SURFACE-BASED 3D MEASUREMENTS OF AEOLIAN BEDFORMS ON MARS AND THEIR APPLICATION TO ESTIMATING EXOMARS ROVER SURFACE HAZARD M.R. Balme[1], E. Robson[2], R. Barnes[3], B. Huber[4], F.E.G. Butcher[1], P. Fawdon[5], S. Gupta[3], G. Paar[4],. [1]School of Physical Sciences, Open University, UK (matt.balme@open.ac.uk), [2]University of Birmingham, UK, [3]Imperial College London, UK, [4]Joanneum Research, Austria, [5]Birkbeck, University of London, UK.

Introduction: The surface of Mars hosts many different types of aeolian bedforms, from small wind-ripples with cm-scale wavelength (e.g. [1,2]), through decameter-scale "Transverse Aeolian Ridges" (TARs; e.g. [3.4]) to km-scale dunes (e.g. [5,6]). To date, all mobile Mars surface-missions ('Rovers') have encountered aeolian bedforms of one kind or another.

Aeolian deposits of loose, unconsolidated material provide hazards to Rovers: sinkage into the aeolian material and enhanced slippage can prevent traction and forward progress, forcing the Rover to backtrack (e.g., MER Opportunity, [7]) and can even 'trap' the rover ending the mission (e.g., MER Spirit, [8]).

The 2020 ESA/RosCosmos ExoMars Rover [9] includes a drill capable of sampling from depths of ~ 2m beneath the martian surface, and has the explicit goal of looking for signs of past life. Drilling on a planetary surface is difficult, time-consuming and not without risk. Selecting optimum drill sites, and being able to reach them, is vital. This makes orbital characterization of hazards – including aeolian bedforms – essential.

Here, we present morphometry measurements of meter-scale ripple-like bedforms on Mars, as observed by the MER Opportunity Rover [10] during its traverse across the Meridiani Planum region of Mars. The aim is to assess whether there is a relationship between bedforms parameters that can be measured from orbit such as length and width, and bedform height, which can only be reliably measured for larger features such as TARs. If such a relationship can be found, it might allow estimates of ripple-height to be made from remote sensing data alone, and hence a better characterization of the hazard presented by these features.

Method: At the time of writing, the MER Opportunity Rover was still functioning on the surface of Mars, having travelled > 43 km, and been active for more than 4465 sols ('sol' = martian day). For much of the first 30 km of the traverse, the Rover travelled across flat plains with meter-scale, ripple-like aeolian bedforms superposed upon them. During the traverse, the Rover acquired stereo imaging data of its surroundings using both its scientific Pancam cameras system and the navigational Navcam system. Using these data, and newly developed Pro3D™ [11] and PRoViP [12] software, we obtained Digital Elevation Models of many areas of the surface at sufficiently high resolution (< tens of cm point spacing) to measure the heights and lengths of aeolian bedforms. Note that by 'length' we mean the distance across the bedform, perpendicular to the ridge crest. This can be confusing, as in many cases a bedform's 'width' is greater than its length.

We used data from sols 550 to 2658 of the mission, allowing 119 bedforms to be measured. Five measurements were performed for each bedform, allowing an estimate of the measurement error. By measuring to either side of the bedform, the effects of a sloping substrate were accounted for. In addition, the same bedforms were digitized from orbital HiRISE [13] image data (25 cm/pix resolution) in ArcGIS software to check for agreement between the ground-based and space-based measurements.

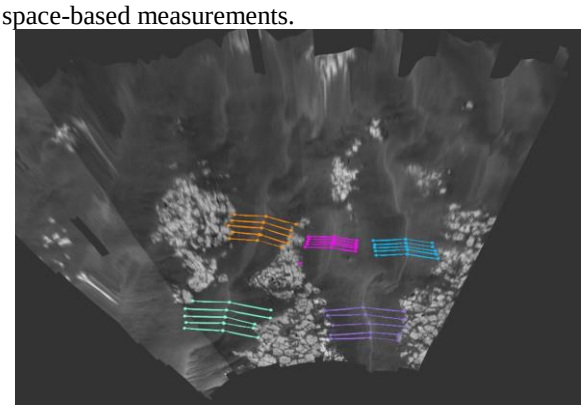

Fig.1. Example measurements of bedforms in PRo3D. Note how DEM/image quality degrades into the scene.

Results: Fig. 2 shows the mean height H of the measured bedforms plotted as a function of their mean length L. The vertical error bars show the standard deviation on the height, based on five measurements per bedform, but horizontal error bars are not shown, being rather small. A simple, unweighted linear regression is provided, together with 95% prediction limits for the data, based on that regression. There is a clear correlation between bedform length and bedform height, with the prediction limit providing a range of predicted heights based on measured lengths. There was no significant difference in the trend for bedforms of different morphology or saturation level. The length measurements made 'from the ground' generally have excellent agreement with the same measurements made using HiRISE orbital data. This suggests that bedform length measured from orbit can, with some assumptions, be used to infer bedform height.

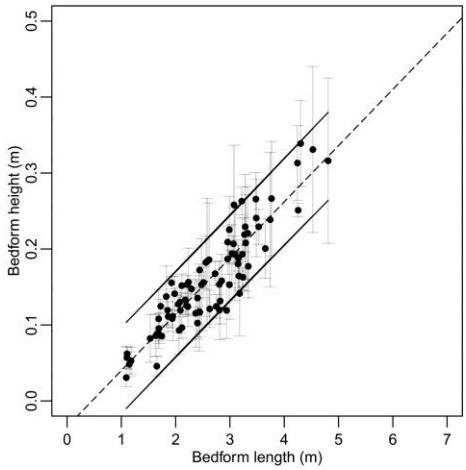

Fig. 2. Pro3D data of bedform height and length as measured from MER Opportunity data.

Discussion: The data collected match well with trends seen in terrestrial length-height relationships for aeolian megaripples. For example, our data have a ripple index (ripple index = wavelength/height or length/height) of ~ 15, the same as megaripples on Earth, suggesting they form in a similar way (e.g. [14]).

These data provide a way of estimating whether the fields of aeolian bedforms observed at the proposed ExoMars Rover landing sites are traversable or not. If ground-based testing of Rover bedform traversability can define a safe maximum bedform height, then this can be converted into an equivalent martian bedform length by comparison with Fig. 2.

For example, if the maximum ripple height the Rover can cross safely is 15 cm, then, from Fig. 2, the average ripple length that matches this height is ~2.5 m. This means that, assuming the bedforms at a given site are of a similar shape population to those seen in the MER Opportunity traverse, a bedform recorded from orbit as having 2.5 m length has a 50% change of being uncrossable. Similarly, a bedform of about 3 m length has a 95% chance of being uncrossable, but a bedform of ~1.75 m length will have a 95% chance of being traversable by the Rover.

To illustration this approach, we measured bedform lengths at five sites in the proposed Oxia Planum ExoMars site, which contains extensive fields of small aeolian features (Fig. 3a). We measured mean lengths of 2-3 m for ripple-like bedforms (Fig. 3b), and slightly higher lengths for TAR-like features (site 1 only). If the Rover bedform height traversability threshold was 15 cm, then, from Fig. 2, the average bedform in these sites would have a ~50% chance of being too high for the Rover to cross. On the other hand, if the threshold height was 25 cm, then (from Fig. 2), most of the bedforms here would probably be traversable.

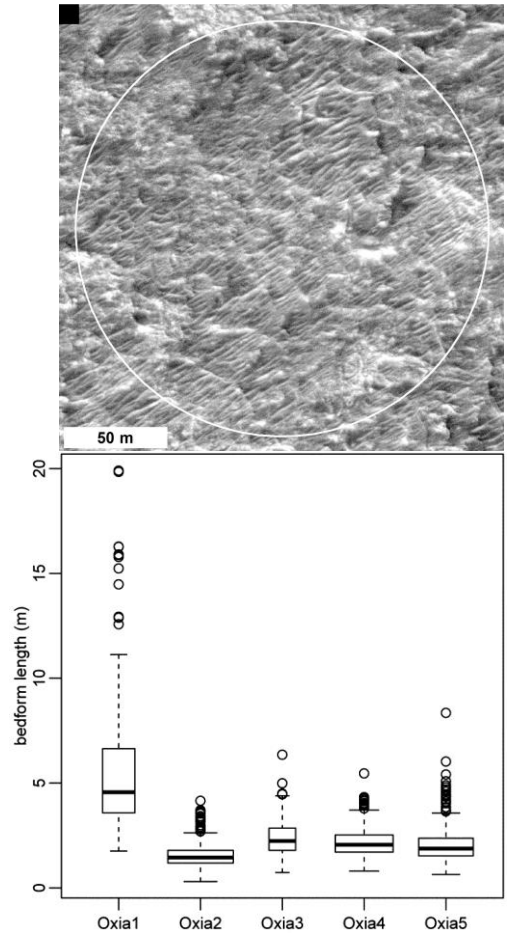

Fig. 3a. Ripple-like bedforms in Oxia Planum – white circle shows 100 m radius example study area. 3b distribution of bedform length across 5 study areas.

Conclusion: Rover-based stereo imaging can be used to measure aeolian bedform height to gain insight into their formation mechanisms. With enough data, correlations of bedform length and height can allow orbital data to be used to determine traversability of proposed Rover landing sites. Lab/field studies of Rover bedform traversability are also needed.

References: [1] Sharp, R. & Malin, M. (1984) *GSA Bull.* 95, 12, 1398-1412 [2] Sullivan, R. et al. (2005) *Nature* 436, 58-61. [3] Balme, M. et al. (2008) *Geomorphology* 101, 4, 703-720 [4] Berman, D. et al. (2011) *Icarus* 213, 116-130 [5] Cutts, J. & Smith, R. (1973) *JGR* 78, 4139-54 [6] Hayward R. et al. (2007) *JGR* 112, E11007 [7] Arvidson, R. et al. (2011) *JGR* 116, E7 [8] Arvidson, R. et al. (2010) *JGR* 115, E7 [9] Vago, J. et al. (2015) *Sol. Sys. Res.* 49, 7, 518-528 [10] Squyres, S. et al. (2004) *Science* 306, 1698-1703 [11] Barnes R., et al. (2015) *GSA Abstracts* 47, Abstr.#35-17 [12] Paar, G. et al. (2015) *EPSC* Abstr.#2015-345 [13] McEwen, A. et al (2007), *JGR* 112, E05S02 [14] Zimbelman, J. et al., (2012) *ESPL* 37, 10, 1120-25.