Artemis Simulation of Curiosity Rover Traverse Across Dingo Gap. N. T. Stein[1], R. E. Arvidson[1], P. Bellutta[2], M. Heverly[2], [1]Washington University in St. Louis, Dept. of Earth and Planetary Science, St. Louis, MO (n.stein@wustl.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Introduction: On Sols 533 and 535, Curiosity traversed across a ~8m wide aeolian sandy bedform straddling Dingo Gap. This traverse differs significantly from other terrains traversed by Curiosity to date, which have been typically across hummocky plains or bedrock surfaces characterized by low wheel sinkages and rover slippage [1]. During the traverse across Dingo Gap, Curiosity experienced relatively high sinkage (~7cm), slip values approaching 50% (from visual odometry), and high currents on the left rear drive actuator. To understand how these conditions arose and to predict future performance for drives over sand ripples and dunes, Artemis (Adams-based Rover Terramechanics Mobility Interaction Simulator [2]) was employed to model the Dingo Gap traverse. In addition, to understand how larger wheels (50 cm diameter) improve mobility, models were also run with our Artemis model for the Opportunity rover [2] with its 26 cm diameter wheels.

Artemis is a software tool used to simulate the motion of rovers over realistic terrains. Artemis consists of mechanical models of the Curiosity and Opportunity rovers, a wheel-terrain interaction module that models wheel-terrain interactions on deformable and non-deformable surfaces, and terrain topographic models. Wheel-soil interactions on deformable surfaces are modeled using terramechanics-based pressure-sinkage and shear-displacement expressions [3]. To model wheel-soil interactions on-deformable surfaces, Artemis utilizes a velocity-based friction model to calculate coefficients of static and dynamic friction. Quantities such as wheel slip, wheel torque, and shear and normal stresses are then calculated. Both the Opportunity and Curiosity Artemis models have been validated through the simulation of single wheel and field tests [2,3].

Simulation of Dingo Gap Traverse: A realistic terrain for the traverse was generated from Sol 533 telemetry data under the approximation of limited roll and longitudinal bedform symmetry. A representative view of the Curiosity model on this terrain and simulated pitch are shown in Figures 1 and 2, respectively.

Field tests of the Scarecrow test vehicle in the Dumont Dunes, California provide a basis for estimating soil parameters [2,4]. Sand terramechanics properties for the Dumont Dunes were estimated using Artemis simulations of SSTB-lite (Opportunity test rover) and Scarecrow (Curiosity test rover) traverses, combined with relevant laboratory simulations [2,4]. Adjustments to these parameters were made to account for differences in slip between Dumont Dunes and Dingo gap. Specifically, Curiosity encountered higher wheel sinkage and lower slip as a function of pitch for Dingo Gap relative to the Dumont Dunes. This is not surprising because imaging of the Dingo Gap bedform shows poorly sorted and angular grains as opposed to the well-sorted and rounded grains characteristic of Dumont Dunes. Compaction at Dingo Gap must also be less to explain the higher wheel sinkages. The soil parameters used for the Artemis simulations are shown in Table 1.

Perhaps the most important metric for evaluating drive performance is slip. In Figure 3 slip as a function of drive distance for the Curiosity traverse and what we predict would have happened for the Opportunity rover are compared with Curiosity telemetry data from Sols 533 (up the ripple) and 535 (down the ripple). Simulated slip is relatively constant for low values of pitch at the base of the ripple, quickly increasing as pitch increases. On Sol 533, Curiosity encountered a maximum pitch in excess of 13° accompanied by slip of 40-50%, similar to simulated values. During the descent on Sol 535, Curiosity experienced skid in excess of 20%, consistent with simulated quantities. The simulated crossing by Opportunity predicts significantly higher slip for a given pitch, consistent with the expectation that smaller-wheeled vehicles experience lower traction and higher resistance relative to larger-wheeled vehicles, assuming constant ground pressure. Artemis predicts that Opportunity would have failed to reach the crest of Dingo gap before reaching 100% slip (Fig. 3).

On the Sol 533 ascent with a frontward drive telemetry, data show that Curiosity's left rear drive actuator experienced a significantly higher maximum current relative to the other drive actuators. Although Artemis does not measure currents directly, applied actuator torque is approximately proportional to actuator current and can be used to approximate trends in current. During the uphill portion of the Curiosity simulation, the maximum torque of the rear drive actuators was ~25% higher than that of the mid and front drive actuators, consistent with increased loading experienced by the rear wheels of Curiosity. Simulated actuator torque does not capture the particularly high current drawn by the left rear drive actuator relative to the right rear drive actuator due to the assumption of limited roll in the models. It is likely that increased loading on the left rear wheel due to both roll and the high degree of pitch accounts for the high currents experienced during the drive.

Future Work: Artemis is currently used and will continue to be used to model Opportunity and Curiosity traverses to derive information about Martian terrain properties and to help understand likely behavior as a function of path chosen. As Curiosity continues the journey to Mount Sharp, Artemis will be an important tool to simulate rover drives both to infer soil properties and to predict performance on various terrains.

Fig. 1: View of Curiosity Model on Dingo Gap terrain.

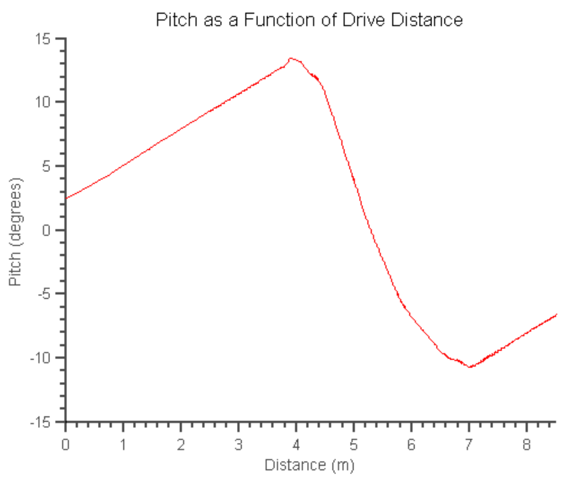

Fig. 2: Simulated pitch as a function of simulation time.

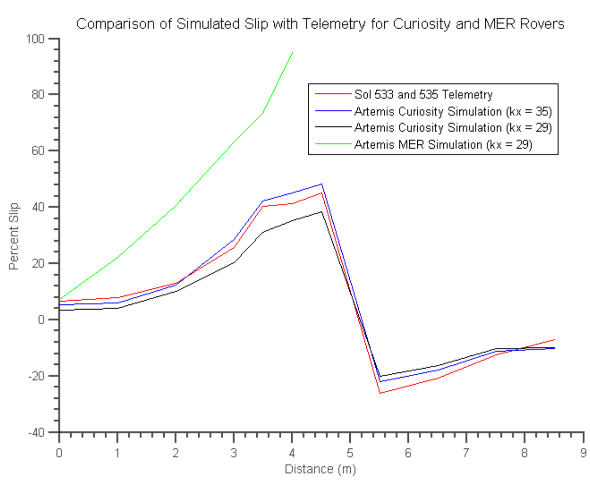

Fig. 3: Comparison of slip during sols 533 and 535 with simulated Curiosity and MER slip as function of drive distance. Plotted quantities start at the base of the ripple.

Density(kg/m^3)	C(kPa)	Φ(deg)	K_x(mm)	n_o	n_1	Kc'	k Φ'	a_1	a_2	Soil rebound ratio
1650	0.2	30	29-35	1.65	0.45	9.1	500.8	0.33	0.11	5%

Table 1: Simulation parameters.

References: [1] Arvidson et al. (2014) J. Geophys. Res., in press. [2] Zhou, F. et al. (2013) *J. Field Robotics.* doi: 10.1002/rob.21483: 1-20. [3] Stein, N. et al. *2013 AGU Fall meeting.* Abstract #P51G-1826. [4] Heverly, M. et al. (2013) *J. Field Robotics.* doi: 10.1002/rob.21481.