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Remotely sensed dune celerity and sand flux measurements of the world's fastest barchans (Bodélé, Chad)

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[1] Quantifying sand flux with field measurements is an expensive and time-consuming process. We here present an alternative approach using the COSI-Corr software package for Earth surface deformation detection. Using pairs of ASTER satellite images, we detected dune migration in the Bodélé depression of northern Chad over time intervals of one month to 6.5 years. The displacement map can be used to automatically distinguish dunes from interdunes, which is a crucial step towards calculating sand flux. We interpolated a surface between the interdune areas and subtracted it from a digital elevation model, thus obtaining dune heights and volumes. Multiplying height with celerity yields a pixel-by-pixel estimate of the sand flux. We applied this method to large diatomite dunes in the Bodélé, confirming that these are some of the world's fastest moving barchans. Plotting dune height against inverse celerity reveals sand flux at the dune crest of >200 m^3/m/yr. Average dune sand flux values for the eastern and western Bodélé are 76 and 99 m^3/m/yr, respectively. The contribution of the dunes to the total area-averaged sand flux is 24–29 m^3/m/yr, which is ~10% of the saltation flux determined by previously published field measurements. **Citation:** Vermeesch, P., and N. Drake (2008), Remotely sensed dune celerity and sand flux measurements of the world's fastest barchans (Bodélé, Chad), *Geophys. Res. Lett.*, *35*, L24404, doi:10.1029/2008GL035921.

1. Introduction

[2] Measuring dune celerity and sand flux is a crucial step towards understanding aeolian systems, which represent some of the most dynamic geomorphic environments on our planet. Traditionally, such measurements have been carried out by (a) geodetic field surveys and/or long term monitoring of stakes set out in the (inter)dunes [e.g., *Stokes et al.*, 1999; *Bristow and Lancaster*, 2004], (b) short term sand trap and anemometer studies [e.g., *Greeley et al.*, 1996] or more recently (c) the use of saltation flux impact responders [*Baas*, 2004]. We here propose an approach for measuring sand flux using pairs of high resolution optical satellite images. Although remote sensing has been used to study dune migration before [e.g., *Crippen and Blom*, 1991; *Brown and Arbogast*, 1999; *Yao et al.*, 2007], our method is new in that it is fully automated and because dune celerity is combined with a digital elevation model (DEM) to determine sand flux. To detect dune migration we use the software package COSI-Corr, which stands for *Co-registration of Optically Sensed Images and Correlation* and was developed for the purpose of detecting surface deformation caused by earthquakes [*Leprince et al.*, 2007, 2008]. Because co-seismic deformation is typically on the order of centimeters to meters, their detection requires sub-pixel accuracy and precision, which can only be achieved by carefully projecting and resampling the two satellite images ('before' and 'after') onto a common reference frame. COSI-Corr currently performs this operation for SPOT, ASTER and QuickBird imagery as well as aerial photographs. ASTER is the only one of these formats that is freely available to the research community while routinely producing DEMs and these are the main reasons why we have chosen it over the higher resolution alternatives. We use pairs of the 15 meter resolution ASTER nadir near infrared band (V3N) with COSI-Corr to determine dune celerity. We employ all three 15 m visible and infrared bands (VNIR) to produce colour composites that allow us to discriminate between dunes that have different chemical compositions. Finally we employ the DEM to calculate dune volumes. ASTER's nadir-looking V3N and backward-looking V3B sensors form a stereographic pair that allows the calculation of DEMs with a spatial resolution of 30 m and a vertical precision of 13 m [*Cuartero et al.*, 2005].

[3] We have tested our approach on barchan dunes because they are better suited to this kind of study than more complex dunes as they completely overturn over relatively short time spans and often lack second order features that might otherwise 'confuse' the image correlation algorithm. We chose the Bodélé depression of northern Chad (Figure 1) as our test area for two reasons. First, the Bodélé is characterised by extremely strong north-easterly winds [*Washington et al.*, 2006] ensuring easily detectable dune migration over relatively short time spans. Second, two types of dunes exist in the area (Figure 2), making it a particularly interesting target for understanding the mechanics of dune migration. The Bodélé is a subbasin of Palaeolake Megachad [*Drake and Bristow*, 2006] and is covered by lacustrine diatomite [*Washington et al.*, 2006; *Warren et al.*, 2007]. Dunes around the edges of the depression consist mostly of quartz whereas dunes in the center also contain diatomite pellets [*Warren et al.*, 2007]. The low density of the latter further increases dune celerity and the false colour contrast between the blue dunes and the white interdunes facilitates their identification (Figures 2c and 2d). The combination of readily eroded lake sediments and strong winds make the Bodélé depression the 'dustiest place on Earth' [*Giles*, 2005] and the dune sand flux rate may well be related to the amount of dust produced [*Chappell et al.*, 2008].

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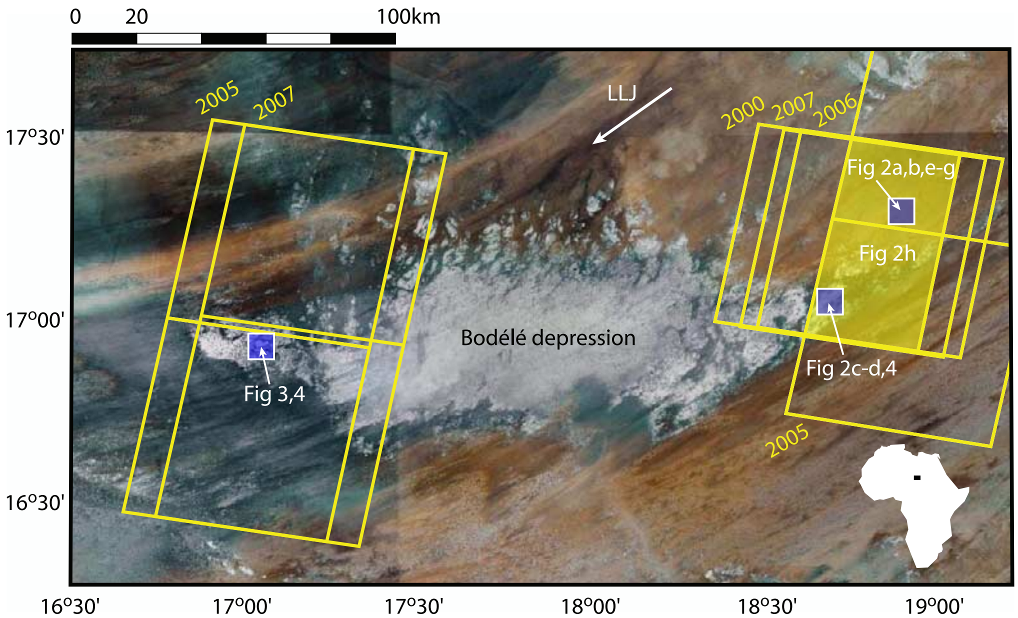

Figure 1. Landsat image of the Bodélé depression with indication of the footprints of the ASTER images used in this study. LLJ, Bodélé Low Level Jet.

[4] In the following paragraphs, we will demonstrate that COSI-Corr is very successful at orthorectifying otherwise relatively imprecise ASTER imagery; illustrate that ASTER imagery orthorectified by COSI-Corr accurately shows dune migration over relatively short timescales; explain how to automatically extract displacement maps and display them as vector fields; show how the calculations break down when the time interval between two images is too long; confirm that dune celerities are highest in winter when winds are strongest; introduce an algorithm for using the displacement field to extract a base level from ASTER-generated DEMs, which can then be used to calculate dune volumes; calculate sand flux for some very large diatomite barchans in the eastern and western Bodélé; show that the dunes move faster and have higher sand flux rates than any others that have been reported in the literature; and conclude with some proposals for future research.

2. Orthorectification, Correlation, and Dune Migration

[5] We will first consider four sets of overlapping ASTER images (using band V3N) from the eastern part of the Bodélé depression, taken in 2000, 2005, 2006 and 2007 (Figure 1 and auxiliary material[1]). Because the footprints of these images differ (causing parallax errors), and because of uncertainties in the satellite orbit and optics, it is not possible to directly compare the raw images. COSI-Corr provides a series of tools to precisely coregister and resample two images onto a common reference frame, correcting for all of the above effects. This requires the identification of a number of tie points that have not moved during the time interval between two images. In the Bodélé, such tie points are abundant in the form of patches of massive diatomite crust that can be easily identified as intricately shaped white patterns (Figures 2a and 2b). Using the 2000–2007 image pair as an example, it is possible to see, with the naked eye, how small barchan dunes move significantly faster in a southwesterly direction than larger ones do (Figures 2a–2d).

[6] After the orthorectification and resampling step, the two images are fed into the correlation engine. Using a square sliding window, COSI-Corr employs a Fourier algorithm to calculate the relative N-S and E-W displacement fields by maximising their cross-correlation [*Leprince et al.*, 2007]. We used a variable window size of 64 to 32 pixels wide with a step size of two pixels. This causes the output resolution of the displacement field to be 30 m, i.e. half of the ASTER VNIR system resolution, but identical to the DEMs generated by combining the satellite's stereographic V3N-V3B pair. This common resolution facilitates the calculation of sand flux, as discussed below. The N-S and E-W displacement maps can be visualised as a vector field or converted to a Euclidean distance map (Figure 2h). COSI-Corr successfully detects dune displacements of as little as 5 m over a period of only one month (Figure 2e). The precision of the correlation is ±3 m (1 σ), as determined from the residual displacement over stable ground. The signal-to-noise ratio (as defined by *Leprince et al.* [2007, equation (43)]) of the displacement map improves over somewhat longer time scales of 15 months (2005–2007; Figure 2f), but then decreases again for even longer time scales of 6.5 years (2000–2007; Figure 2g). The reason for this is that dune shapes and patterns change over such time scales as small dunes overtake larger ones, are shed from them or absorbed by them, thus complicating the correlation process. Two image displacement maps can be directly compared on a pixel-by-pixel basis because they are projected onto a common reference frame. This reveals that

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL035921.

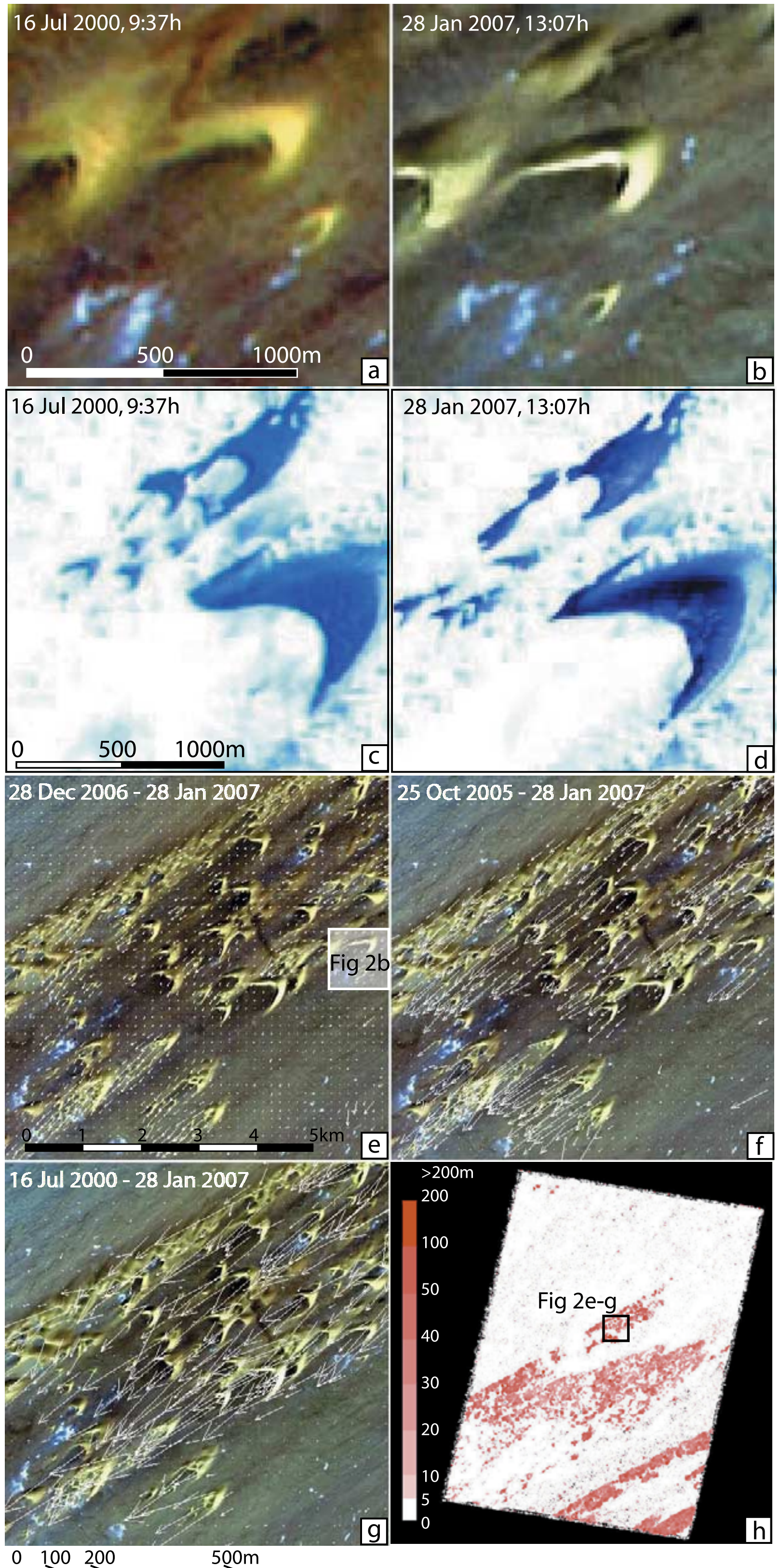

Figure 2. (a and b) Orthorectified ASTER images of quartz dunes and (c and d) diatomite dunes, taken in 2000 (Figures 2a and 2c) and 2007 (Figure 2b and 2d) in the eastern Bodélé. (e, f, and g) Displacement maps of three image pairs shown as vector fields; (h) Euclidean distance map of the 2005–2007 pair. Wind comes from the northeast.

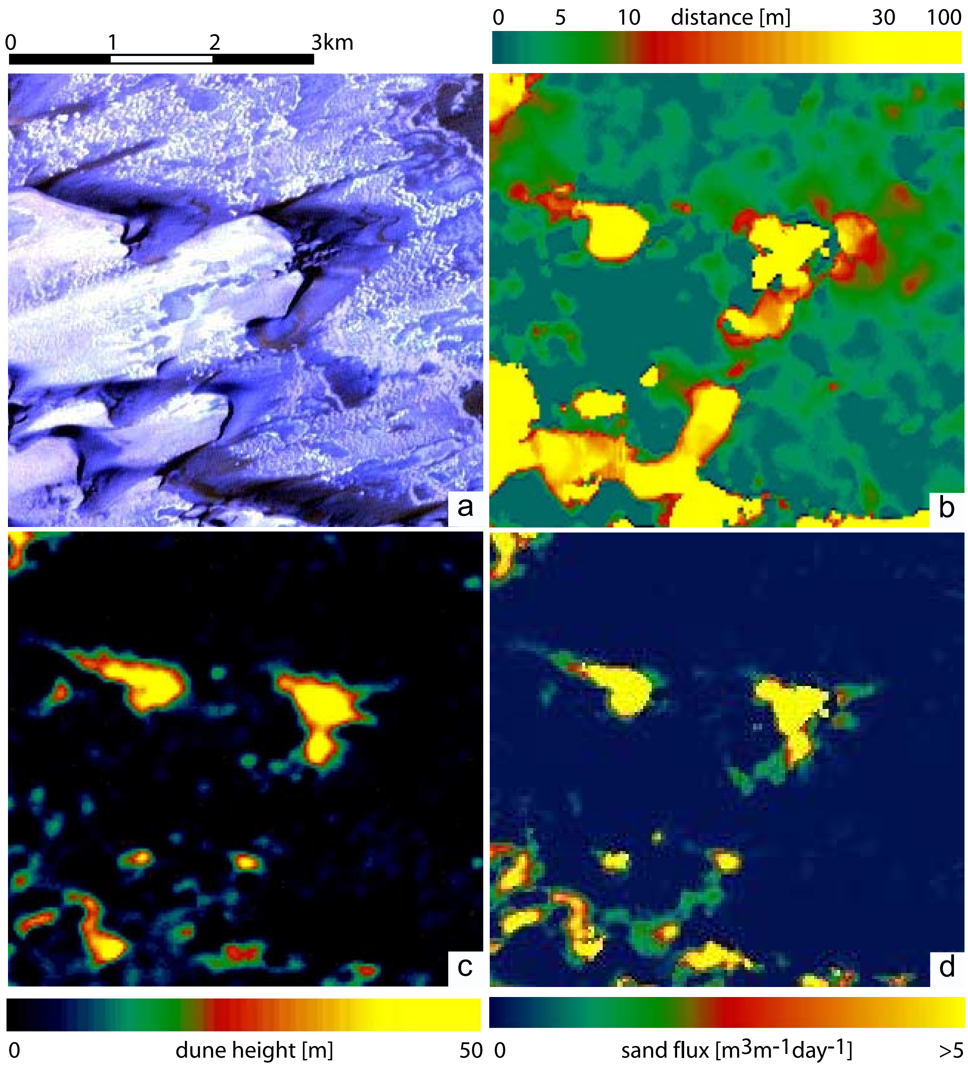

Figure 3. Sequence of operations for calculating sand flux. (a) ASTER image of a diatomite barchan field in the western Bodélé. (b) Euclidean distance map, the minimum values (<0.1 m) of which are used to define the interdune areas. (c) Dune height, calculated by subtracting the interpolated interdune surface from a digital elevation model. (d) Sand flux, calculated by multiplying Figure 3b with Figure 3c and dividing by 432 days.

dune celerities between December 2006 and January 2007 are 2.5 times faster than between October 2005 and January 2007, consistent with the higher wind speeds of the Bodélé 'Low Level Jet' during winter [*Warren et al.*, 2007].

3. Measuring Sand Flux

[7] In this section, we will study the diatomite area of the Bodélé depression, where barchans reach heights of 50 m, well above the detection limit of ASTER DEMs (Figure 3). In order to calculate dune volumes, the 'base level' must be subtracted from the raw DEM. Rather than doing this by hand, we use the displacement map by selecting all pixels with a displacement less than 0.1 m and interpolating their elevations (Figure 3b). Because the Bodélé depression is very flat, this creates a smooth and even surface. We estimated the precision of the dune elevation map as 9 m (RMSE) by measuring the difference between two different DEMs that were closely spaced in time. Sand flux is defined as the volume (or mass) of dune sand passing through a line of unit length perpendicular to the wind direction per unit time. For a sand column of width w and height h, moving over a distance d in time t, the volume is given by $h \times w \times d$, so the instantaneous sand flux equals $h \times w \times d/(w \times t) = h \times d/t$. In other words, the sand flux of any given location on a sand dune is calculated by multiplying its elevation above 'base level' with the celerity at the same location.

[8] We follow the recommendations of *Ould Ahmedou et al.* [2007] and consider a number of possible definitions for the dune sand flux. The first definition is the flux measured at the summit of a dune (Q_o), which is estimated by simply multiplying dune height with dune celerity. Although Q_o in itself is not a particularly interesting quantity, it is very useful in that it is an objective point of comparison with other dune fields. We compared the dune celerity of 75 large diatomite dunes from the eastern and western Bodélé with barchan fields in Mauritania [*Ould Ahmedou et al.*, 2007], California [*Long and Sharp*, 1964], and Saudi Arabia [*Fryberger et al.*, 1984] (Figure 4). Not only are the Bodélé

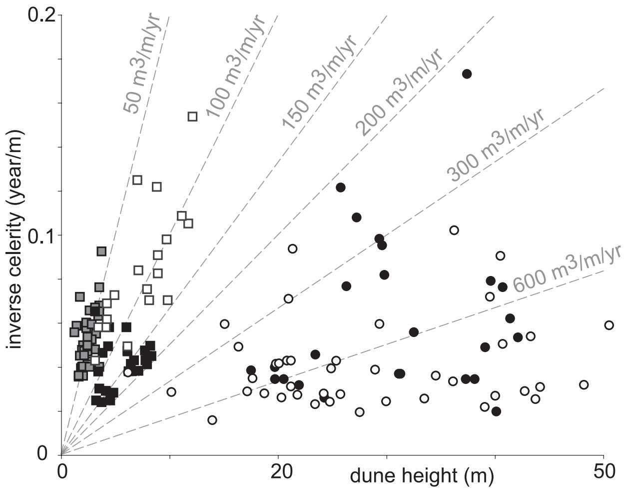

Figure 4. The ratio of dune height and inverse celerity estimates the sand flux at the dune summit and is a point of a comparison between the Bodélé dunes (circles) and barchans in other deserts (squares). Black circles, eastern Bodélé; white circles, western Bodélé; black squares, Salton Sea [*Long and Sharp*, 1964]; gray squares, Mauritania [*Ould Ahmedou et al.*, 2007]; white squares, Saudi Arabia [*Fryberger et al.*, 1984].

dunes much larger than these other active barchans, they are faster too, with $Q_o > 200$ m^3/m/yr. There appears to be no difference between the eastern and the western parts of the Bodélé, although this is hard to assess because of the significant amount of scatter in the results, which is caused by the limited precision of the DEM and by noise in the correlation results.

[9] A second and arguably more relevant definition of dune sand flux is the average flux of all the dunes in a certain area (Q_{dune}). We calculated this by selecting all the pixels above 5 meters height and averaging the corresponding sand flux values. The results are 76 and 99 m^3/m/yr for the western and eastern diatomite dune areas, respectively. To quantify the spatial variability of these estimates, we divided the dune areas into 10 equal parts and calculated the average dune sand flux for each of them. The resulting Q_{dune}-values vary from 30 to 190 m^3/m/yr, with an average and median value of 101 m^3/m/yr, a standard deviation of 50 m^3/m/yr and an interquartile range of 55–140 m^3/m/yr. This substantial scatter at least partly reflects real variations of the dune flux in different parts of the dune field. *Chappell et al.* [2008], for example, measured the total sand flux of three Bodélé dunes by a conventional sand trap and anemometer study and found a similar degree of variability both within and between the dunes.

[10] Finally, one can simply average the contribution of sand dunes to the sand flux of the entire area (dunes + interdunes), yielding the bulk transport rate (Q_{field} [*Ould Ahmedou et al.*, 2007]). We measured values of 24 and 29 m^3/m/yr for the eastern and western Bodélé, respectively. These values are, of course, strongly dependent on which area is chosen for the analysis. We did not attempt to quantify the variability of the bulk sand flux, as some of the subregions would not contain enough dunes to calculate a meaningful Q_{field}. Comparison with a similar analysis in Mauritania (2.5 m^3/m/yr [*Ould Ahmedou et al.*, 2007]) confirms that sand flux in the Bodélé is an order of magnitude higher than in other deserts.

[11] *Chappell et al.* [2008] measured integrated horizontal saltation mass flux values of between 57 and 12,500 tons/m/yr for the dunes and interdunes of the eastern Bodélé, with averages of 1350–3800 tons/m/yr. Using a bulk density for the diatomite dunes of 0.9 g/cm^3 [*Chappell et al.*, 2008] yields averaged volume fluxes of 1500–4200 m^3/m/yr. Therefore, the flux associated with dune migration is ~10% of the saltation flux, consistent with earlier experiments [*Ould Ahmedou et al.*, 2007].

4. Conclusions and Outlook

[12] COSI-Corr is an exciting new tool for the remote sensing of changes in Earth surface form. We have demonstrated the first application of this tool to aeolian geomorphology. We presented a case study of the Bodélé depression of northern Chad, successfully measuring dune celerity over a time interval of as little as one month. Most importantly, we have outlined and demonstrated, for the first time, a method for measuring sand flux from satellite images. We do this by combining the displacement map with a high resolution DEM calculated from the same set of satellite images. The displacement map is used to detect the interdune areas, which define the 'base level' that is subtracted from the topography to yield dune volumes. The advantages of this remote sensing approach over field measurements of sand flux are obvious. Remote sensing is cheaper, can be applied to larger areas and over longer time scales than field measurements, and allows us to study otherwise inaccessible places, independent of logistic or political constraints. Because of the relatively low resolution of ASTER imagery (15 m), the method currently only works for the largest barchans in our study area. Applying our algorithm to the higher resolution SPOT (2.5–5 m) and QuickBird (0.6–2.4 m) systems will significantly improve the accuracy and precision of the method and allow us, for example, to compare the sand flux of the diatomite and quartz sand dune areas within the Bodélé area. As new satellite systems come online, the possibilities will further increase, opening tremendous opportunities for aeolian research.

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