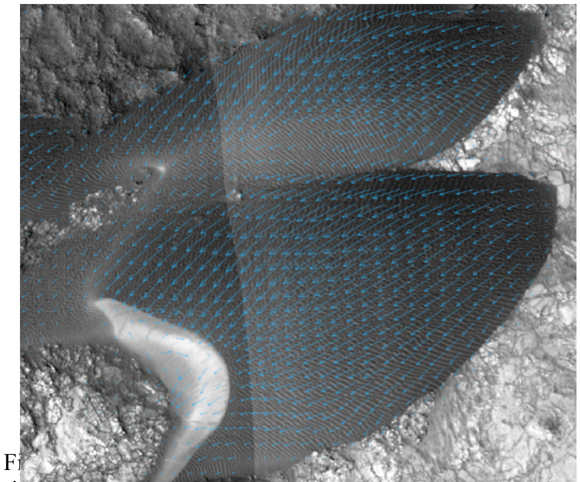
Understanding ripple and whole-dune motion at active Martian dune fields. K. P. Roback[1], K. D. Runyon[2], J. P. Avouac[1], C. E. Newman[3] and F. Ayoub[4] [1]California Institute of Technology, Pasadena, CA, USA (kroback@caltech.edu), [2]Johns Hopkins APL, Laurel, MD, USA, [3]Aeolis Research, Pasadena, CA [4]Jet Propulsion Laboratory, Pasadena, CA, USA.

Introduction: Recent observations of Martian dune fields by the Mars Reconnaissance Orbiter's HiRISE camera have documented the existence and present-day movement of meter-scale ripples on sand dunes and sheets [1, 2, 3, 4, 5]. Measurements of whole-dune sand flux have been made [2, 4, 5, 6], but this motion has been difficult to constrain due to the slow rate of sand dunes. Since these earlier studies, the length of timeseries of imagery collected at some Martian dune fields has increased to over 10 Earth years. We apply long timeseries imagery at three Martian dune fields (Nili Patera, Meroe Patera, and Gale Crater's Bagnold Dunes) to study annual and interannual variability in sand flux, and compare sand fluxes associated with ripples to sand fluxes associated with movement of entire dunes. We further use patterns of annual variability in sand fluxes to reveal seasonal wind trends and to calculate effective shear stress thresholds for sand motion initiation.

Methods: To measure sand fluxes associated with ripple movement, pairs of raw HiRISE images were orthorectified and correlated using digital elevation models (DEMs) and the COSI-Corr software package [7]. COSI-Corr measures displacements of patterns within images using statistical techniques; for ripples, the favored technique uses the Pearson statistical correlation coefficient to match a patch of an image with its closest match out of all possible candidate patches in the second image; the code outputs a displacement map showing the distance between the correlated patches.

PCA (principal component analysis) and ICA (independent component analysis) techniques filter out apparent but false displacements (e. g., of immobile bedrock) in the correlation maps arising from spacecraft jitter, HiRISE viewing geometry, and other sources of error.

Measurement of whole-dune speed was completed by manually tracking changes in position of dune crestlines and slipfaces in orthorectified HiRISE imagery and dividing the displacement by the time between images. Whole-dune sand fluxes were derived from estimates of dune height extracted by multiplying dune speeds by their heights estimated from HiRISE DEMs; heights of sand-free bedrock were extracted and extrapolated under sand-covered areas, to estimate the height of the bedrock surface and thus the dune height for various dunes in the dune field. Lastly, we plan to calculate effective shear stress thresholds for sand motion from our ripple-flux results and MarsWRF GCM outputs, applying the methodology of [8] to correct GCM outputs for boundary-layer turbulence and gustiness not resolved by these models.



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rived from COSI-Corr analysis, shown here as a vector field, on a barchan dune in the Nili Patera dune field.

Results: Plots of our full timeseries of ripple-based sand flux measurements at Nili Patera, Meroe Patera, and Gale Crater are given in Fig. 1. In all of our sites, whole-dune-averaged fluxes exceed ripple fluxes by a factor of 6 or higher, with Nili Patera exhibiting whole dune fluxes of ~ 6 m^2/m/Earth yr, and Meroe Patera exhibiting dune crest fluxes in excess of 10 m^2/m/Earth yr. Ripple fluxes averaged over a Martian year at our sites are less than 1 m^2/m/Earth yr. Notably, the overall magnitude of ripple flux and seasonal variation are consistent from year to year at Nili Patera, our site with the longest available timeseries of imagery, and highest temporal resolution of sand flux measurements. Gale Crater shows extremely low fluxes with dune fluxes less than ripple fluxes measured at other sites, and more inconsistency in yearly-averaged sand fluxes relative to Nili Patera.

At Meroe and Nili Pateras, we observe a seasonal maximum in the sand flux around a solar longitude of ~240 degrees, corresponding to northern hemisphere autumn/winter. At Nili Patera, high sand fluxes during this period lead to decorrelation of ripple patterns and prevent measurement of ripple fluxes. At Gale Crater, large time spans between image pairs generally prevent characterization of seasonal flux variation in most Mars years; ripple fluxes are also observed to be relatively variable year-to-year.

Discussion: The meaning of the large variation between our ripple-based and whole-dune-based measurements of sand flux is debatable, given recent developments in the study of Martian ripples. Initially, the meter-scale-ripples were assumed to be impact ripples, and their flux representative of the flux of reptons, a low-energy population of grains ballistically (as opposed to fluid-mechanically) moved by the impacts of higher-energy saltons [2].

However, recent work [6, 7] has suggested an alternate dynamical origin on the basis of rover observations of the ripples motivated from the coexistence of two distinct populations of meter and decimeter-scale ripples [9]. It is suggested that the meter-scale ripples are wind-drag ripples, which form from winds generating shear stresses similar to the magnitude of the "impact threshold" shear stress, rather than the higher fluid threshold. The meter-scale ripples are inferred to be formed in a sand transport regime dominated by low-energy, near-bed movement of particles. The decimeter-scale ripples are thought to occur from reptons mobilized by saltons in the same manner as terrestrial decimeter-scale ripples.

If this dynamical interpretation of ripple motion is correct, it makes the physical meaning of the variation in flux between ripples and dunes less clear. The flux variation may represent a partitioning between lower-energy and higher-energy sand transport, analogous to the reptating/saltating populations reflected by earlier interpretations of the flux differences. Higher dune fluxes relative to ripple fluxes could indicate more long-hop saltation, and perhaps stronger winds. Bimodal densities and/or grain sizes in the sand population could play a role [11]. However, a major limitation of these measurements is the possibility and unknown magnitude of sand transport parallel to ripple crests; differences in along-crest transport from region to region, related to variation in direction of sand-transporting winds, could contribute to apparent variations in ripple flux between regions.

The increased ripple flux in northern-hemisphere autumn and winter suggests increased winds at a variety of northern-hemisphere sites during this season. This pattern of variation is in broad agreement with GCM-predicted winds at Nili Patera, but is not in good agreement with model predictions at Meroe Patera. The far lower sand fluxes observed at Gale Crater imply less windy conditions there relative to our other studied sites. Further study of seasonal variations in ripple flux at more locations can help to validate predictions of winds by Martian GCMs.

[1] S. Silvestro et al. (2010) *GRL, 37,* doi: 10.1029/2010GL044743. [2] N. T. Bridges et al. (2012) *Nature, 485,* 339-342. [3] F. Ayoub et al. (2014) *Nat. Comms., 5,* doi: 10.1038/ncomms6096. [4] K. Runyon et al. (2017) *EPSL*, *457*, 204-212. [5] K. Runyon et al. (2017) *Aeolian Res.*, *29*, 1-11. [6] M. Chojnacki et al. (2017) *Aeolian Res.*, *26*, 73-88. [7] S. Leprince et al. (2007), *Presented at IEEE Geosci. & Remote Sensing*. [8] S. Michel et al. (2018) *EPSL, 497,* 12-21. [9] M. G. A. Lapotre et al. (2016) *Science, 353,* 55-58. [10] M. G. A. Lapotre et al. (2018) *GRL, 45,* 10229-10239. [11] S. L. de Silva et al. (2013) *GSA Bulletin*, *125*, 1912-1929.

Fig. 2: Full timeseries of ripple sand flux measurements collected at Nili Patera (top), Gale Crater (middle), and Meroe Patera (bottom). Orange bars indicate ripple-based flux measurements corresponding to individual image pairs. Grayed-out areas indicate periods in which excessively large ripple displacement & pattern rearrangement prevented measurement of sand flux. For Nili Patera, a curve showing seasonal variation in sand flux averaged over several Mars years is overlaid in purple.