Use of Digital Terrain Models of Martian Sand Dunes to Assess Wind Flow Patterns

Paper 133-1 (#347)
Session T171

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Abstract

Digital Terrain Models (DTMs) of Martian sand dunes with one meter postings are available from stereo pairs of High Resolution Imaging Science Experiment (HiRISE) images. Several publicly released DTMs of Martian dunes are available from the HiRISE web site, but we have also produced two DTMs of small (low-relief) Martian sand dunes using SOftCopy Exploitation Tool SET (SOCET SET) software at the Astrogeology Branch of the U.S. Geological Survey at Flagstaff, Arizona. Automated feature matching is often difficult on the relatively featureless Martian dunes, but through close attention to a favorable illumination angle and to minimizing the time elapsed between the stereo images, we obtained excellent DTM data where the ripples could provide many control points on the sand dunes. The DTM data supported a quantitative assessment of the magnitude of the possible deflection of ripple orientation (with respect to the formative wind direction) when a ripple is formed on the sloping surface of a sand dune [2]. We conclude that ripple deflection on Martian dunes is minimal (<17°) for small dunes (surface slopes <10°) that lack a substantial slip face. Ripple orientation can therefore be correlated to the direction of the formative surface wind flow over shallow-sloped sand dunes, so that mapped ripple orientations can provide constraints on the most recent wind flow across Martian sand dunes. The DTMs have also been used in freeware (Wind Ninja) to investigate how dune shape may influence the local wind flow over the dunes, with the result that low-relief dunes do not appear to alter significantly the expected flow paths of the surface winds. However, dunes possessing slip faces may have both some deflection of ripple orientation and altered wind surface flow near the slip face; ripple orientation data for such dunes should only be used well removed from regions where slip faces are present. It is remarkable that HiRISE images, along with the DTMs derived from stereo pairs, allow the documentation of wind flow patterns for individual sand dunes on the surface of another planet.

Introduction

Ripple orientations have been documented using High Resolution Imaging Science Experiment (HiRISE) images of sand dunes at widely distributed sites across Mars, in order to identify the most recent wind directions at these locations [1]. Before attempting to interpret the ripple orientation data, it was important to assess how well the observed ripple patterns correlate with the most recent sand-moving wind at the studied locations on Mars. Howard [2] derived an expression for how surface slopes on a sand dune can deflect ripple orientation with respect to the formative wind direction. We applied Howard's equation to measured ripple orientations on sand dunes in Lopez crater (Fig. 1), where we had generated a Digital Terrain Model (DTM) using stereo HiRISE images [3]. We had also previously generated a DTM of sand dunes within Sitrah crater [4]. These DTMs of Martian sand dunes were sufficiently detailed that we wanted to explore how the DTMs could be used to assess the effect of dune shape on wind flow across the dunes. At the 2014 Fall AGU conference, the freeware "Wind Ninja" was used to evaluate the wind patterns associated with sand dunes on Earth and Titan [5], which led us to explore applying Wind Ninja to DTMs of sand dunes on Mars.

Methodology

A DTM of sand dunes on the floor of Lopez crater (14.55°S, 97.77°E) in Tyrrhena Terra was produced using SOftCopy Exploitation Tool SET (SOCET SET) at the Astrogeology Branch, U.S. Geological Survey, Flagstaff, Arizona (Figs. 1 and 2). Stereo HiRISE images ESP_026609_1655 and ESP_026675-1655 were obtained only six Earth days apart under excellent illumination conditions, which greatly facilitated automated feature matching. A slope map was derived from the DTM (Fig. 3), from which the direction and magnitude of the local slope was obtained for locations where ripple orientation was documented. These data provide the input needed for Howard's equation [2], which then provides a quantitative evaluation of the magnitude and orientation of ripple deflection from the formative wind direction, resulting from the slope of the dune surface altering the vector relationships between gravity and the force of the wind (see Figs. 4 and 5). A DTM of sand dunes on the floor of Sitrah crater (59.1°S, 218.0°E) in Terra Sirenum was also produced using SOCET SET on HiRISE stereo images ESP_023928_1205 and ESP_024060_1205 (Fig. 6). Both DTMs have 1 meter postings, resulting in remarkably detailed topographic data about the sand dunes on Mars. Such DTM information provides the opportunity for a quantitative evaluation of how the wind blowing above Martian sand dunes may be affected by the shapes of the sand dunes (see next section).

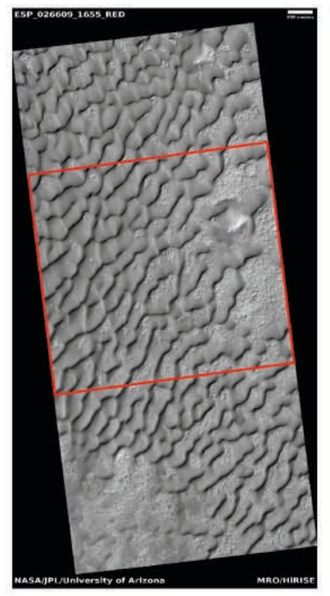

Figure 1. Browse version of HiRISE image ESP_026609_1655 showing a portion of the dune field on the floor of Lopez crater. The red box indicates the area over which a Digital Terrain Model (DTM) was generated (equivalent to the area shown in Figs. 2 and 3). This image makes a stereo pair with HiRISE image ESP_026675_1655. Both images have 25 cm/p spatial resolution of the Martian surface.

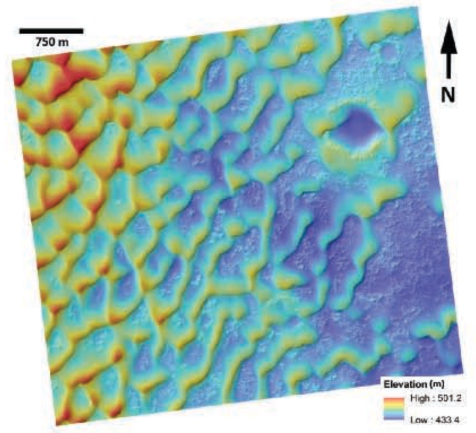

Figure 2. DTM derived from a portion of a HiRISE stereo pair (see Fig. 1). The floor of the crater rises to the west at this location, but the relief of individual sand dunes is relatively constant across the area shown. The DTM was produced using SOCET SET software at the Astrogeology Branch of the USGS-Flagstaff. Slip faces are present on many dunes, and in general the dunes have vertical relief of about 20 meters.

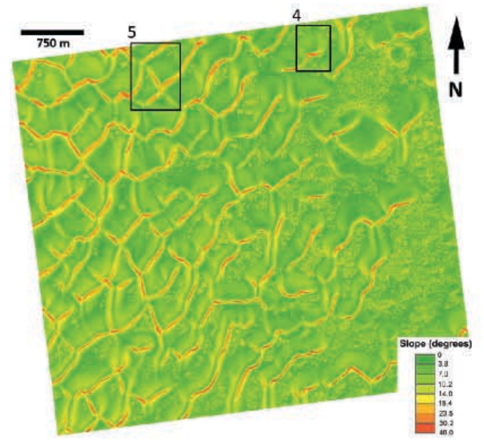

Figure 3. Slope map derived from the DTM shown in Fig. 2. The relatively constant east-dipping floor of the crater across the entire scene has virtually no effect on individual dune slopes. Steep areas on the dunes correspond to slip faces, whether or not they cast shadows in the images (which is due to the orientation of solar insolation with respect to slip face orientation). Boxes show the locations of Figs. 4 and 5.

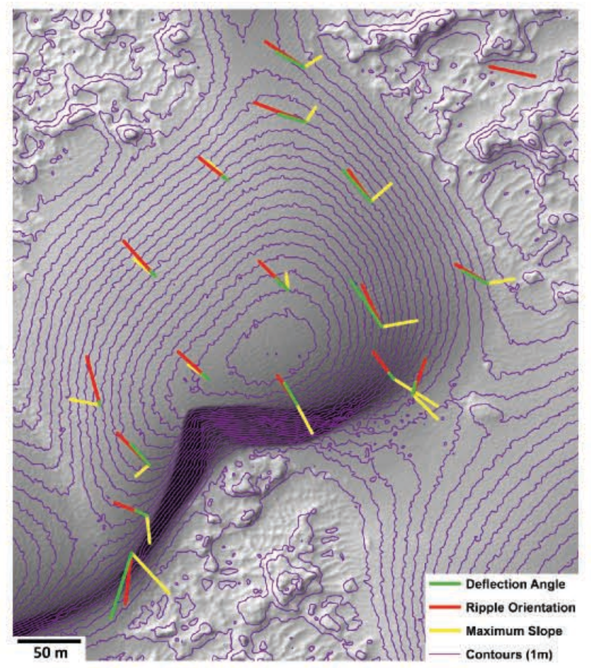

Figure 4. Wind ripple patterns on a dune near the eastern margin of the Lopez dune field [3] (see Fig. 3 for location). Red lines: measured orientation perpendicular to ripple crests; line length is scaled to 10X the ripple wavelength (at image scale). Yellow lines: direction of steepest local gradient; line length is scaled to 5X the surface slope (in degrees, at image scale). Green lines: calculated direction of surface wind after including the slope-induced deflection [2]; line length is scaled to 5X the deflection angle (in degrees, at image scale). Purple lines: 1 m topographic contours.

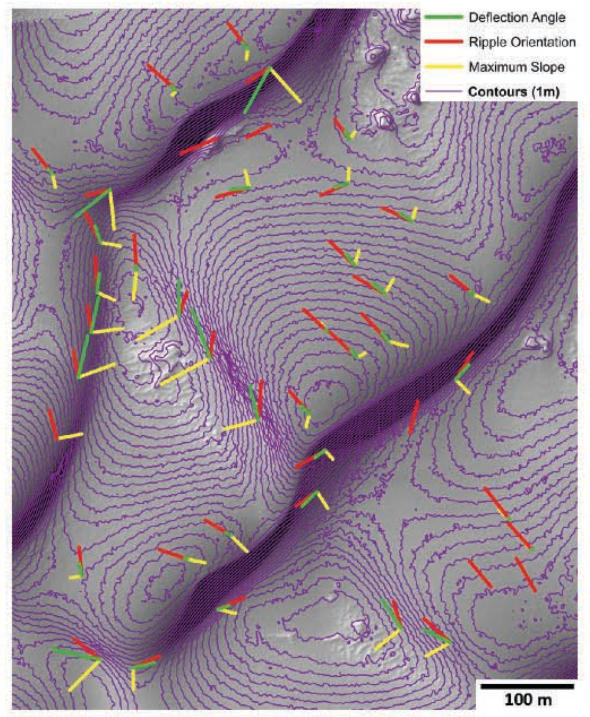

Figure 5. Wind ripple patterns on a dune near the eastern margin of the Lopez dune field (see Figs. 1 and 3). Line color scheme is the same as that used in Fig. 4, except that yellow line length is scaled here to 3X the slope (in degrees), and green line length is scaled here to 2X the deflection angle (in degrees).

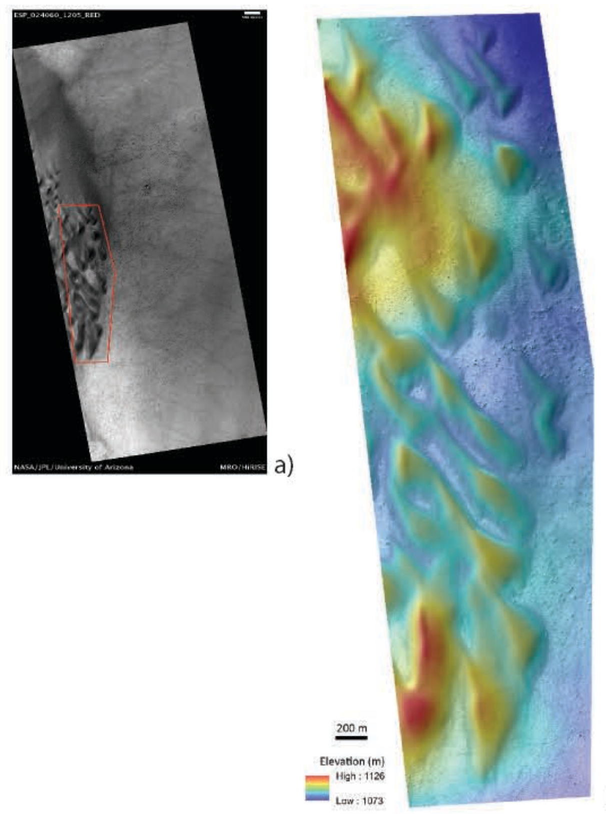

Figure 6. DTM of sand dunes on the floor of Sitrah crater. a) Browse version of HiRISE image ESP_023928_1205, with red box showing the location of the DTM. b) DTM of sand dunes in Sitrah crater. Slip faces are not present on these dunes, and the dunes have vertical relief of about 10 to 15 meters.

Wind Flow Patterns

"Wind Ninja" [6] is free computational fluid dynamic (CFD) software for predicting surface winds over DTM data, developed for use by fire fighters, but which has proven to be very useful for evaluating wind flow patterns for sand dunes on both Earth and Titan [5]. We used publicly released HiRISE DTM data for large to medium-scale sand dunes in order to evaluate how well Wind Ninja might work with DTMs of Mars. Portions of DTMs of sand dunes on the floors of Kaiser crater (DTEED_016907_1330_016973_1330; 46.74°S, 20.14°E; Fig. 7) and Wirtz crater (DTEEC_021893_1315_021603_1315; 48.24°S, 334.68°E; Fig. 9) were used in Wind Ninja for 20 mph wind blowing from the east (Fig. 8) and west (Fig. 10), respectively.

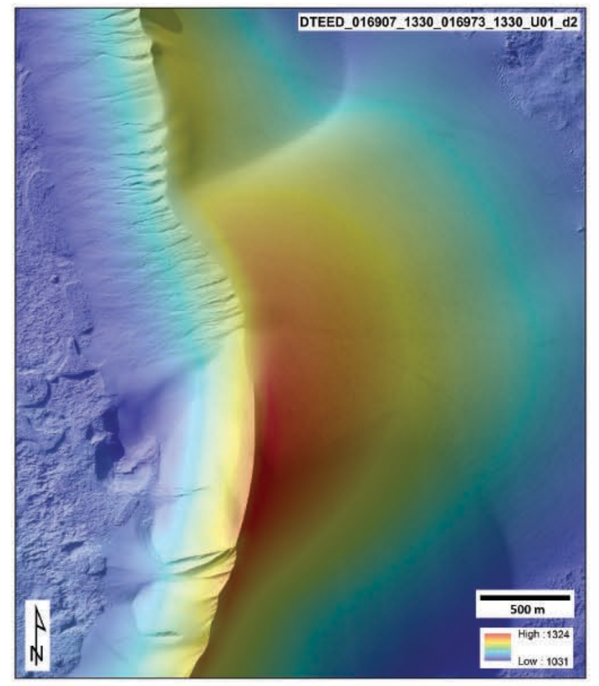

Figure 7. Portion of DTM covering one large sand dune within HiRISE DTM DTEED_016907_1330_016973_1330_U01. The large dune has vertical relief of almost 300 meters.

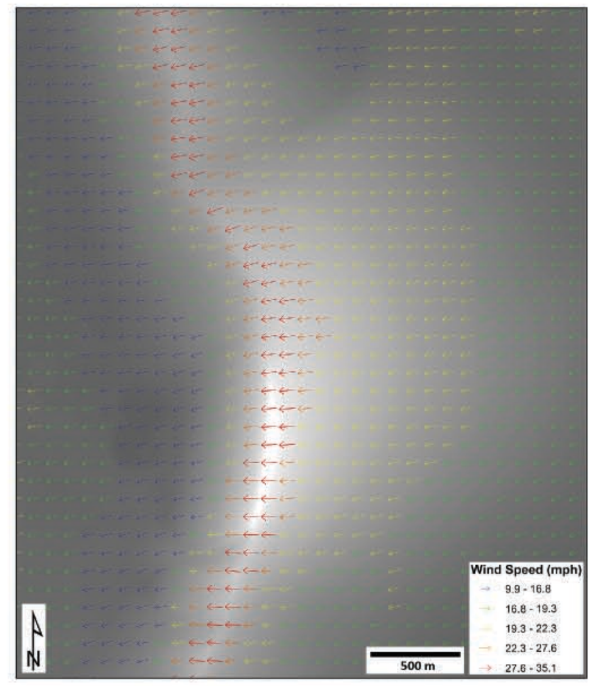

Figure 8. Wind Ninja flow patterns formed by a 20 mph wind from the east moving over the DTM shown in Fig. 7. Little deflection of wind direction is caused by these large dunes, but the wind speed increases moving up the stoss side and then decreases moving down the lee side.

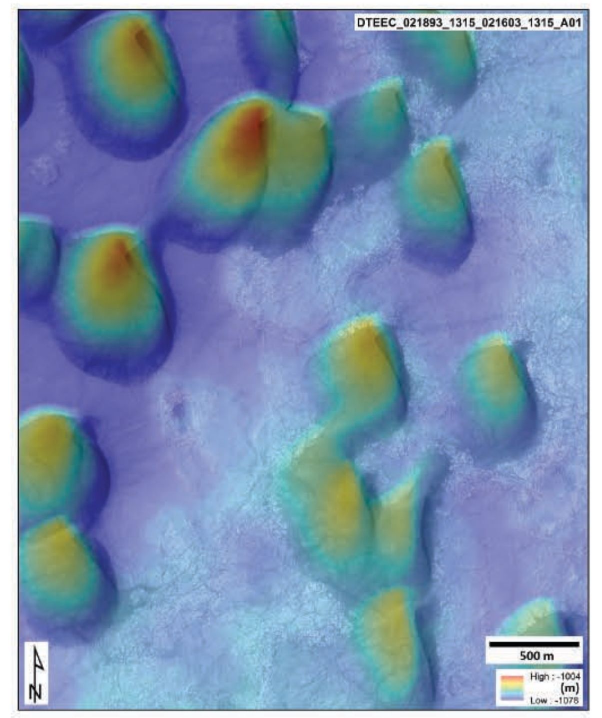

Figure 9. Portion of DTM that includes several sand dunes within the HiRISE DTM DTEEC_021893_1315_021603_1315_A01. Individual dunes have vertical relief of 20 to 25 meters.

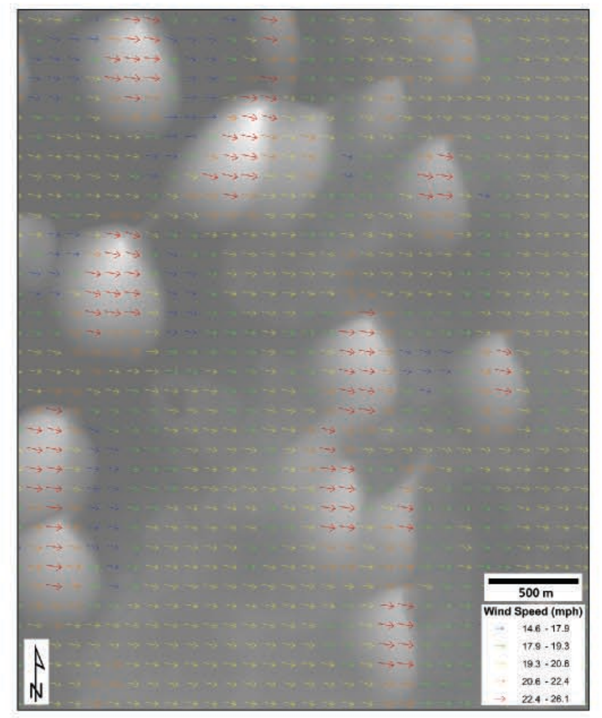

Figure 10. Wind Ninja flow patterns formed by a 20 mph wind from the west moving over the DTM shown in Fig. 9. Little deflection of wind direction is produced by the dunes, but the wind speed increases moving up the stoss side and then decreases moving down the lee side, as was observed for a dune with >10X the vertical relief on the dunes in the DTM in Fig. 9.

Results

The slope map (Fig. 3) showed that 34% of the Lopez DTM has slopes of 0° to 5°, 41% has slopes of 5° to 10°, 21% has slopes of 10° to 20°, and only 4% has slopes >20° (all associated with slip faces). Two areas (boxes in Fig. 3) were examined in detail to calculate deflection angles (Figs. 4 and 5), but these results should be applicable across the entire Lopez dune field. For a dune with slopes <6° over the surface (excluding near a slip face), deflection angles are <5° (Fig. 4), illustrated by the close correspondence of red lines (measured ripple orientation) with green lines (calculated deflection angle and direction), even where the maximum slope direction (yellow lines) is at a large angle with respect to the ripple orientation. For dunes with slopes up to 10°, maximum deflection angles are <17° (Fig. 5). We therefore are confident that mapped ripple orientations do provide insight into recent surface wind flow, as long as slip faces are avoided [1, 7]. The Wind Ninja results show that the dunes do not alter the wind flow direction very much, but wind speed increases going up the dune and then decreases going down the dune (Figs. 8 and 10), a demonstration of the Bernoulli principle in action.

Discussion

Results for the magnitude of predicted deflection of ripples [2] applied to the Lopez crater sand dunes support the premise that ripples on sand dune surfaces are useful indicators of recent wind patterns. DTMs can reveal the presence of some slip faces that may not be readily apparent in the images. The Wind Ninja results are encouraging from the standpoint that DTMs of sand dunes on Mars seem to be more than adequate to allow CFD calculations to predict how surface winds move over the dunes. It is not clear how well the differences in atmospheric density between Earth and Mars will affect the details of CFD calculations, but we hope to explore the implications of questions such as this in the future, perhaps including the use of robust CFD software packages (e.g., OpenFOAM [8]).

Conclusions

- Three-quarters of the area covered by sand dunes within Lopez crater have surface slopes <10°, where ripple deflection angles should be <17°.
- Therefore, ripples are good indicators of the most recent surface wind over dunes on Mars, as long as areas either on or near slip faces are avoided.
- DTMs of sand dunes on Mars hold great potential for CFD calculations of surface wind patterns on and around sand dunes.

Acknowledgement: This work was supported by NASA MDAP grant NNX12AJ38G.

References: [1] Johnson M. B. and Zimbelman J. R. (2015) Lunar Planet. Sci. 46, Abstract 1539. [2] Howard A. D. (1987) Geol. Soc. Am. Bull., 88, 853-856. [3] Zimbelman J. R. and Johnson M. B. (2015) Lunar Planet. Sci. 46, Abstract 1478. [4] Johnson M. B. and Zimbelman J. R. (2014) Geol. Soc. Am. Abs. Prog., Abstract 244691 (session 329-11). [5] Cisneros J. et al. (2014) Am. Geophys. Union Fall mtg, Abstract EP43B-3570. [6] http://www.firelab.org/document/windninja-software. [7] Liu Z. Y.-C. and Zimbelman J. R. (2015) Icarus, 261, 169-181. [8] Smyth T. A. G. et al. (2012) Geomorph., 177-178, 62-73 (use of OpenFOAM software to study sand dunes).