MARS SCIENCE LABORATORY CURiosity ROVER TERRAMECHANICS INITIAL RESULTS. R. Arvidson1, D. Fuller2, M. Heverly3, K. Iagnemma4, J. Lin5, J. Matthews6, R. Sletten7, and N. Stein1. 1Earth and Planetary Sciences, Washington University in Saint Louis, Saint Louis, MO, 63130, arvidson@wunder.wustl.edu, 2Jet Propulsion Laboratory, Pasadena, CA, 3MIT, Boston, MA, 4SpaceX, Los Angeles, CA, 5University of Washington, Seattle, WA.

Introduction: Terramechanics is the study of how vehicles interact with terrains and materials, and in this abstract initial results are presented using the MSL Curiosity rover as a virtual terramechanics instrument to sense terrain properties during drives at Gale Crater. This includes comparisons with field trials in the Mojave Desert using the Scarecrow rover (3/8 Curiosity’s mass to simulate Mars wheel loading and to use in field tests of Curiosity mobility capabilities) [1], retrieval of terrain properties from engineering data during Curiosity’s drives through sol 90, and drive simulations using Artemis dynamical models [2].

Curiosity Drives: Curiosity is a ~900 kg rover with a rocker-bogie suspension system designed to conform to topography and drive over obstacles that are smaller than the 0.5 m diameter wheels. Curiosity’s wheels exert approximately the same ground pressure as the Mars Exploration Rover wheels. Curiosity drives during the first 90 sols included use of visual odometry [3] to estimate slip at predetermined times, in addition to measuring and recording at high frequency the rover tilt vector, wheel turns, suspension angles and motor currents. Slip is defined as 100*(1-commanded distance/actual distance traversed) and is due to slip of the wheels by shear failure in soil and/or stick-slip motions over bedrock [4].

Drives during the first 90 sols occurred on two basic terrain types: a. hummocky terrain characterized by relatively smooth, rolling plains with hard-packed soil exhibiting both embedded rock clasts and loose surface rocks, and b. cratered terrain with intersecting craters and a slightly higher concentration of rock clasts embedded in and covering hard-packed soil [Figs. 1-3]. Analysis of rover slip and pitch data shows that the transition from hummocky to cratered terrain corresponds to an increase in the range of slip and pitch and the mean value of slip [Figs. 4-5]. Pitch is defined as the rover tilt in the longitudinal or drive direction and is a vector component of terrain tilt as sensed by the rover system. Detailed examination of Hazcam and Navcam image data shows a slight increase (~1 cm) in wheel sinkage values for the cratered as opposed to the hummocky terrain [e.g., Fig 3]. Rock clasts have been pushed into the soil in both terrains, implying that the soil cover depth is at least ~10-20 cm, with a pressure-sinkage relationship typical of densely packed soil as opposed to bedrock.

Comparisons to Field Trials and Artemis Models: The Scarecrow rover was deployed in May 2012 to the Dumont sand dunes and hilly dissected layered bedrock in the Tecopa area in the Mojave Desert to evaluate mobility on these two terrain types [1]. The classical evaluation for drives in deformable soils is to consider slip vs slope, along with wheel sinkage, and to model the results as a function of wheel motor torques and thus the shear stress applied to the wheel-soil contacts [4]. Fig. 5 shows the standard slip vs slope (as rover pitch) plot for the hummocky and cratered terrains overlain with data from an uphill drive on a Dumont Dune face. As expected slip increased as pitch increased with a sharp increase at highest pitch angles due to the transition to slip sinkage where the wheels transferred a great deal of sand to their rears as the wheel torques increased to maintain the commanded angular velocities. The SSTB-lite (3/8 mass Mars Exploration Rover) was also driven up the same slope face and its slip-slope curve was found to be displaced upward from the Scarecrow curve, i.e., the SSTB-lite did not make it all the way up the dune face. This demonstrates that larger wheels are better for mobility when given the same absolute amount of sinkage. More longitudinal force in the drive direction and thus greater traction is provided with larger radius of curvature wheels.

The Curiosity slip-pitch data were also simulated using Artemis, a fully dynamic model of Curiosity that includes use of Mars gravity, terrain topographic models and realistic soil (scaled for gravity) and bedrock properties, using flight-like drive commands and recording flight-like engineering telemetry (e.g., slip) and wheel sinkage estimates [2]. A representative model is shown in Fig 5 with soil parameters that have less shear slippage as compared to the Dumont Dunes. Additional Artemis simulations indicate that the cratered terrain drives are best modeled statistically using slightly higher wheel sinkages (slightly more deformable soil) and a wider range of slopes as compared to the hummocky terrain drives.

Future Work: Terramechanics analyses are planned for drives in bedrock-dominated terrain in Glenelg, for the route across the plains and dunes to the base of Mount Sharp, and up the sides of Mount Sharp as Curiosity explores that array of strata exposed on this ~5 km high mountain. Results will be used to
understand terrain properties, relate these to surface processes and geologic history, and to help define efficient and safe strategic routes for Curiosity’s drives.


Fig. 1- Drives from the landing site to Rocknest are shown on a HiRISE base map, with selected end of drive sol locations shown. Note the intersecting craters for the cratered terrain location.

Fig. 2- View looking to the northeast showing relatively rugged terrain due to overlapping craters and strewn rocks.

Fig. 3- View looking back at the wheel tracks after the sol 50 drive showing that wheel sinkage is minimal in the hard-packed soil, along with a rock that has been pushed into the soil by wheel pressure.

Fig. 4- Slip vs rover time showing the increase in slip range in transitioning from the hummocky to cratered terrains.

Fig. 5- Slip vs rover pitch results shown for an uphill drive on the Dumont Dunes (actual terrain slope because the pitch was in the uphill direction), Curiosity drives on the hummocky and cratered terrains, and a representative Artemis simulation to extend the Dumont Dunes data to smaller slip values. The break in slope at ~12 degrees for the Dumont data corresponds to the initiation of slip-sinkage at relative high slip values. The mean values for Curiosity drives are shown as a large blue square for the hummocky and red triangle for the cratered terrain data. The cratered terrain drives show a wider spread of values and a higher mean slip value, indicating a more complicated and different set of terramechanics interactions as compared to the hummocky terrain drives. Spread in model data is a consequence of the very narrow model time intervals and the detailed interactions of the six driven wheels with the vehicle’s suspension system.