that the differences should form themselves from the edge data itself.

Typically, the main parameter that is required for K-Means is the value K , which is the number of clusters. In this problem set, the goal is to seperate the crestline group from all other non-crestline edges. Therefore, the parameter is simply set to $K = 2$, to seperate the gradients into two distinct groupings⁷.

In order to get normalized results for the clustering algorithm, the gradients themselves are normalized. To normalize the gradients, the average gradient magnitude of the detected edges is computed as:

⁷So far, only using two clusters has been investigated. Using more clusters may have more valuable information and better seperation.

$$\bar{\mu} = \frac{\sum_{i=0}^P \sqrt{\delta_{x_i}^2 + \delta_{y_i}^2}}{P}$$

where P is the total number of detected edges from the Canny edge detector, δ_{x_i} and δ_{y_i} are the x and y gradient component of the i th point. Each gradient is then normalized by dividing by the average magnitude $\bar{\mu}$.

$$\dot{\delta}(x_i, y_i) = \left(\frac{\delta_{x_i}}{\bar{\mu}}, \frac{\delta_{y_i}}{\bar{\mu}} \right)$$

The set of normalized gradient vectors are then clustered using the K-Means algorithm with $K = 2$. In Figure 4, the results of the clustering method are shown. The blue points are gradient vectors which potentially belong to the dune crestline. Studying the points, we notice that there is a skew towards the stronger edges in the blue cluster, which we will call the dominant cluster. This is determined by computing the centroids of each cluster. The cluster with the larger overall gradient magnitude is therefore assumed to be the set which contains the crestline points.

The centroid values for each cluster are displayed in 4, which clearly indicates that the blue cluster contains the stronger edges, which are more likely crestlines. To prove this, figure 5a. shows the results of rejecting all weaker cluster gradients, and keeping the dominant cluster gradients.

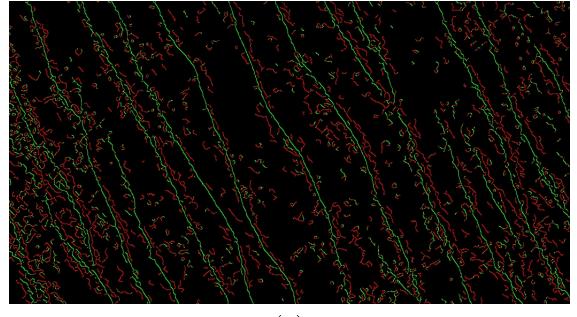
Once the weak edges have been filtered out, the remaining edges are used as crestline candidates. The K-Means cluster removes a majority of false positives, but does preserve some small edge segments which are most likely noise. By using connected components technique, these smaller less significant edge segments can be removed, keeping only longer contiguous segments⁸.

Results of this processing is displayed in section 5.

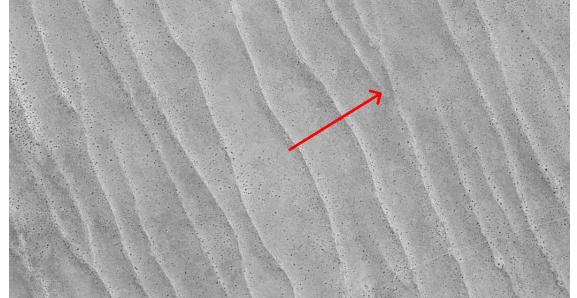
Using Histograms of Gradients: An alternative to the clustering method is to compute a histogram of the gradients based on orientation (REFERENCE NEEDED!!!). Quantizing the space allows us to split edges according to their orientation, where each bin in the histogram represents an edge orientation. Each bin then covers an angle of $\frac{2\pi}{N}$ radians, where N is the number of bins.

Each bin of the histogram is weighed by the magnitude of edges. Once the histogram is constructed,

⁸More research can be done here. There may be techniques used to fuse smaller segments into larger ones to achieve higher detection accuracy



(a)



(b)

Figure 5: (a) Results of filtering out edges (red) which belong to the cluster with the weaker edges. Potential crestline edges (green) are preserved for use. (b) Average orientation of the dominant cluster, which correctly appears to be perpendicular to the trend of the crestlines.

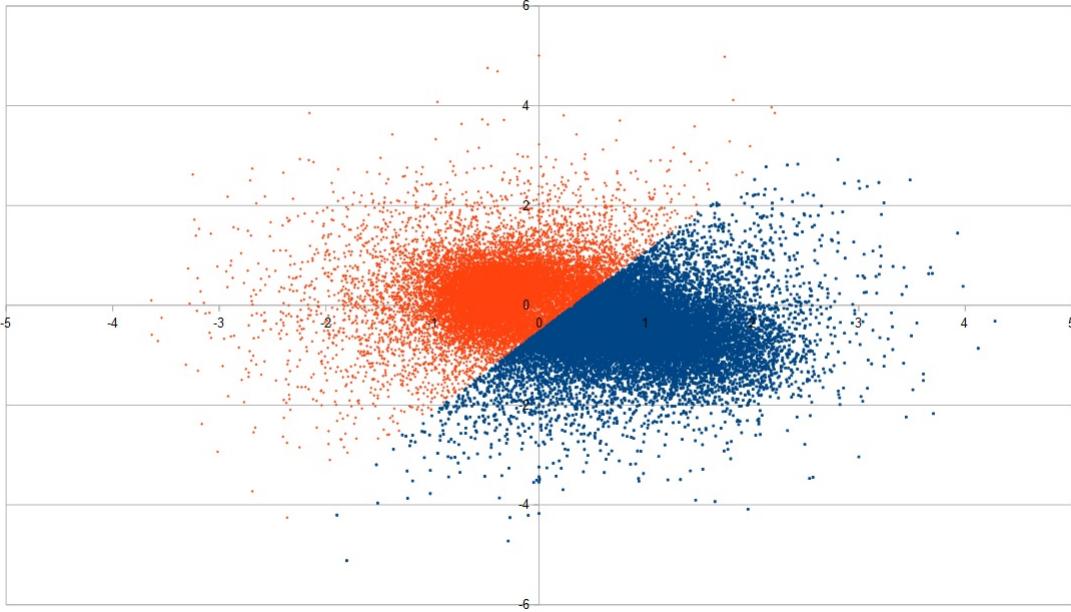


Figure 4: Results of K-Means clustering algorithm with $K = 2.$, on the edge gradients detected using Canny, from Kalahari. The blue cluster represents the dune crestline gradients, and the red represents all other non-crestline edges. The cluster centers of blue is $(0.8958, -0.5496)$, and the cluster center of the red is $(-0.4111, 0.2705)$.

peaks in the magnitude will help determine the dominant orientation (Φ) of the dune crestlines. The approach poses two main problems:

1. Determining N : In practice, a larger value for N has shown to provide finer grain resolution which improves dominant orientation determination. In Figure 6 a value of $N = 18$ is used⁹
2. Multiple Peaks: Often, images may have multiple peaks in the histogram, but only one of the peaks should represent the true dominant orientation of crestlines.

One assumption made is that the bin with the largest value represents the orientation of the crestline edges. Although this assumption holds for many cases, it is not always the case. The Skeleton Coast test image provides a good example of this case in Figure 6. In this particular case, there are two major peaks in the histogram, where the stronger is not the part of the crestline edge group, and the weaker one is.

Choosing the higher peak will cause invalid crestlines to be chosen. In order to determine which peak best represents the crestline edge group, some normalization can be applied. The normalization process begins by computing the mean vector of the gradients from the edge image as follows:

⁹The optimal value for N has not yet been determined, but at first glance, smaller values for N will cause issues, while larger values seem to improve results.

$$\hat{\mu} \langle \bar{x}, \bar{y} \rangle = \left\langle \frac{\sum_{i=0}^P \delta_{x_i}}{P}, \frac{\sum_{i=0}^P \delta_{y_i}}{P} \right\rangle$$

where P is the total number of detected edges from the Canny edge detector, δ_{x_i} and δ_{y_i} are the x and y gradient component of the i th point. The mean orientation is computed from the mean vector as:

$$\bar{\theta}_\mu = \arctan \left(\frac{\mu_y}{\mu_x} \right)$$

The gradients are then normalized by simply subtracting the mean vector from each gradient:

$$\dot{\delta}(x_i, y_i) = (\delta_{x_i} - \mu_x, \delta_{y_i} - \mu_y)$$

The normalized orientation $\dot{\theta}_i$ can then be computed:

$$\dot{\theta}_i = \arctan \left(\frac{\dot{\delta}_{y_i}}{\dot{\delta}_{x_i}} \right) - \bar{\theta}_\mu$$

To determine which bin the i th edge point belongs to, we simply calculate $\left[\frac{\dot{\theta}_i \cdot N}{2\pi} - 0.5 \right]$, and increment that bin by the magnitude of the normalized gradient by $\sqrt{\dot{\delta}_{x_i}^2 + \dot{\delta}_{y_i}^2}$. In essence, this normalization process removes the uneven skew of the gradients in the

overall image. Removing this skew allows true crestline edges to be fairly compared with other stronger edges. As shown in Figure 6, the normalization process softens the stronger dominant edge and enhances the true crestline edges. This process enables crestlines to be accurately detected in images where the valleys of dunes are sharp and contain strong edges¹⁰.

The dominant orientation can be used to filter out most non-crestline edges by keeping all edges using the following criteria:

$$P(x_i, y_i) = \begin{cases} 1 & \left\| \arctan \left(\frac{\delta_{y_i}}{\delta_{x_i}} \right) - \Phi \right\| \leq \varphi \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

P is a crestline candidate if it satisfies the orientation criteria, where φ is an angle tolerance value which is experimentally set to $\varphi = \frac{\pi}{2}$ ¹¹.

In order to improve the robustness, a connected components method is used to find all segments from the canny image. For each segments if the number of points along the segment satisfy the criteria from 1 is greater than some ratio R , then the segment is considered to be a dune segment, where $0 < R < 1$. Choosing a small R generally improves the true positive detection, while increasing false positive rate¹².

Dune segment linking

With the dominant orientation computed, many false positives have been rejected. The next step of the process is to group segments which link together. Since each crestline candidate segments is a collections of two dimensional points, an intuitive step is to fit a line to the candidate segments. The line fitting algorithm used is from the OpenCV library [1], which aims to minimize:

$$\sum_i \rho(r_i)$$

where r_i is the distance between a point on the line, and $\rho(r_i)$ is the function used. We use the simplest least square method, $\rho(r) = \frac{r^2}{2}$. The result of the line

¹⁰The gradient normalization process has not been proven to work for all cases, only for the images from the test set. There may be cases where the normalization may have the opposite effect and remove all true crestline. More investigation and sample images are required to determine the effectiveness of the normalization.

¹¹The value of φ has not been extensively tested yet, and may have an effect on the results, more testing is required to determine the sensitivity of this parameter.

¹²During initial testing, R (~ 0.1) was set to a very low value, which allowed many of the true positive to be found at the expense of a higher false positive rate. This technique is very simplistic and does require more investigation to improve on.

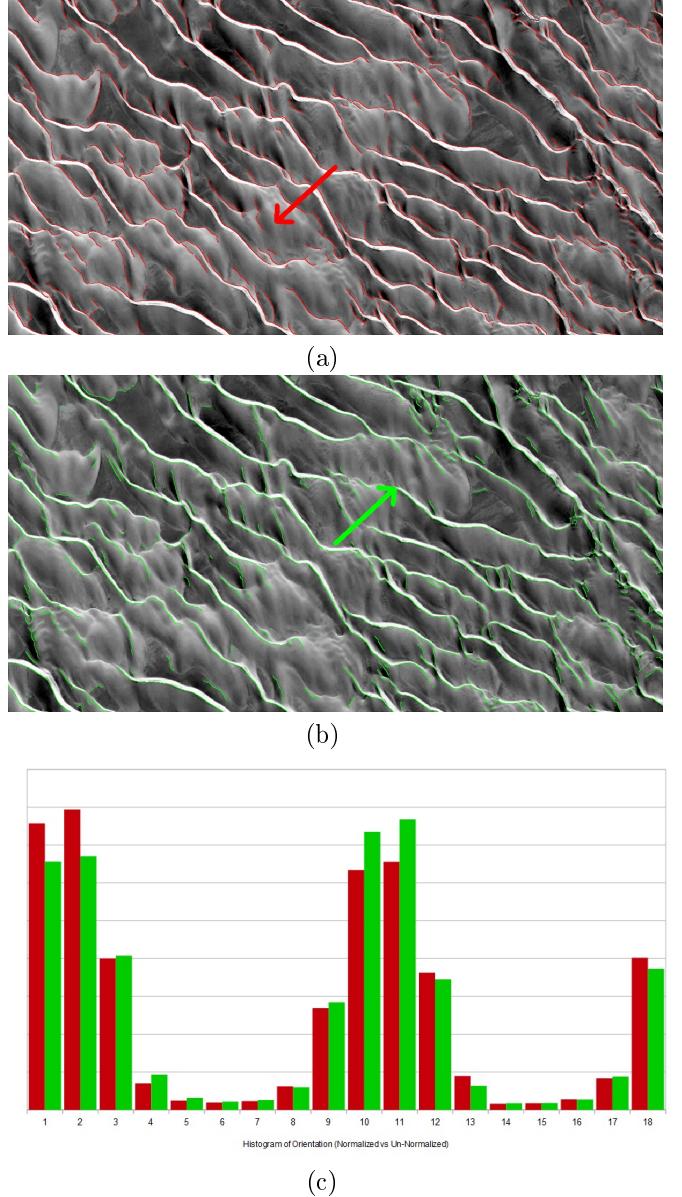


Figure 6: Results of unnormalized (red) and normalized (green) histograms of gradients ($N = 18$). The histogram contains two major peaks, but the crestline is the weaker of the two peaks. (a) Edges which belong to the dominant orientation which are invalid crestlines. (b) With normalization, the true crestlines now have the higher overall magnitude. (c) The 18 bin histogram of gradients with and without normalization.

fitting produces a vector of four values $\langle x, y, v_x, v_y \rangle$, where the (x, y) components are the position of the line, and (v_x, v_y) is the normalized vector which is co-linear to the line, encoding the orientation of the line.

With all segments fit with a line, we can filter the segments based on the orientations of the lines. To get a general view of the distribution of the orientation of the lines, a histogram of the line orientations can help determine dominant lines. The histogram can be constructed based on the orientation of the lines, weighed by segment length. As shown in figure 7(a), the histogram appears to have a unimodal distribution. When choosing all lines which belong to the peak bin in the histogram, the resulting in the output image 7(b). The results show that many of the false positives have been filtered out.

Since the shown distribution appears to be unimodal, a better approach may be to simply compute the mean and standard deviation of the line orientations. Choosing the appropriate sigma value to filter out the noise and false positives depends on the distribution. In some cases, such as images with crestlines which are more curved, the variation orientations may be more significant.

In order to avoid the filtering of true positives, a linking algorithm should be used to link segments which belong to the same crest-line.

3.1.3 Method #3: Watershed Segmentation

In an approach similar to 3.1.1, the goal of this approach is to segment out the brighter region of the image, which represents the sunny side of the dune, using the watershed transform. This powerful segmentation tool is used to determine the boundary of the bright dune region, better than a simple thresholding method.

In order to extract reliable regions, image illumination normalization is applied, to make the illumination more evenly distributed across an image. After applying some pre-processing to the image (Median and Gaussian blurring to remove as much noise as possible), the illumination normalization¹³ is applied to the image as shown in Figure 8.

The normalization process is done in a fairly simple and efficient way, using integral images. The integral images was originally proposed in [4], and was popularized for computer vision applications by [26]. The integral image representation allows rectangular features to be computed very efficiently. Each pixel (x, y) of the integral image is the sum of the pixels above and to the left of it, as described in [26]:

$$ii(x, y) = \sum_{x' \leq x, y' \leq y} i(x', y')$$

¹³The illumination normalization presented is very basic, and better normalization schemes should be tried.

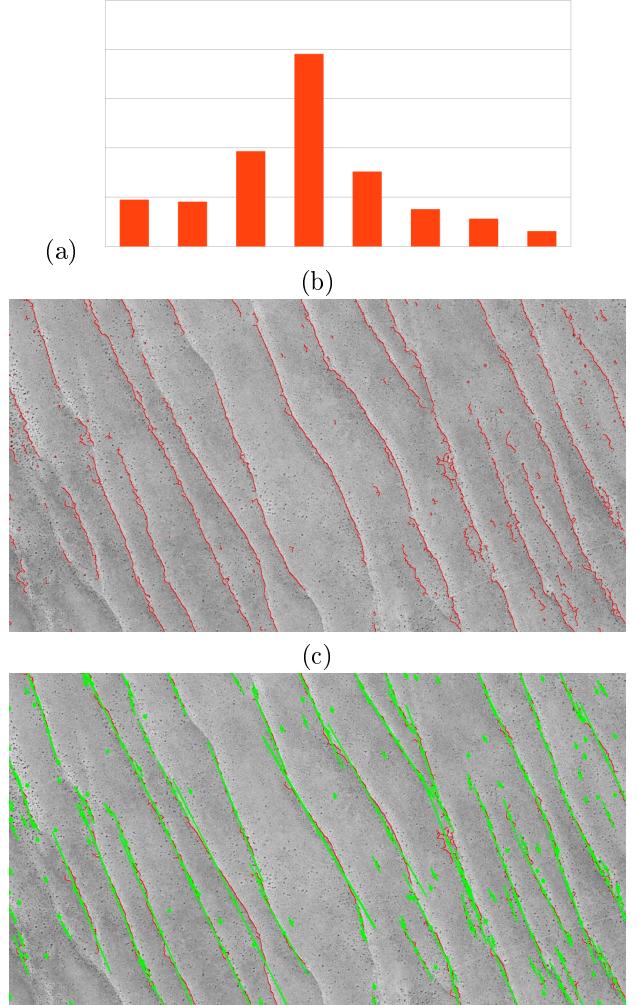


Figure 7: Results of filtering based on the line orientation fitting, and choosing the peak in the histogram. (a) the histogram of line orientations weighed by segment lenght, (b) segments which have orientation matching the peak in the histogram, (c) the fitted lines from the dune segments.

To normalize using integral images, the mean μ_i of the image, which can be done efficiently once the integral images is computed, given an $N \times M$ image.

$$\mu_i = \frac{ii(M, N)}{M \cdot N}$$

The goal of the illumination normalization is to bring pixel intensities value closer to the mean intensity of the image for a more even distribution of intensities. To accomplish this we simply compute a ratio multiplier of the mean intensity μ_i over the square local area ($w \times w$) mean intensity centered around a pixel (x, y) . The mean of a local area can be computed efficiently using the integral image theory:

$$\mu_l(x, y) = D - C - B + A$$

$$A = ii\left(x - \frac{w}{2}, y - \frac{w}{2}\right)$$

$$B = ii\left(x + \frac{w}{2}, y - \frac{w}{2}\right)$$

$$C = ii\left(x - \frac{w}{2}, y + \frac{w}{2}\right)$$

$$D = ii\left(x + \frac{w}{2}, y + \frac{w}{2}\right)$$

Then, the ratio of image intensity to local mean intensity simply is $r_{\mu_l(x, y)} = \frac{\mu_i}{\mu_l(x, y)}$. The pixel intensity value at that location is then multiplied by this ratio to get the normalized value:

$$\tilde{i}(x, y) = r_{\mu_l(x, y)} \cdot i(x, y)$$

With the image illumination normalized, the watershed transform can be used to segment out the brighter regions of the image which will be the dune sunny sides. The watershed implementation used is provided by the OpenCV library, and is a variant of the implementation proposed in [15]. The watershed uses an initial seed rough image of the desired locations to segment out, which in this application is the brighter regions of the image.

The desired regions to extract are the bright and shaded areas. The threshold values for these can be determined from the image's mean and standard deviation intensity values:

$$T_{high} = \mu_i + \rho_{high} \cdot \sigma_i$$

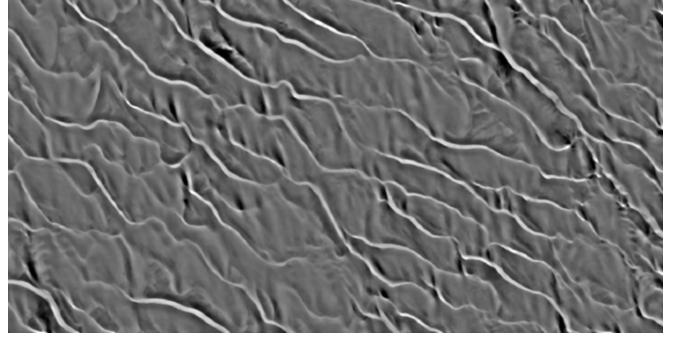


Figure 8: Illumination Normalization using integral images with $w = 30$

$$T_{low} = \mu_i + \rho_{low} \cdot \sigma_i$$

Where the ρ_{high} and ρ_{low} are scalar values determined empirically. All pixels above the high threshold are labeled as the desired region to segment (in white), and all pixels below the lower threshold are set to the non-desired region (in gray). A morphological eroding operation is applied to better separate the regions for the watershed transform. Using the labeled image and normalized illumination image, the watershed algorithm is able to segment out the dune regions reliably, as shown in Figure .

After computing the watershed segmentation image, the regions extracted from it can be retrieved using contour detection, as done in section 3.1.1.

The contours retrieved are closed loops where one segment will be along the dune crest line and the other not. To determine which segments of the contour belong to the dune crestline, we can use what was learned from section 3.1.2. Building a histogram of the image gradients, choosing the dominant orientation, and filtering out all contour points which do not agree with the dominant orientation.

The results of the filtering are shown in Figure 14, and the accuracy of these results are shown in Table 1. There are a few drawbacks so far:

1. An assumption that a dune contains a bright side. Not all images (especially the Simpson image), have crestlines that have a bright edge.
2. The edges of the contours appear to be slightly noisier than edge-based approaches.
3. Localization of the segments is poor. Some segments do not lie on an actual edge, which may be reported as a false positive.

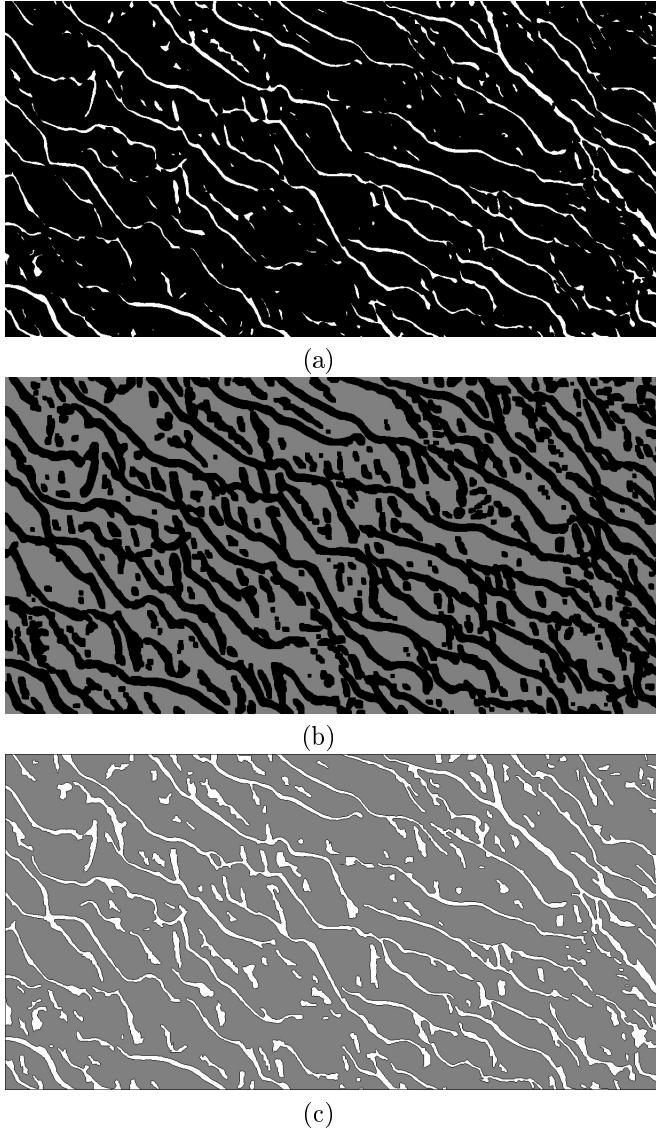


Figure 9: Watershed segmentation process with $\rho_{high} = 0.8$ and $\rho_{low} = 0.4$, (a) Result of the high threshold, (b) Result of low threshold, (c) Watershed segmentation results

On the other hand, the watershed approach appears to have some benefits:

1. Better connectivity of dune crestline segments. When edges become weak between two connecting segments, the edge based approaches produce gaps, where the watershed is able to fill the gaps.
2. Watershed method could be further expanded to include color image processing.

3.1.4 Method #4: Frequency Domain

In this approach, we take advantage of the fact dune-field patterns seem to have some periodic pattern, which could possibly be extracted from the frequency domain. Converting the images into the frequency domain using the Discrete Fourier Transform (DFT) (REFERENCE NEEDED) provides a method for applying some processing on individual frequencies of the image.

Feature extraction from the frequency domain:

In this application, the features we desire to extract are the dune crest-lines, which in the spacial domain are edges. In the frequency domain, the crest-lines may belong to some of the higher frequencies (or possibly a subset of the frequency spectrum). The shifted frequency domain output of the DFT is shown in Figure 10.

From the frequency domain, dominant frequencies can be extracted by searching for large magnitudes of frequencies ¹⁴. Typically, from the dataset used, it can be shown that a dominant orientation in the frequency appears to be present in the dune-field images. From preliminary observations, the dominant orientation seems to correlate exactly with the orientation of the dune crests.

In order to determine this dominant orientation, the frequency domain magnitude image is thresholded based on the mean and standard deviation of the frequency magnitudes, as shown in Figure 10. Because output of this threshold is somewhat noisy, a median filter is applied to create a smooth region for the dominant frequency. The contour of the region is then extracted, which is used to fit an ellipse.

The computed ellipse's orientation appears to match the orientation of the dune gradients. The information provided by the ellipse may prove useful ¹⁵. Currently, we use this ellipse to generate the mask for high-pass filtering. The mask shown in Figure 10 simply rejects all lower frequencies (close to the center of the

¹⁴Determining which frequencies to extract will be key for this application. More research needs to be done on how to extract features from the frequency domain.

¹⁵Fitting an ellipse is currently mainly used for determining the orientation of the gradients of the dune crests. Since I am not too familiar with the frequency domain, there may be a better approach to extract this, or other features.

spectrum), and allows all higher frequencies to pass through. The effect produces a kind of edge detection filter, where lower values could potentially be used to determine locate dune crests. At first glance, the results appear to be promising.

3.1.5 Method #4: Edge Direction Based Approach

In this approach, we used knowledge learned from a previous edge based approach. In section 3.1.2, we learning that the dominant orientation of the dune field could be determined based on the derivative of the image. In that approach, we used the gradient magnitudes to find major crest-line edges, and filtered out edges which do not agree with the dominant orientation of the gradients.

Using edges provides good localization but is prone to discontinuity of edge segments. A better alternative explored is to use the image of the gradient directions and find regions which agree with the dominant orientation. The regions produces by the gradient direction map have been shown to be typically smooth and have good continuity in this application.

The main reason for this is the nature of the problem itself, since dunes have a bright and shaded side. As gradients approach the crest-line, their direction component point towards the crest line. The shaded side of the dune can be seen as a color gradient ranging from dark to bright as it approaches the crest-line. This trend is plotted clearly in Figure 11. Once this pattern is identified, it is simply a matter of thresholding the gradient direction map to retrieve regions which have gradients along the dominant orientation.

The main benefit of this approach is that the resulting regions have sharp and defined edges along the dune crest-line, regardless of how sharp an edge is in actuality. In many cases, as is the case in Figure 11, dunes in the same image may have some sharp edges along the crest-line while others have less defined crest-lines. Using gradient magnitude in areas with poorly defined crest-lines yields poor results, while the gradient direction maps provides a sharper edge and a better estimate of where a crest-line may be. The downside of this method is that not using the gradient magnitude results in poor localization of the actual crestline.

Once the gradient direction map has been thresholded, the binary image provides well defined regions which allows the use of contours to determine the crest-lines. The contours extracted provide good continuity of the crest-lines, but also contain many elements which are not part of the crest-line. In order to reject false positivies, segments of the contour which are on brighter regions of the image are considered to be part

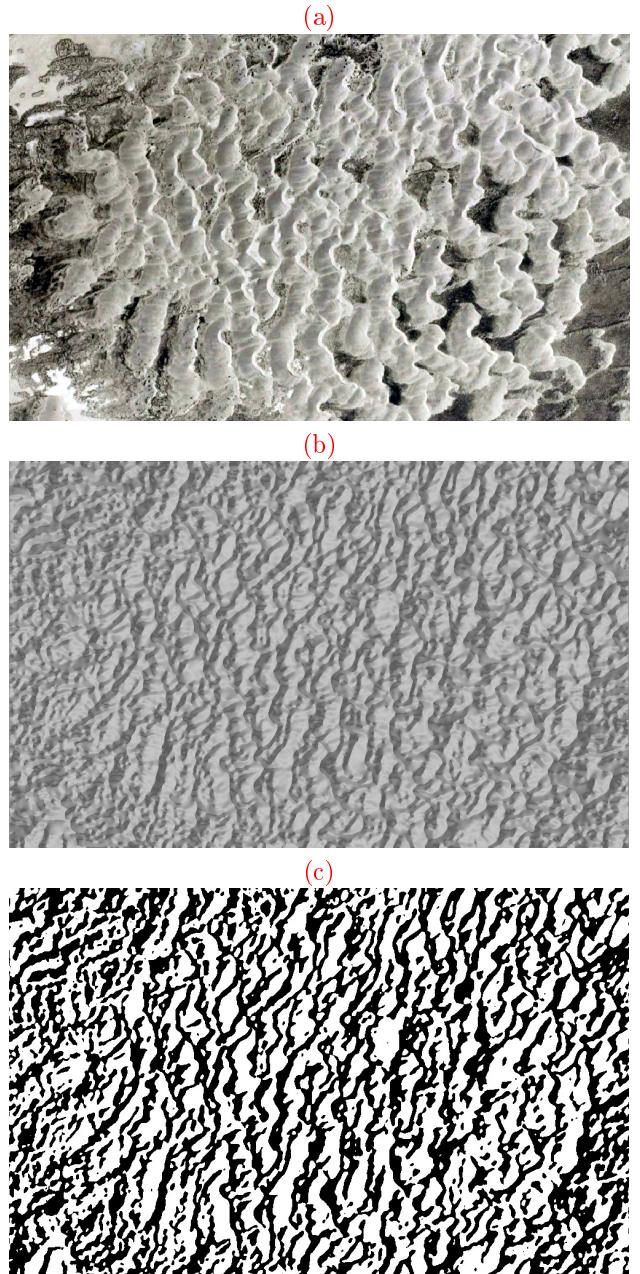


Figure 11: The gradient direction map based on the dominant orientation calculated for (a) WDC image. (b) The normalized gradient direction based on the dominant orientation. Brighter regions represent pixels which are along the dominant orientation, while darker regions are gradients which oppose the domination orientation. (c) The gradient direction map thresholded. Pixels with $\|\theta_i - \theta_{dominant}\| \leq \frac{\pi}{2}$ are said to agree with the dominatn orientation, and set to white, all others to 0.

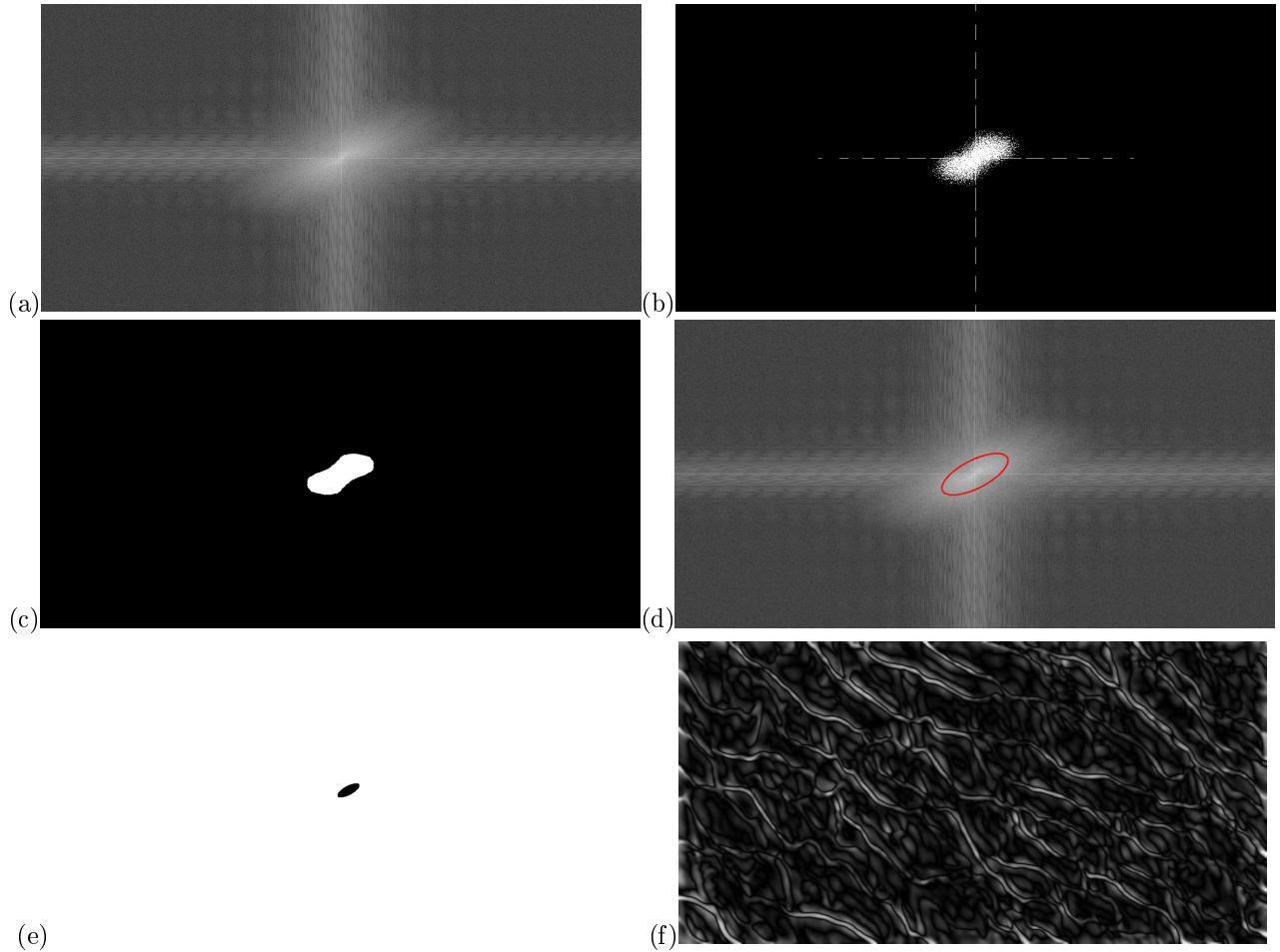


Figure 10: Frequency spectrum processing results from the Skeleton-Coast image. (a) Log-normalized shifted frequency domain, (b) Result of thresholding frequency domain magnitude based on average magnitude and standard deviation of the magnitudes, (c) Median filtering of the binary image of the frequency domain, (d) Result of ellipse fitting of the dominant frequencies region, (e) Mask used for high-pass filtering of the frequency domain, (f) Result inverse DFT of the high pass filter applied on the frequency domain.

of the crest-lines¹⁶. More detail about this method will be further provided later on.

3.2 Dune Morphology

With the reliable crest line data extracted, morphology parameters of the target image can be computed. The desired properties include crest line length, dune scale, distance between dune crests, and other properties. TODO (more research on this later).

4 Experiments

Since the goal of this project is to automatically segment dune crest lines, a dataset of images with labeled ground truth is used to measure the accuracy of the dune detection algorithm. The current dataset is a small sample set of six images taken from different regions, at various scale and various illuminations. The regions include: Kalahari, Namib, Simpson, Skeleton Coast, WDC, and White Sands, as shown in figure 12.

TODO.

5 Results

The dune line crest detector is applied to the labeled benchmark images shown in figure 12. The results we are interested in for detection purposes are the true positives (correctly detected dune lines) and false positive (segments that are not dunes). The results are computed in a brute force manner:

- True Positives:** The *TPs* are computed by taking each ground truth pixel, and finding the nearest detected dune segment pixel. If the distance between the nearest detected and the ground truth is smaller than some error e , the ground truth is considered to be detected. The *TP* rate is then the number of correctly identified ground truth points, over the total number of ground truth points.
- False Positives:** The *FPs* are computed by taking each detected dune candidate, and finding the nearest ground truth point. If that distance is greater than some error e , then the detected dune candidate is a false positive. The *FP* rate is then expressed as the number of incorrectly detected dune points over the total number of dune points detected.

¹⁶The use of intensity values to determine which segments of a contour are on the actual crest-line may not be an optimal solution, but has provided adequate means of rejecting many false positives for the time being.

The *TP* and *FP* rates are shown in table 1. The results shown in figure 13 visually overlaps the ground truth with the dune detected.

6 Conclusion

TODO.

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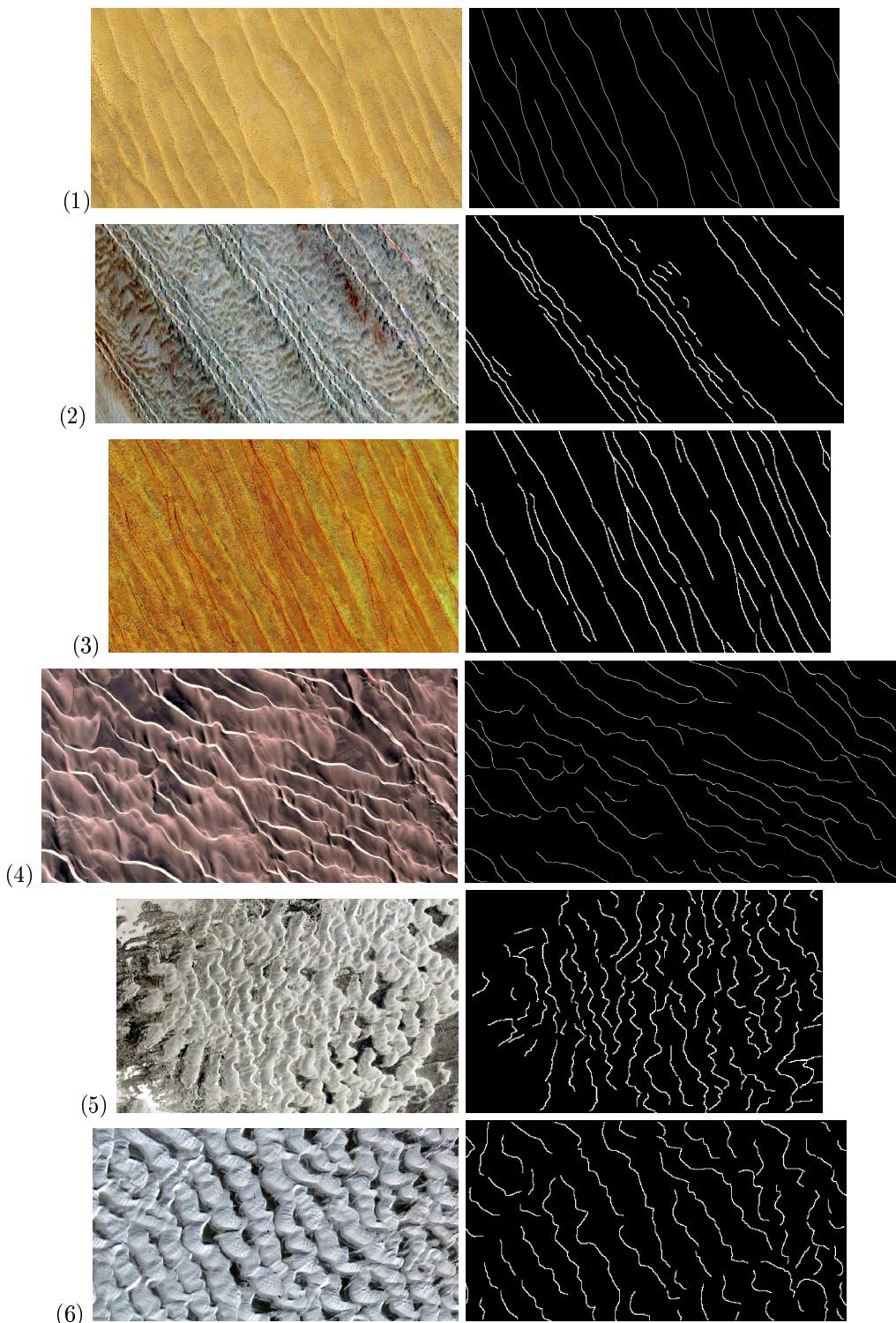


Figure 12: Dune dataset with corresponding dune crest line ground truth map. The images are labeled as (1) Kalahari, (2) Namib, (3) Simpson, (4) Skeleton Coast, (5) WDC, and (6) White Sands.

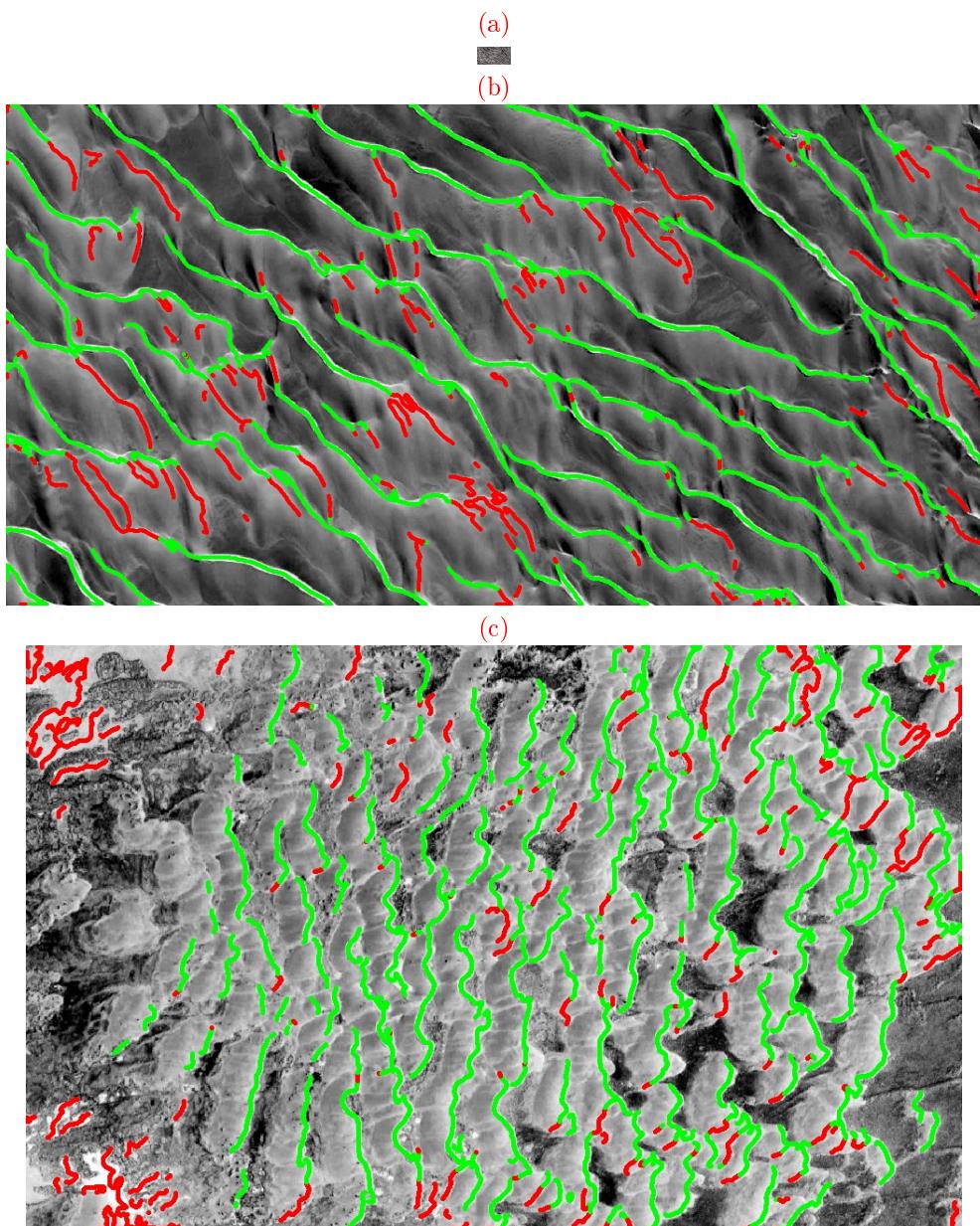


Figure 14: (a) Dune Crestline detection using Watershed Algorithm (Method #3). (b) and (c) Results of the Gradient Direction approach (Method #4) with TP in green and FP in red, for Skeleton Coast and WDC.

| Images | Method #1 | | Method #2 (K-M) | | Method #2 (HoG) | | Method #3 | |
|----------------|---------------|---------------|-----------------|---------------|-----------------|--------|---------------|--------|
| | TP | FP | TP | FP | TP | FP | TP | FP |
| Kalahari | 0.7094 | 0.2178 | 0.9396 | 0.2495 | 0.9852 | 0.7155 | 0.9239 | 0.5229 |
| Namib | 0.7493 | 0.6026 | 0.9281 | 0.4924 | 0.9626 | 0.6850 | 0.8591 | 0.7290 |
| Simpson | 0.1364 | 0.6512 | 0.7464 | 0.4979 | 0.8977 | 0.6478 | 0.4968 | 0.6979 |
| Skeleton Coast | 0.8033 | 0.3253 | 0.7605 | 0.1517 | 0.8187 | 0.2178 | 0.9221 | 0.4461 |
| WDC | 0.5581 | 0.3731 | 0.5111 | 0.4849 | 0.7478 | 0.5399 | 0.7005 | 0.5819 |
| White Sands | 0.2614 | 0.6926 | 0.6231 | 0.4762 | 0.7634 | 0.5740 | 0.3889 | 0.8257 |

| Images | Method #4 *** | |
|----------------|-----------------|-----------------|
| | TP | FP |
| Kalahari | 0.937056 | 0.367829 |
| Namib | 0.988362 | 0.60665 |
| Simpson | 0.569738 | 0.667744 |
| Skeleton Coast | 0.993523 | 0.297289 |
| WDC | 0.930268 | 0.295656 |
| White Sands | 0.642978 | 0.642087 |

Table 1: Results of the dune detection algorithms for the benchmark dataset using a value of $e = 5$ pixels. Method #2 used $R = 0.1$, *** Because localization of Method #4 is not as good, we use $e = 10$ pixels

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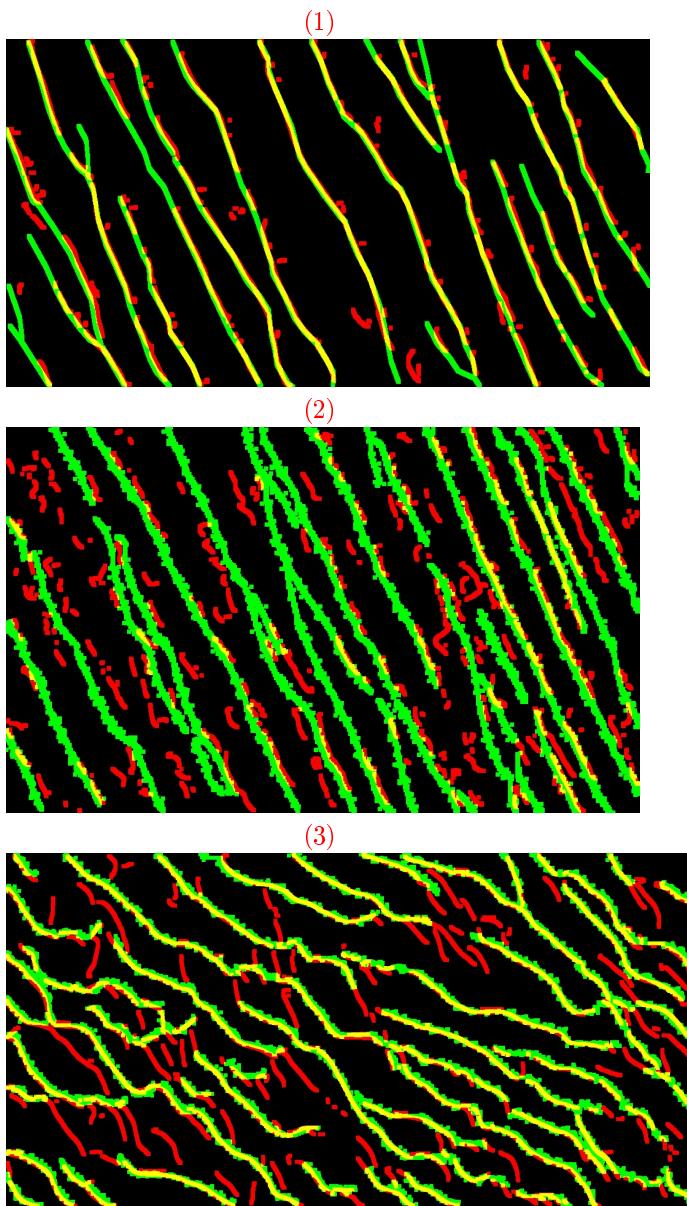


Figure 13: Dune detection results (red) compared to the ground truth (green), overall is shown in yellow. Shown are results for (1) Kalahari, (2) Simpson, and (3) Skeleton Coast benchmark images

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