THE FINAL 2½ MINUTES OF TERROR – WHAT WE LEARNED ABOUT THE MSL LANDING FROM THE IMAGES TAKEN BY THE MARDI DESCENT IMAGER. J. Schieber[1], M.C. Malin[2], T.S. Olson[3], F. Calef[4], K. Comeaux[4] and the MSL Science Team, [1]Indiana University, jschiebe@indiana.edu, [2]Malin Space Science Systems, [3]Salish Kootenai College, [4]Jet Propulsion Lab.

Introduction: The MARDI descent imager [1], a downward looking camera attached to the left front corner of the rover, took 622 images of the martian surface from the time of heat shield separation to touchdown. The final images were of higher resolution than MRO images, allowed precise location of the MSL landing site, and helped to plan rover traverses in the initial days after the landing. The MARDI image series has been used by the project as well as by numerous amateurs to make video reconstructions of the descent that allow engineers and geologists alike to better understand the nature of the final descent to the martian surface. We report here on two data sets derived from descent images: (1) The apparent ground-track of the MARDI camera; and (2) The interaction of the descent stage rocket thrusters with the martian surface.

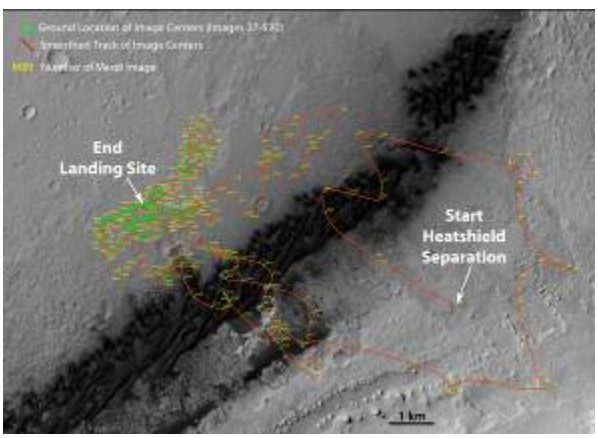

Figure 1: A plot of the ground track of MARDI image centers (red line) from the time of heatshield separation to the time of landing.

MARDI Ground Track: The ground-track of the MARDI camera is represented by the centers of successive images as plotted on the HiRise surface map (Fig. 1). At the time of heatshield separation the craft was attached to the parachute, and the ground track records a gradually decaying pendulum motion with a period of approximately 1.7 seconds. Although the track seems to gyrate rather erratically, the craft itself rotated steadily (1.6 degrees per second, clockwise) around its vertical axis, probably a residual after derotation of the craft before entry. Pendulum motions and rotation cease with the onset of powered descent, the images record a left to right roll, and from 184 m elevation and lower the camera centers are locked into a 2 m diameter circle, narrowing to 1 m diameter at 164 m and lower. Thus, the craft moved downwards on an almost perfect straight line. Even though the rover was tethered to just three wires during final descent (Skycrane stage), the images did not record any noticeable swinging or rotation.

Descent Stage Interaction with Surface Materials: At an elevation of 64 m the rocket exhaust began to interact with the surface and produced strongly asymmetrical dust plumes in spite of the non-tilted orientation of the craft (Fig. 2). The images suggest that, in order to keep the craft stationary, the thrusters were compensating for winds blowing from a southwesterly direction. Further data analysis will provide a profile of the wind encountered by the rover during its descent.

Figure 2: MARDI image #526 that shows the asymmetrical interaction of the descent stage thrusters with the ground. The northern dust plume is much larger, suggesting that the thrusters were compensating for southerly winds.

Examination of MARDI images from the point where the descent rockets interacted with the surface shows the following sequence of events: (1) removal of fine dust from the landing site area (descent from 68 to 56 m elevation); (2) with further descent first sand, and then gravel size materials began to move (Fig. 3);

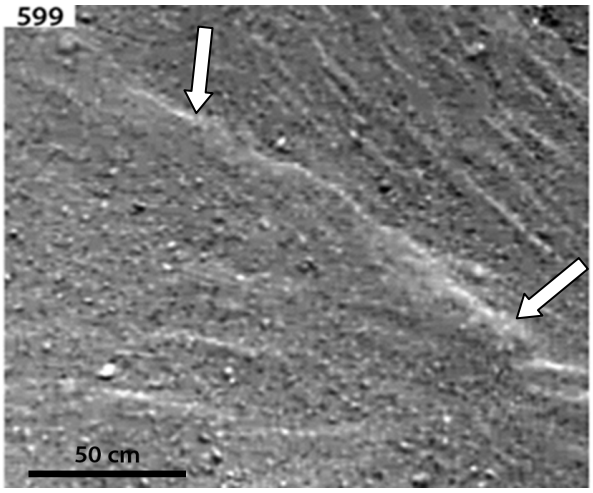

Figure 3: MARDI frame #599 shows movement of gravel sheet (arrows) across landing site.

(3) by the time the rover hovered 5-6 m above the surface, particles as large as 4 cm in size were mobile on the surface, and particles of comparable size were seen airborne. Airborne particles moved at velocities ranging from 1 to 190 m/s (Fig. 4);

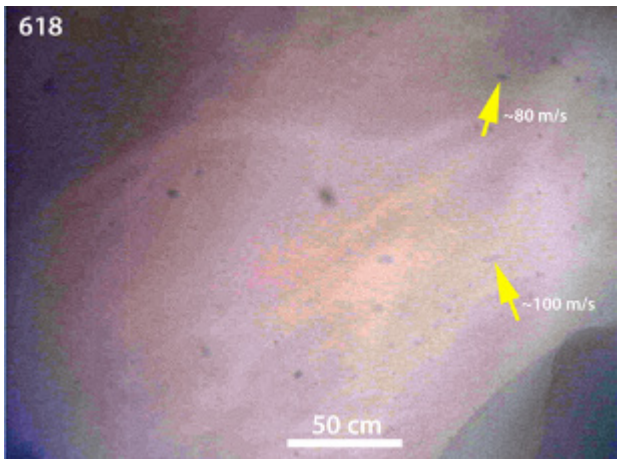

Figure 4: MARDI frame #618, strongly enhanced for contrast. Dark particles are flying pebbles. Yellow arrows point to motion streaks that, on the basis of shutter speed, suggest particle velocities between 80 and 100 m/sec.

(4) sand and fine gravel was moving in sheets/waves across the surface, covering and uncovering stationary objects (rocks) from frame to frame (0.25 seconds apart). These debris sheets may have moved in a flow regime comparable to base surge deposits of volcanic explosions; (5) at close approach the descent stage jets kicked up golf-ball size and larger debris and exposed cemented bedrock. This debris was partially directed towards the rover and reached high enough to potentially hit the rover (Fig. 5).

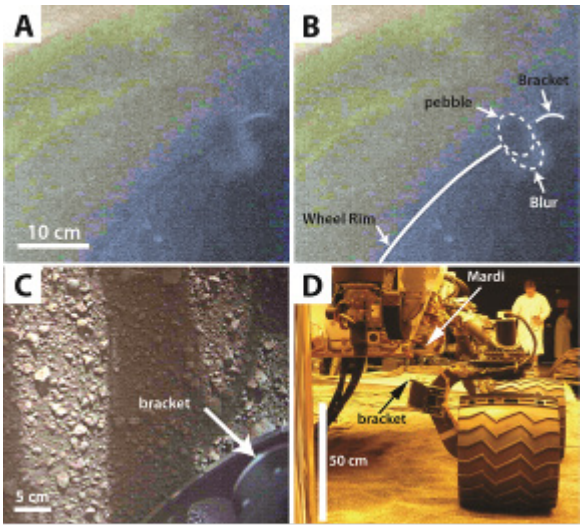

Figure 5: (A) Subframe of MARDI image 622, showing part of the left front wheel, and a pebble that partially obscures the wheel suspension bracket (pointed out with arrows in B, C, D). The scale bar is calculated for a distance of 50 cm below the camera. (B) The same view but with labels for features. From the relation between pebble and blur, we can see that the pebble was moving towards the rover. (C) A view of the wheel and the suspension bracket after landing. (D) The spatial relationships between the wheel suspension bracket and the camera. The vertical separation is only about 12 cm when the rover is on the ground, but approximately 80 cm before touchdown.

This debris was partially directed towards the rover and reached high enough to potentially hit the rover. Judging from post-landing images that show up to cm-size pebbles on the rover deck, and little damage to the sides of the rover aside of some nicked wires of the wind speed sensors, it seems that the rover was "lucky" with regard to the damage it sustained and the damage that potentially could have sustained. The engineering decision to do the "fly away" of the descent stage (after separation of rover and descent stage) with throttled (to 60%) thrusters may well have been essential to prevent serious and mission critical damage to the rover. Interaction with the rocket thrusters substantially altered particle distribution and surface features at the landing site.

References:

[1] Malin, M.C. et al. (2009) *LPS XXXX,* Abstract #1199.