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A study of moving sand dunes by means of satellite images

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Abstract: In several regions of the world, the slow motion of sand dunes is becoming a challenge for human activities and a threat for the survival of ancient places or archaeological sites. It is then important a constant surveying of dunes and an estimate of their migration rate. Several methods exist for this purpose: among them we have the use of satellite images, often freely available on the World Wide Web, which are a convenient resource for the planning of future human settlements and activities. In particular, the Google Earth and its time series are a remarkable resource. Some examples of their use are here proposed.

1. Introduction

The motion of sand dunes, though it seems quite slow, can become a challenge or even a threat for human activities. An example is what is happening at Nouakchott, the capital of Mauritania [1], where the city may be slowly covered with the sand of the moving dunes of the Sahara Desert. As told in Reference 1 and shown by a Landsat satellite image, "hot on the city's heels are sand dunes," threatening to overtake it. Another example is Chinguetti, a medieval trading centre in northern Mauritania, pole of several trans-Saharan routes [2]. Known as a holy town, rich of medieval manuscript libraries, its survival is seriously questioned by the desert dunes [3].

On the motion of sand dunes the climate change could strongly act, with disastrous consequences for local communities. As told in [4] for instance, the inactive Sahel and southern African dune systems are used today by pastoral and agricultural activities that could be disrupted if climate changes alter the dune dynamics. Empirical data and model simulations have established that the dune erodibility and erosivity, which are governed by the interplay of several environmental conditions, are critical for the dune field dynamics. The researchers simulated some scenarios to assess the potential future activity of some dune fields, finding that they are likely to be reactivated, with a consequent motion of dunes, because of the twenty-first century climate warming [4]. According to the United States Geological Survey too, sand dunes are becoming more mobile as the climate changes [5].

Several methods for surveying the dune fields and estimate their migration rate such as engineering solutions for controlling the dunes are available. The most common manner of preventing sand from advancing is to create some fences across the path of the prevailing wind. These fences are trapping the movement of the sand [6], because they slow down the flow of air, causing air to release its load. Experiments were implemented in sandy lands to evaluate the effects of different methods for stabilizing sand dune by means of vegetation restoration [7], creating an environment suitable for it [8]. However, in hyper-arid area, these methods are rather challenging [9].

Sand dunes are hills of sand with different forms and sizes, which can move. As complex systems of particles, the dunes and their motion have attracted several studies in the past [10,11] and recently, see for instance [12], such as several simulations [13-17]. Let us remember that the first systematic study of the motion of dunes was due to Ralph Bagnold, who during 1940s did measurements directly on natural dunes, but also experiments in wind tunnels [18]. This methodology is still used for the collection of experimental data [19].

The researches on dunes are then very important, because a better knowledge of their dynamics can help in predicting their behavior. Therefore, a monitoring of dune movement is fundamental and it can be accomplished through a number of methods, combining surface mapping with aerial and satellite imagery, GPS and LIDAR measurements. The monitoring of dunes then can range from the macro-scale of satellite data to the micro-scale of local sensors distributed on the surface of dunes. A recently proposed method, suitable for monitoring the consolidation of surfaces, is the 3D laser scanning [20]. For the large scale monitoring,

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historical archives containing aerial and satellite imagery can be useful to compile a database for each dune field. Some maps can be created, such as the one proposed in Ref.5, showing the evolution starting from 1953 of the profile of the dune field near the Grand Falls, Arizona.

Here we will discuss the use of satellite images freely available on the World Wide Web, as a convenient resource for the planning of future human settlements and activities, when compared with previous studies from archives and research journals. Possible uses of Google Earth and its time series of images to collect data on the motion of dunes are also investigated. When local meteorological data are available, the dune motion can be linked to the environmental conditions. Before studying some cases, let us shortly discuss the shape and motion of dunes.

2. Shape and motion of dunes

In ancient times, the word "dune" had probably the meaning of a built-up hill [21]. These sand hills are observed having several shapes, according to the quantity of sand, the surface on which the sand moves and the blowing of the winds. Most kinds of dunes are longer on the windward side, the side where the sand is pushed up, and have a shorter side, known as the "slip face", in the lee of the wind. When the ridge is arc-shaped, this dune is a "barchan". The barchan possesses two "horns" (Figure 1 shows some barchans in Peru), the slip face inclined of approximately 35 degrees and the windward side stands at about 15 degrees [22]. We can observe isolated dunes, as those shown in Fig.1, or dune fields, where dunes coalesced. These fields can cover regions hundreds of kilometres wide.

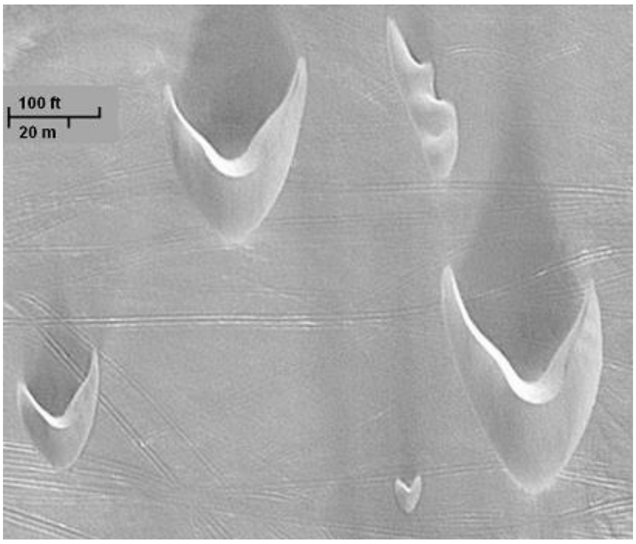

Figure 1 - When the ridge of a dune is arc-shaped, the dune is a barchan. The dune has two "horns" and a slip face. In the image we see some barchans in Peru. The wind are blowing due North. The image is from the Google Maps.

Using the images from satellites, we can see that the dunes shown in Fig.1 have their origin in a coastal area of Peru. The sand is transported inland for great distances by unidirectional winds from the oceanic shoreline. Although the dunes are usually associated with coastal regions, such as those in Peru, the largest dune fields are inland in the deserts, the Taklamakan Desert for instance, or within dry lakes or dry seabeds. Let us note that sand dunes can exist in cold places too, such as in Antarctica and on Mars and Titan, the largest moon of Saturn [23].

Sand dunes move forced by wind through different mechanisms. They can move through a mechanism known as "saltation", where the particles of sand are removed from the surface and are carried by the wind, before landing back to the surface. When these particles land, they can scatter other particles and cause them to move as well. Another mechanism is present on the steep slopes of the dunes, where the sand is falling down: this is the sand avalanche. Therefore, if we are on the sloping windward side, we can see the sand grains that jump few centimetres above the surface of the dune. At the dune's crest, the airborne sand grains fall down the steep lee slope as small avalanches. With strong winds, the sand particles moves in a sheet flow. This is an overland motion of the sand, having the form of a continuous layer over the soil. The mass transferred by this flow is extremely large. Then, during a strong dust storm, the dunes may move more than several meters.

As told in Ref.14, the shapes of dunes depend mainly on the amount of sand and on the yearly wind regime. The simplest type of dune is the barchan, which occurs when the wind is bowling from the same direction throughout the year. As we can see in Fig.1, barchans exist if there is not enough sand to cover the entire surface. As deduced by Bagnold, the barchans move proportionally to the wind velocity and inversely proportionally to their height. Refs. [13-17] tell that these dunes have heights between 1.5 and 10 m, their bases are typically 40 to 150 m long and 30 to 100 m wide.

In [13-17], the researchers simulated with detailed models the creation and motion of a barchan. Let us try to show using a simple approach, how a crescent-shaped dune can originate. Let us assume a heap of sand with a Gaussian profile z=H(x,y) in a Cartesian frame of reference, where the plane x,y is the horizontal surface (the orientation is shown in Figure 2). The height of the heap is H_o=1 in arbitrary units. The profile of the dune is represented by means of grey tones corresponding to H. The white tones correspond to H=0, whereas the black tones to H=1. The radius of the heap is R=250 (arbitrary units).

A wind is blowing in the horizontal x-direction. For each fixed value y=Y, the profile of the heap changes and, in particular, the dimensionless height of the corresponding profile changes. It is given by $h(Y)=\max(H(x,Y)/H_o)$. Let us subdivide the dune in several thin layers, parallel to the x,z plane, having constant y, that is, y=Y. Let us suppose that each layer has a velocity, given by the dimensionless quantity $v(Y)=1/h(Y)$, then inversely proportional to the height of the layer h(Y). Assuming the rate of the mass transport as a constant, we can imagine that the layer corresponding to y=Y is simply shifted with this speed, without changing its profile. We can see the evolution of the dune as a function of time in the same Figure 2; we see the profile after a time interval assumed as $n\Delta t = nR/50$ (arbitrary units), where n is an integer. The profile of the dune is then modified in a new profile that assumes the arched shape.

This is a quite simple phenomenological approach, not considering the true mechanisms as in [13-17]. However the model shows why a barchan is developing with its arc-shape. In the figure for n=0, we have the Gaussian profile: the following evolution is shown for n=5 and 10.

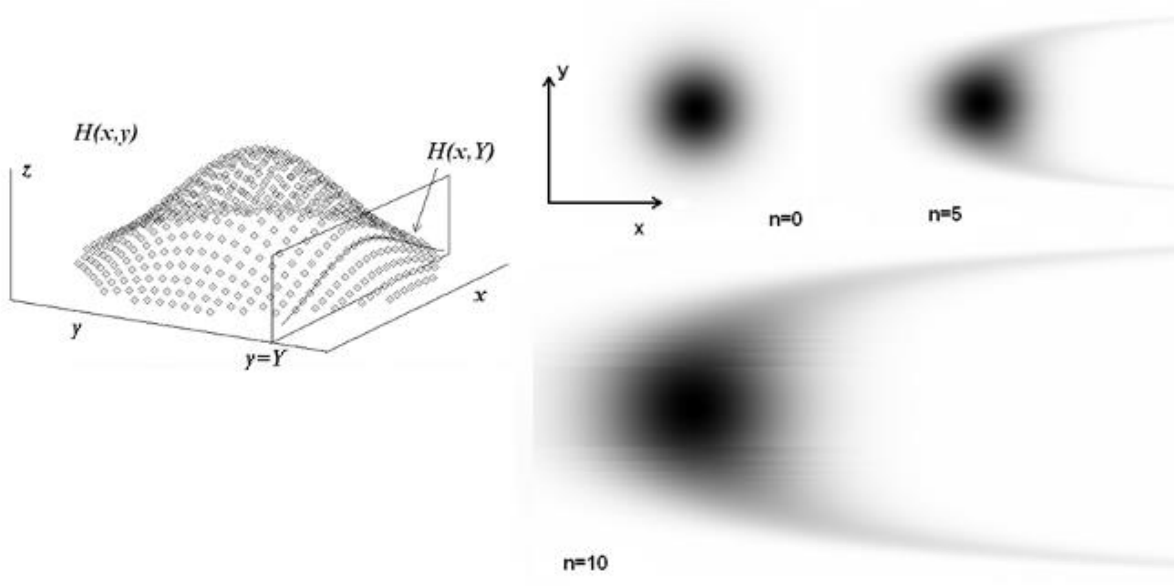

Figure 2 - At the beginning, we have a heap of sand with a Gaussian profile H(x,y) on the horizontal surface x,y. The profile of the dune is represented by means of grey tones corresponding to H. The white tones correspond to H=0, whereas the black tones to H=1. The radius of the heap is R=250 (arbitrary units). The height is H_o=1 (arbitrary units). The wind is blowing in the x-direction. For each vertical plane with fixed y=Y, the profile of the heap changes. The dimensionless height of the corresponding profile is $h(Y)=\max(H(x,Y)/H_o)$. The dimensionless velocity of the layer is $v(Y)=1/h(Y)$, inversely proportional to the height of the profile H(x,Y) of the dune corresponding to y=Y. We can see then the evolution of the dune as a function of time. Assuming the time step as $\Delta t = R/50$ (arbitrary units), after n steps, each layer H(x,Y) moves of different distances with respect to the others.

Since the speed depends on y, we obtain the crescent-shaped profile h(x,y). The “horns” have a greater speed than the central part of the dune.

3. Comparing scientific literature and satellite images

In fact, in the past, the survey of a dune field was obtained from air-photos and then the data represented on maps. But, as we can see from the Figure 1, the dunes can be easily found and observed in the Google Maps. Let us suppose then that we want to study a specific dune field that we can see in a recent satellite image and investigate its motion. We can try to find out some maps in past publications to compare with. Here an example.

Let us consider the case of the dunes in the Nazca to Tanaca area of southern Peru, we can use a research reported in Ref.24 that had been done from 1959 to 1961. This rather interesting study was previously published in Spanish [25]. The author studied some barchan dunes and plotted the rates of movement versus the dune widths. In this way, he quantified the work of Bagnold telling that the speed of a barchan is inversely proportional to the barchan size, given by its height or width. The conclusion that the researcher proposed in Ref.24 is that all barchans in a given dune field, regardless of size, sweep out approximately equal areas in equal times. There is also another interesting observation on the collisions between small and large dunes. Let us suppose a larger dune in front of a small dune: the collision does not result in destruction or absorption of the smaller dune if the collision is a ‘sideswipe’. It is observed that during the collision the dunes merge into a compound dune. After the collision, the smaller dune had passed the larger dune, retaining its approximate original size and shape. Another result of these studies was a map documenting the dune fields that have origin from the sand of the Pacific coast beaches (in the Ref.21 the locations of these dune fields is shown).

Fifty years ago, the author of Ref.24 was a geophysicist on the exploration staff of Marcona Mining. The Marcona mine is an open-pit iron mine, on the Pacific coast of Peru, 400 km southeast of Lima. In that period, a problem for this mining activity was the movement of large barchan sand dunes across the road that connected the mine with the shipping port of San Juan (see Figure 3). However, the dunes travelled. Now they are far from the road. To obtain the Figure 3, we have adapted the data from the map in Ref.24: we can see the barchan dunes crossing the San Juan–Marcona highway and their positions in 1943 and 1952.

The dunes have been scattered in this long period. Since this dune set is under constant winds and the composition of the sand is constant too, what is causing their scatter is the changing slope of the topography [24]. In fact, the dunes are moving on an irregular topography.

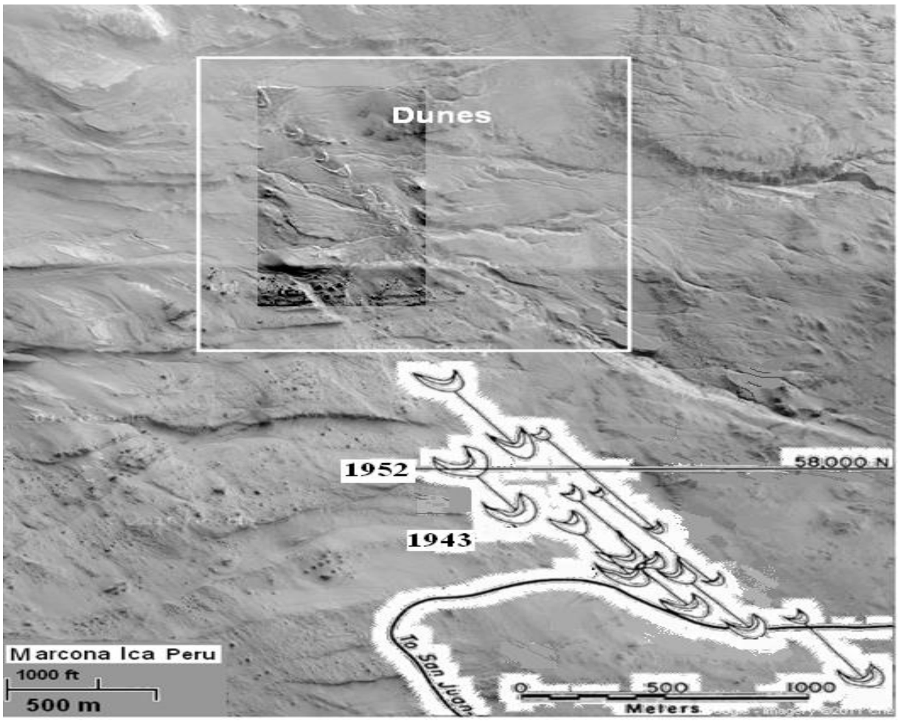

Figure 3 **-** On the satellite image of the Google Maps we can superimpose the data of a dune map from Ref.24. We see the barchan dunes crossing the San Juan–Marcona highway and their positions in 1943 and 1952. After fifty years, the dunes travelled far away from the road.

S. Parker Gay Jr. concluded the paper telling that the resurgent interest in aeolian geomorphology at the end of the twenty century had been very little directed to the coastal sand dunes of the Atacama Desert in Peru and Chile, "a region containing some of largest and most varied dune forms found any place in the world." We can found other quantitative studies of dune fields in Peru in Ref.26 and probably other references exist.

4. Peruvian barchans in Goggle Earth time series

As we can see in the satellite Google Maps, the coastal area of Peru is rich of dune fields and of isolated barchans. We have discussed in the previous section the dunes near Marcona that fifty years ago S. Parker Gay Jr. studied. Let us consider here a shorter time-lapse. And for this purpose we can use Google Earth and its time series.

An interesting location is 15°08'19.60''S, 75°15'25.63''W. In Google Earth, four images of June 10, 2009, August 23, 2009, June 10, 2011 and April 18, 2012 are available. Each image is enhanced using GIMP (the GNU Image Manipulation Program) [27], as shown in the Figure 4, and then converted in grey tones; each image is then used as a semitransparent layer, which is combined with the others to have the map of Figure 5. In this manner, a map like those of Ref.24 is obtained: instead of being a drawing, it is the superposition of real images. Using the scale on the left, we see that the barchans are moving of more than 200 meters in three years. We can clearly see that when a dune is small, it moves faster, the velocity of the dune depending on its height. Another interesting example of barchans and their motions can be obtained using the images at coordinates 15°06'48.03''S, 75°14'03.20''W. After processing, the result is shown in the Figure 6.

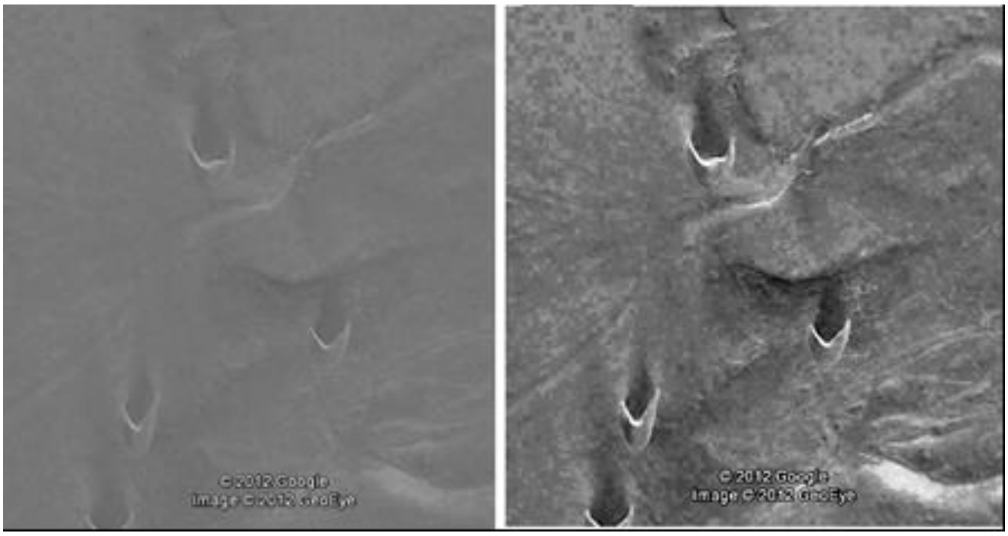

Figure 4 – Before combining the images, they need to be enhanced with GIMP. On the left the original image and on the right the image enhanced.

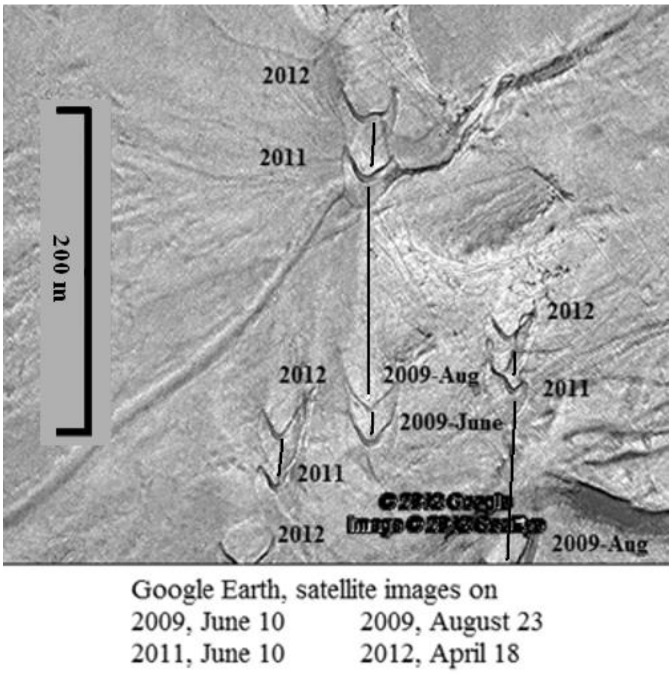

Figure 5 – The motion of the barchans is shown by the black lines connecting the positions of the dunes, each position labeled with years. The barchans move of more than 200 meters in three years.

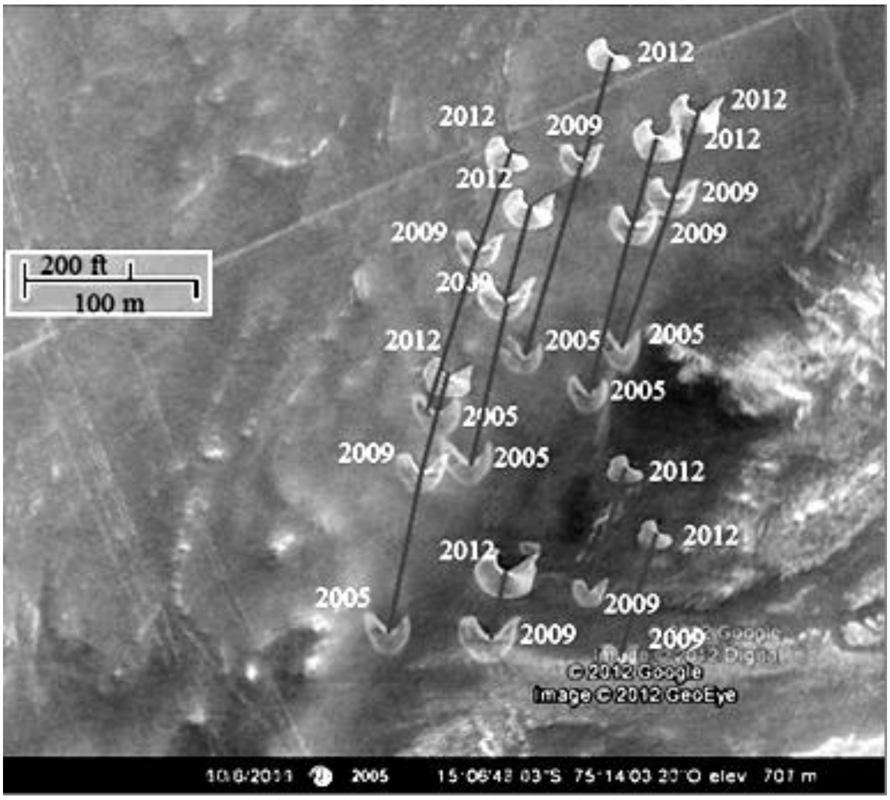

Figure 6 – Motion of barchans. The path of the dunes is given by the black lines, connecting the different positions labeled with years. Note that the small dunes move faster.

In [28], Wikipedia tells that several barchan dunes are near La Joya, Arequipa, Peru (coordinates 16.714564S, 71.834083W); “a number of dunes are readily visible from the Pan American Highway at the intersection with the Carretera Interoceanica just north of La Joya, where they can be seen passing over cement block buildings. In mid-2010, several smaller barchan dunes are approaching the Carretera from the south. These gray-colored dunes are formed from fine-grained volcanic ash from the Huaynaputina eruption in 1600."

And here we have an example of dunes moving towards human infrastructures. We can ask then how fast are moving these dunes. An answer can come from Google Earth. Let us consider the dunes at coordinates 16°40'33.28''S, 71°50'20.09W: there are five images in the time series: 4/23/2003, 6/11/2003, 2/25/2005, 11/20/2006 and 11/10/2009. Let us use two of them, those of 6/11/2003 and 11/10/2009. Then we see the motion over 6.4 years. After combining the two images we have the Figure 7. In this period, the small dunes moved of about 180 meters. The larger dune moved of about 70 meters.

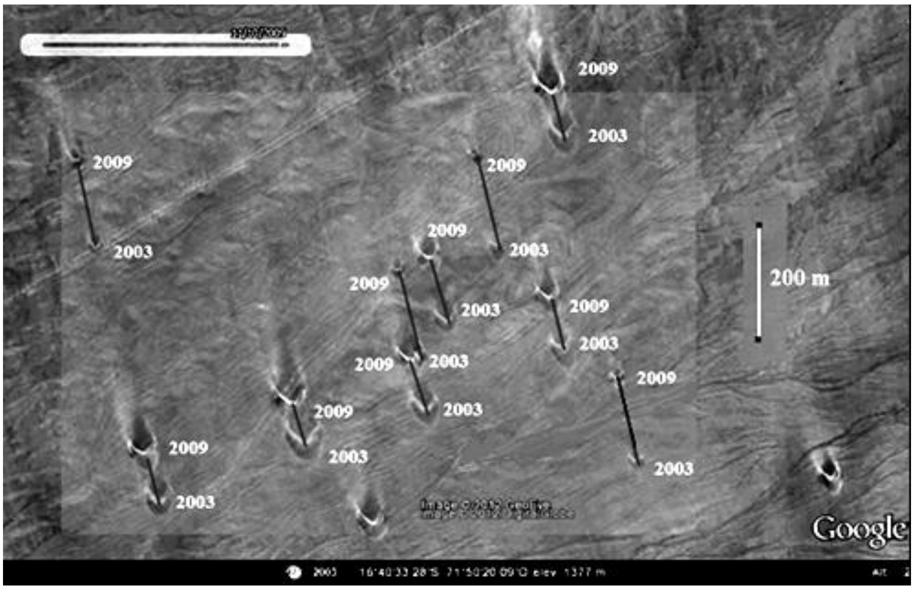

Figure 7 – Combining the images of 2003 and 2009 we can evaluate the speed of each dune.

Fig.8 - A dune at different times.

5. Analysis of a single dune and movies

In the group of the dunes shown in Figure 7, we can isolate one of the dune and analyze how its shape is changing during several years, for instance by the superposition of two images recorded at different times (see Figure 8). When we have several images in the time series we can even prepare a movie of the dune moving on the land. In fact, since, usually, there is a slight shift of the coordinates in the images of the series, one must be careful in preparing the movie, choosing a suitable reference point for all the images and adjust them correspondingly. For instance, in the Figure 8, I added two small black dots on the images to have a good superposition. Some movies are given at http://staff.polito.it/amelia.sparavigna/DUNE/ .

In the Figure 9 we can see another example of two moving dunes. One is smaller and then moves faster. The figure is obtained combining three satellite images.

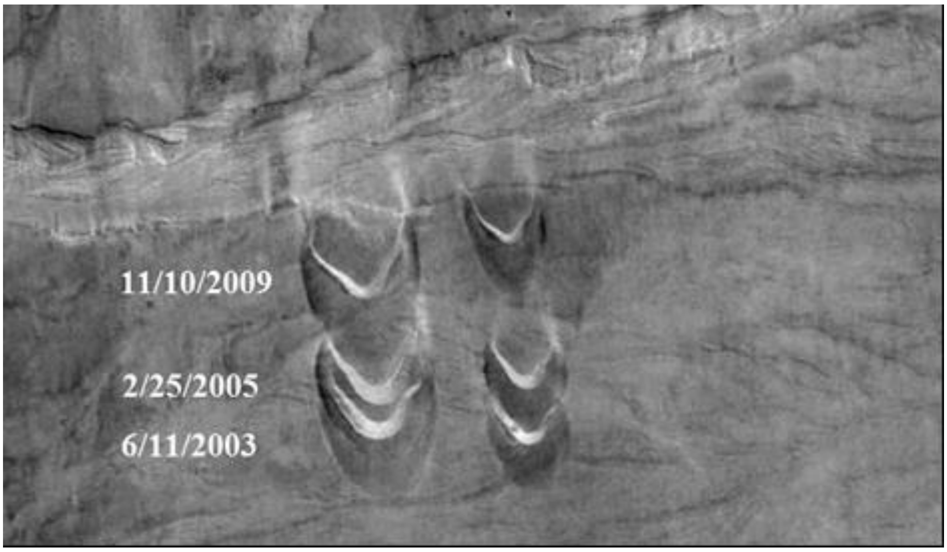

Figure 9 - Two moving dunes

To have a qualitative analysis of a single dune, or of a group of dunes, the use of a grid on the images could be interesting. For instance, if we would like to prepare a plot of the migration rate, that is the speed, of each dune with respect to its size, it would be necessary to measure distances and sizes. The distance travelled by the dune can be easily evaluated with the scales provided by Google Earth. And if we define the "size" as the surface covered by the base of the dune, we can measure it using the grid function of GIMP (an example is shown in the preprint at Ref.29). For the size then, defined as the surface occupied by the dune base, we can have a rough estimate counting the cells of the grid occupied by the dune. Of course, this is a simple approach can be improved by some image processing method, based on thresholding for instance.

6. Dune interaction

For what concerns another interesting phenomenon, the interaction among dunes, it can be easily studied using the Google Earth time series too. Here we simply show an example in the Figure 10.

Figure 10 – Interaction among dunes in the Google Earth imagery.

The discussion and analysis of data will be the subject of a future paper.

7. An example on a dune field in the Google Earth time series

In the Reference 5, the dune field near the Grand Falls has been discussed. The researchers used archival imagery and plotted the migration of the dune field from 1953 to 2010. The dominant wind direction has been from the southwest throughout the time period studied. They concluded that these dunes are migrating at a rapid rate, more than 100 m in just 5 years.

Using Google Earth, after choosing the location of the Grand Falls, we have at our disposal the satellite images corresponding to years 1992, 2007, 2010 and 2012. To evaluate the speed of the dunes, in particular of the front of the field, we have to determine it in the image. For this reason, the image is processed using GIMP [27], applying the filter for the edge detection with the Sobel method. In the following Figure 11, we see the dune field of 2007 on the left, and on the right the image after the edge detection. With Paint software, the front of the field is marked. The same is repeated for the four images of the Google Earth time series.

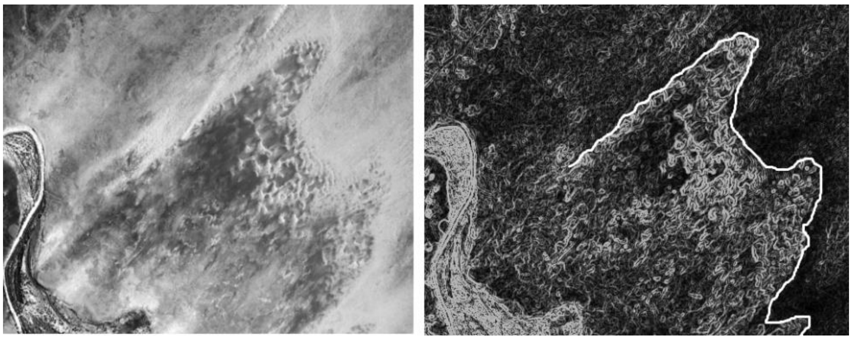

Figure 11 – On the left the field of dunes in the Google Earth images of 2007. On the right, same image after edge detection. The front is marked with a white line.

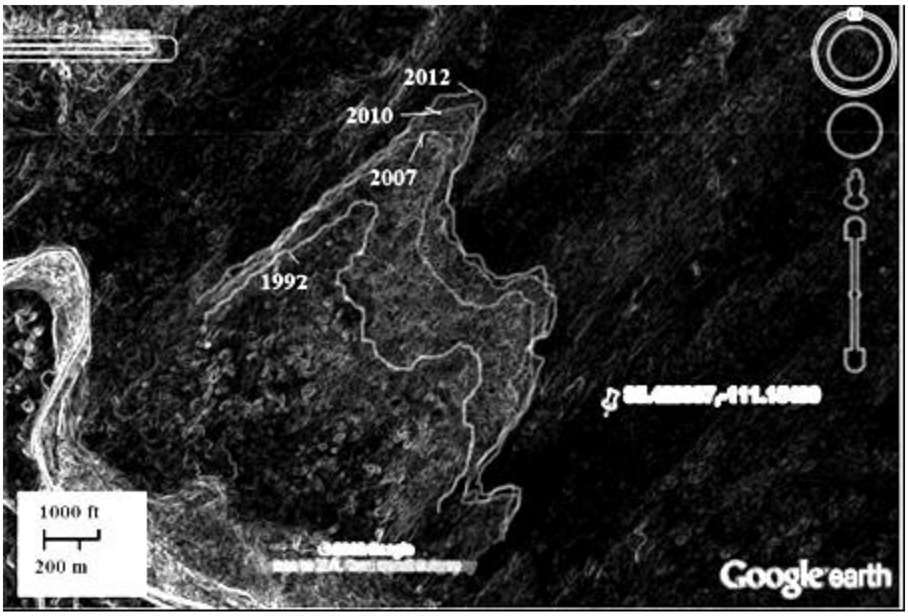

Figure 12 – Superposition of the images from Google Earth recorded at four different times (9/22/1992, 6/21/2007, 9/10/2010, 6/4/2012), after processing with GIMP. The fronts of the field of dunes are labeled with years.

In the Figure 12, we see the superposition, made using GIMP, of the four filtered image corresponding to four different years. The speed of the front is, in some parts of them, in agreement with the speed given in Ref.5.

8. Conclusions

All the examples proposed in this paper are showing how the freely available maps and time series of the Google Earth can help studying the motion of sand dunes, the evolution of their shape and the interaction among them. Another problem where the satellite images can help could be the study of the barchan dune asymmetry, in particular the comparison of satellite images of dunes with recently proposed numerical simulations [30].

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