Quantification of plume-soil interaction and excavation due to the sky crane descent stage

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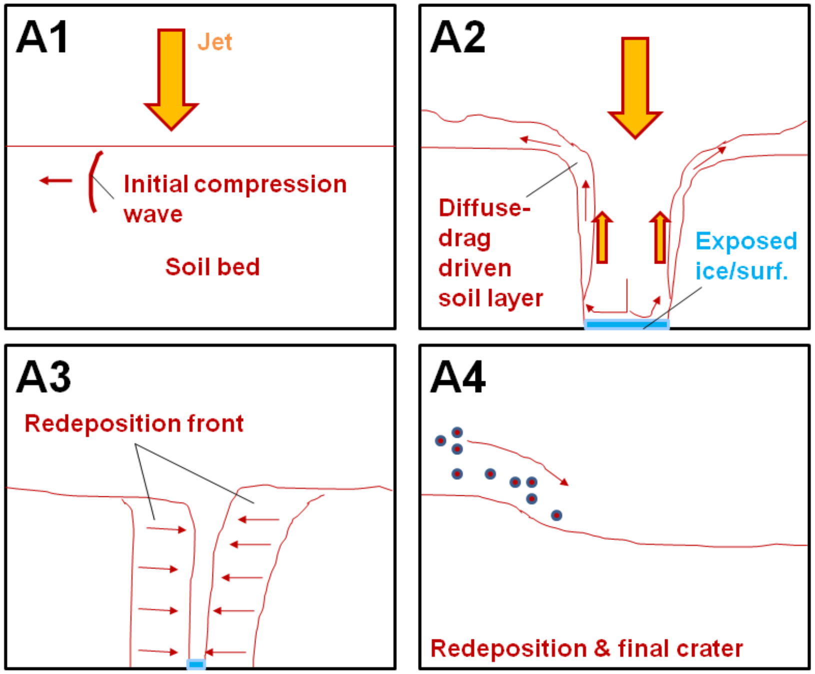
Plume Induced Erosion

- Viscous Shear Erosion (VSE)
  - Dusting or saltation caused by shear forces of fluid friction parallel to the surface.
- Bearing Capacity Failure (BCF)
  - The formation of transient craters with steep walls occurs by a combination of two distinct processes termed bearing capacity failure (BCF) diffusion-driven flow (DDF) when the jet's ground pressure exceeds the shear strength of the soil.



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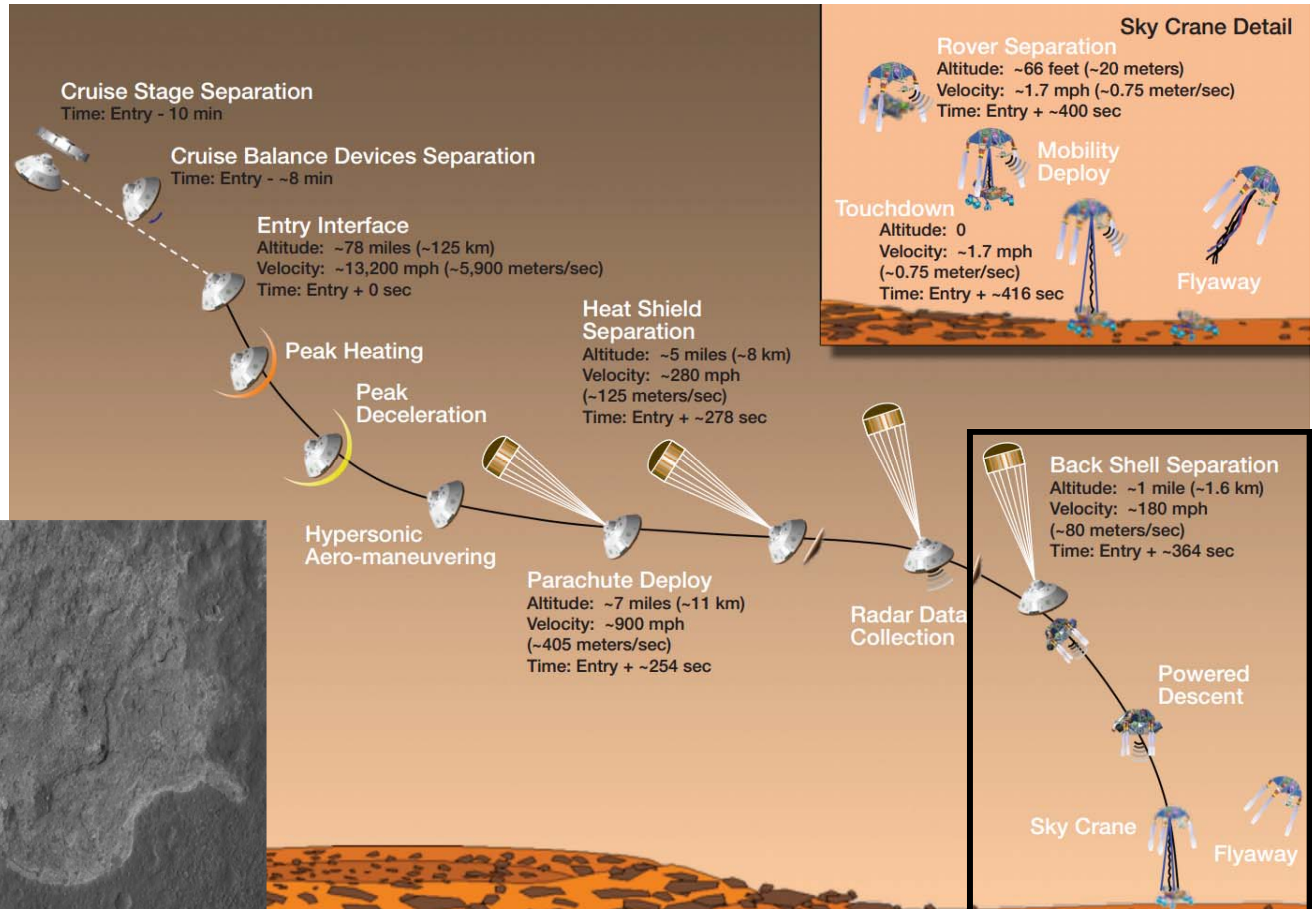
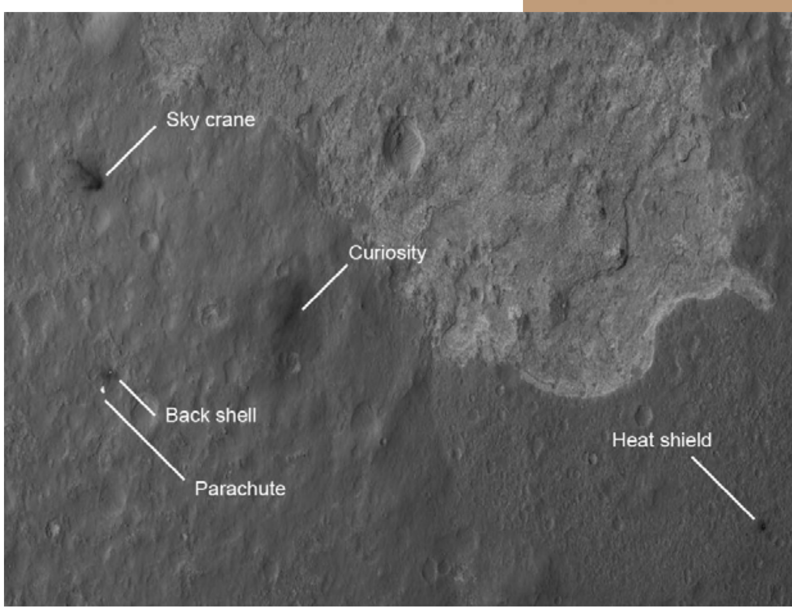
Descent Profile





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Mars Descent Imager (MARDI)

MARDI images taken during descent phase. Correlated MARDI images with trajectory data shows rocket thruster – soil interaction occurs at roughly 63 meters above the surface at 25 seconds before touchdown. Significant erosion occurs within the last 15 seconds.

- Erosion Onset (VSE):
  - Approximately 63 meters
- Severe Erosion (BCF):
  - ~18 meters

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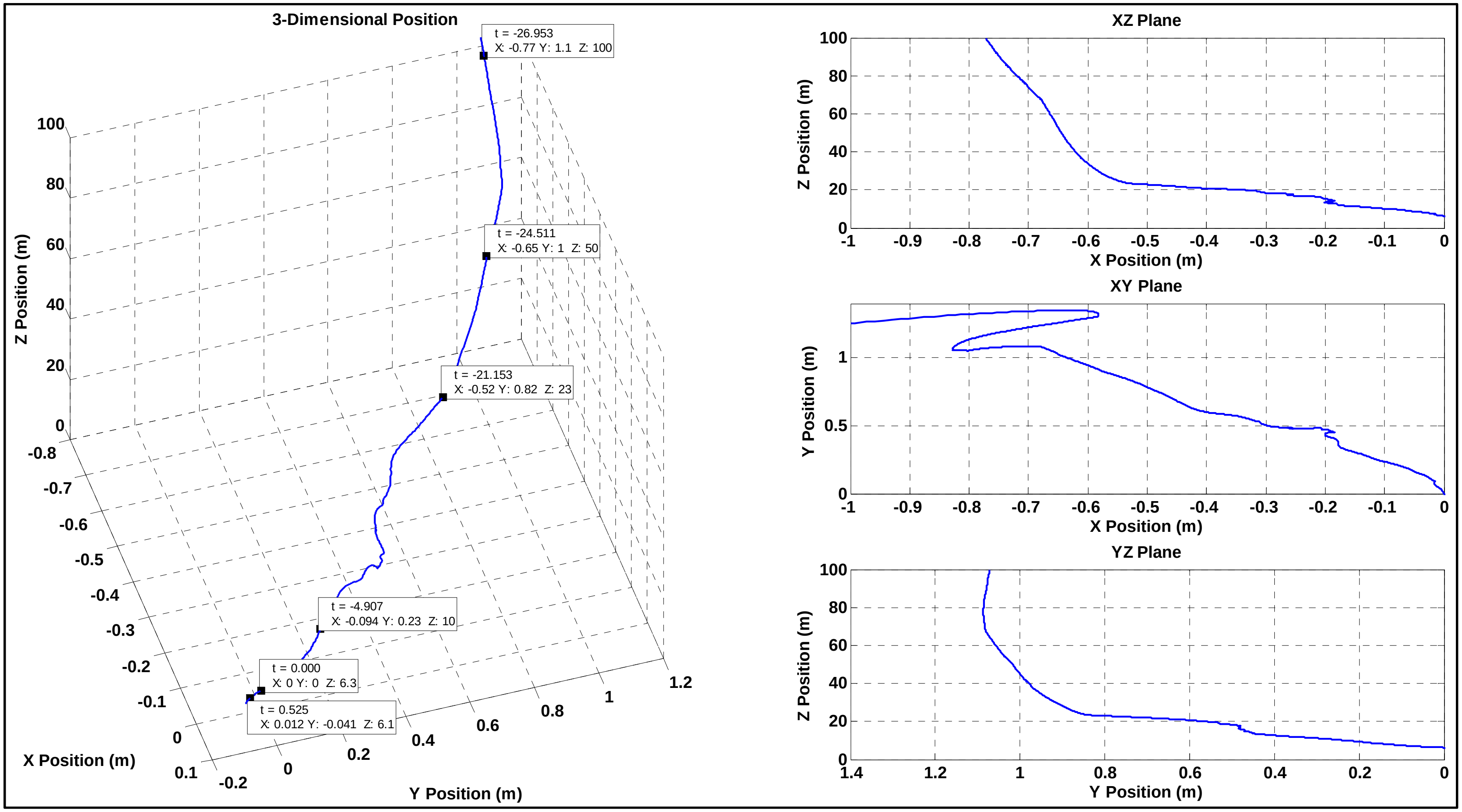
Descent Ground Track



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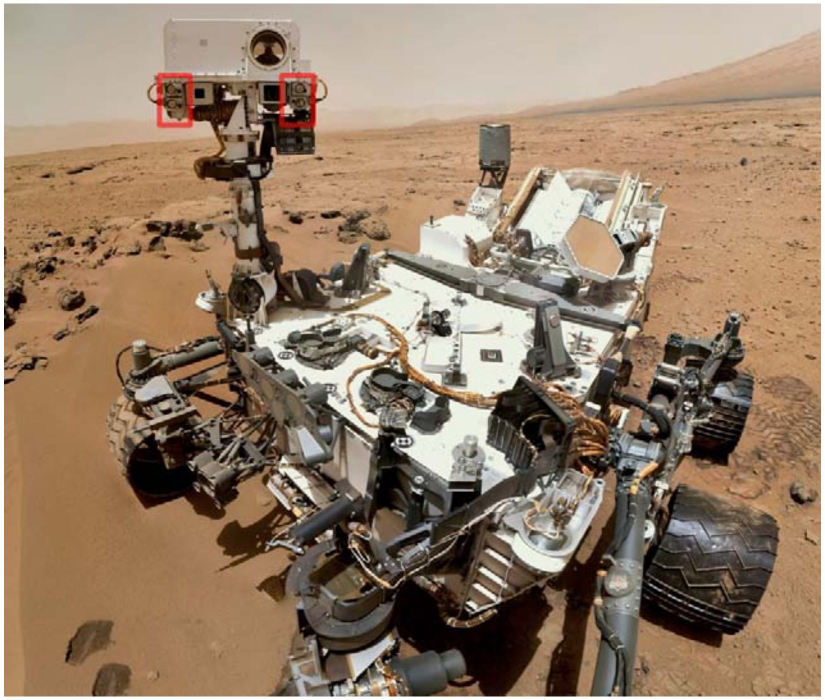
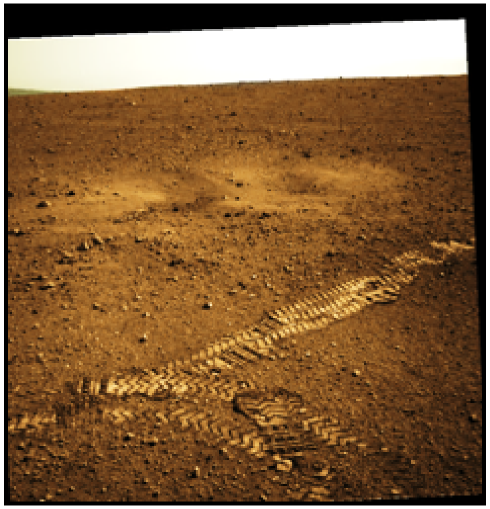
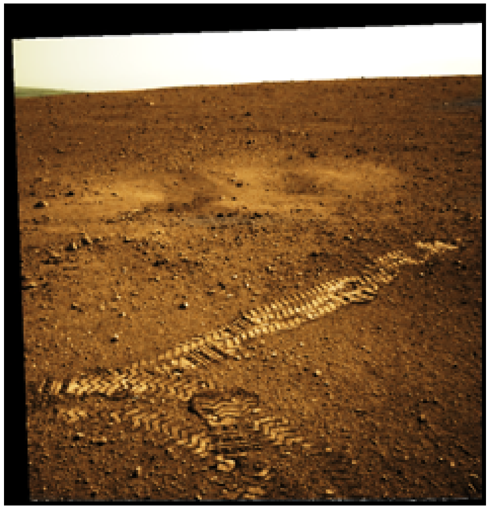
Digital Terrain Mapping

- Image Stereoscopy using MSL NAVCAMs
  - 1024 x 1024 (1 MP resolution)
  - 42 cm spacing
- Composition with Cardinal Systems VR Mapping software
  - Calibration
  - DTM generation







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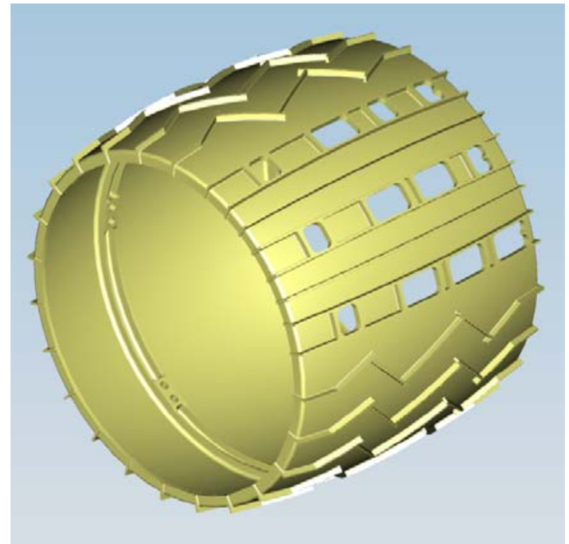
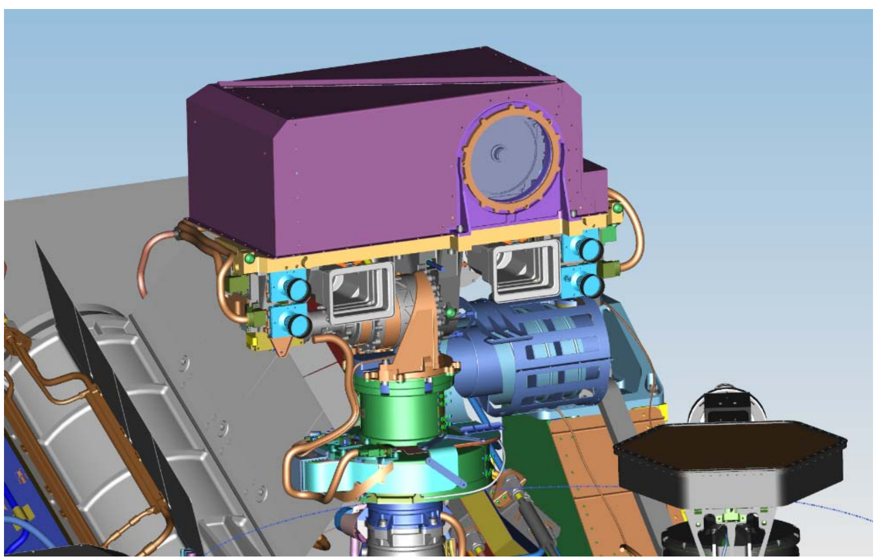
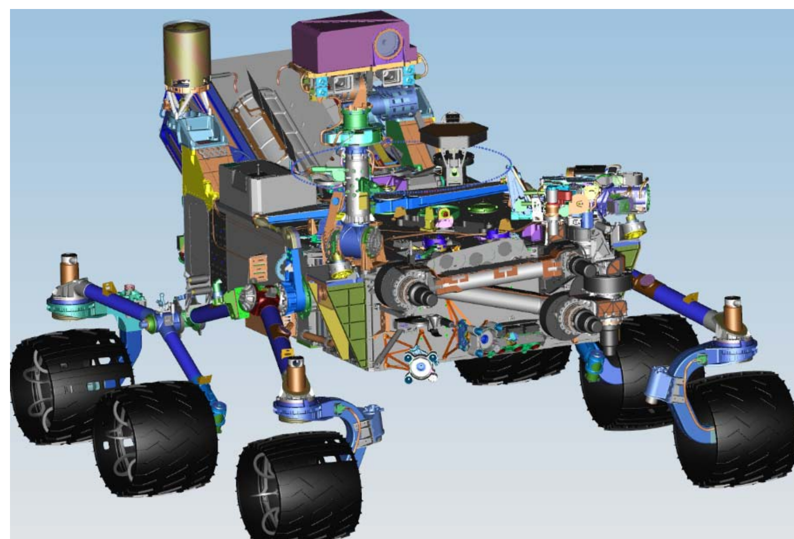
Mapping Calibration: CAD Models

- Detailed engineering CAD model of the Curiosity rover used to provide scaling information for the 3D terrain model.
  - Tire Width
  - Center Tread Length , Tread Spacing, and Wheel Spacing
  - “JPL” Morse Code Spacing and width

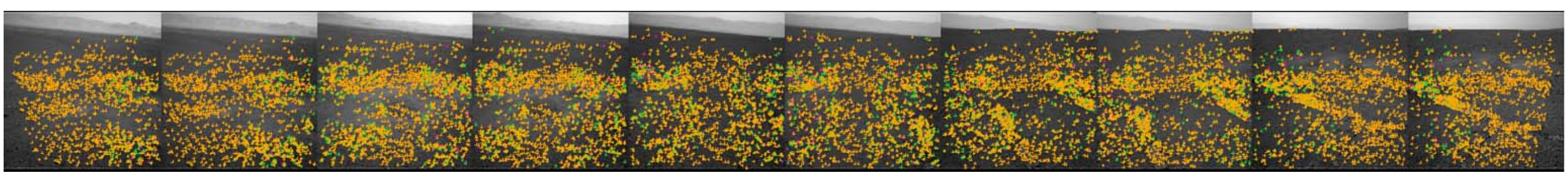






Mapping Calibration: Camera Calibration

- Worked closely with the Cardinal Systems to develop a process to increase the accuracy of the model. “Autotie” function correlates image measurements and scales across multiple images.



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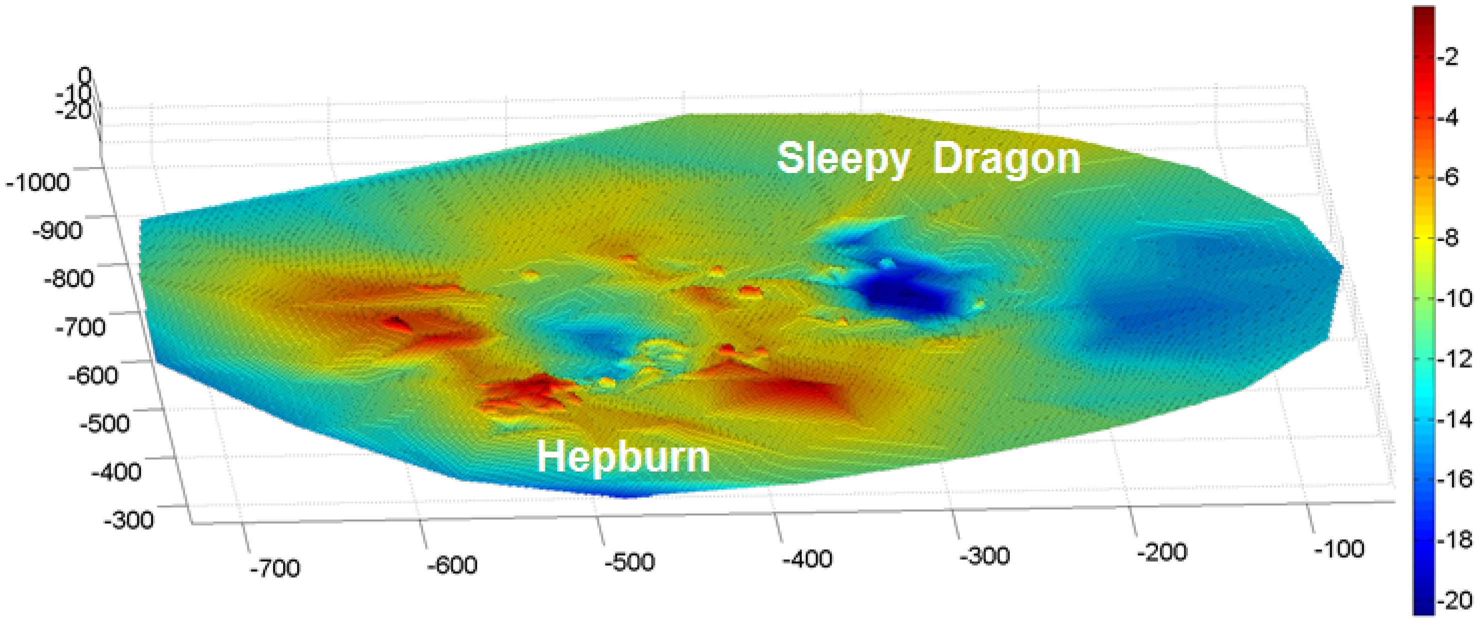
Sleepy Dragon & Hepburn



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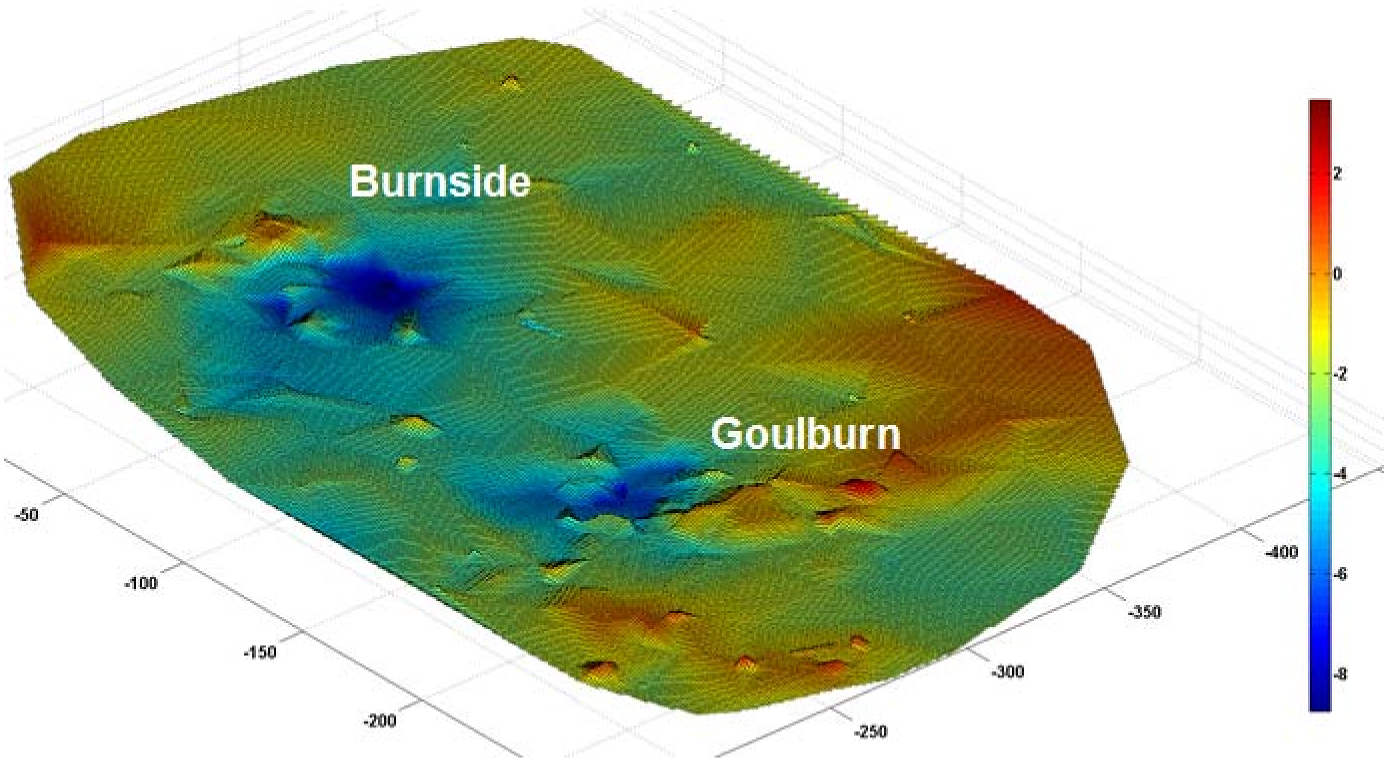
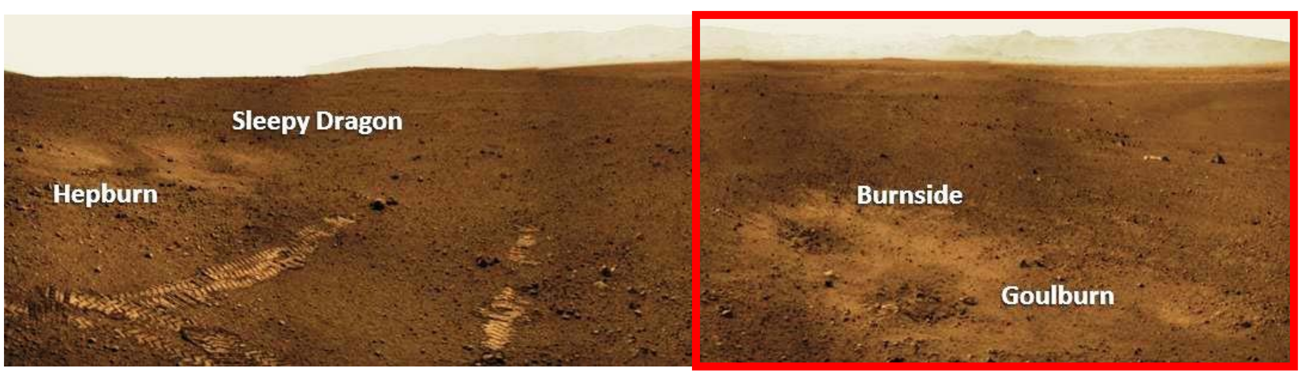
Burnside & Goulburn





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Erosion Rates & Volumes

Eroded Volume / Rate

Test	Test #	Soil Type	Volume (m^3)	Time (s)	Volumetric Erosion Rate (m^3/s)
MSL	8	Mars (Fine Sand)	3.29E-04	0.94	3.51E-04
MSL	7	Mars (Fine Sand)	4.91E-04	0.96	5.12E-04
MSL - Flight	**Goulburn**	**N/A**	**1.09E-02**	**15**	**7.27E-04**
MSL	2	Mars (Fine Sand)	5.86E-04	1.1	5.35E-04
MSL	23	Mars (Coarse)	9.51E-04	1	9.51E-04
MSL	13	Mars (Fine Sand)	1.07E-03	1	1.07E-03
MSL	21	Mars (Coarse)	1.11E-03	0.95	1.17E-03
MSL	6	Mars (Fine Sand)	1.10E-03	0.94	1.17E-03
MSL	16	Mars (Coarse)	1.44E-03	0.95	1.52E-03
MSL	5	Mars (Fine Sand)	1.65E-03	0.98	1.69E-03
MSL	12	Mars (Fine Sand)	1.97E-03	0.98	2.01E-03
MSL	18	Mars (Coarse)	1.64E-03	0.69	2.39E-03
MSL	20	Mars (Coarse)	2.92E-03	1	2.93E-03
MSL	4	Mars (Fine Sand)	2.35E-03	0.78	3.01E-03
MSL	15	Mars (Coarse)	3.85E-03	1	3.85E-03
MSL - Flight	**Burnside**	**N/A**	**5.38E-02**	**15**	**3.59E-03**
MSL - Flight	**Hepburn**	**N/A**	**6.36E-02**	**15**	**4.24E-03**
MSL - Flight	**Sleepy Dragon**	**N/A**	**8.47E-02**	**15**	**5.65E-03**
MSL	22	Mars (Coarse)	5.01E-03	0.89	5.65E-03
MSL	17	Mars (Coarse)	6.69E-03	0.96	6.98E-03
MSL	19	Mars (Coarse)	6.88E-03	0.97	7.09E-03
MSL	14	Mars (Coarse)	1.67E-02	0.97	1.72E-02

Estimated Eroded Mass

Test	Test #	Soil Type	Eroded Mass (m^3)
MSL - Flight	Goulburn	Mars (Coarse)	4.25
MSL - Flight	Burnside	Mars (Coarse)	21.0
MSL - Flight	Hepburn	Mars (Coarse)	24.8
MSL - Flight	Sleepy Dragon	Mars (Coarse)	33.0

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Conclusions

- The MARDI camera allowed us to determine, for the first time, when plume-soil interaction began to occur which was found to be approximately 63 meters above the ground level.
  - Soil erosion continuously increased and visibility decreased as the Sky Crane descends to its final altitude.

- The data extraction methods employed to the MSL data were a value added benefit and was performed without a need to alter the vehicle or collaborate with mission planners during design phase.
  - Scientists analyzing future human and robotic missions utilizing dual stereo camera systems will also benefit from this method as well.

- The effect of subsoil bedrock had a significant effect, as predicted, reducing overall crater diameter and depth (Goulburn and Burnside) when compared to a similar region with loosely packed soil (Hepburn and Sleepy Dragon).
  - The increased thrust loads associated with any possible human Mars mission will naturally intensify the erosion problem. If future vehicles are to use retro-propulsive landing system, it will be important to either choose landing sites with solid foundations or construct a landing site ahead of time.

- Volumetric erosion rates agreed well with experimental tests conducted in similar conditions using soil simulants.
  - This agreement validates vacuum chamber testing methodologies for analyzing plume-soil erosion and will allow for better prediction of erosion rates for similar and derived vehicles in the future.

Future Work & Implications

- This data is integrated into an erosion database compiled from surveys of simulated lunar and Mars plume impingement based erosion for development of empirical models to predict erosion severity.

- Validation future vacuum chamber tests, empirical codes, and CFD codes for plume based erosion.

- Potential for use of plume based erosion as a method of excavation as an alternative for traditional methods

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Acknowledgements

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