Artemis Simulation of Curiosity Rover Traverses. N. T. Stein[1] and R. E. Arvidson[1], [1]Washington University in St. Louis, Dept. of Earth and Planetary Science, St. Louis, MO (n.stein@wustl.edu).

Introduction: Artemis (Adams-based Rover Terramechanics Mobility Interaction Simulator) is a software tool used to simulate the motion of rovers over realistic topographies. Artemis contains a rover mechanical model, a wheel-terrain interaction module that models interactions on both deformable and non-deformable surfaces, and terrain, bedrock, and soil models. Wheel-soil interactions on deformable surfaces are modeled using pressure-sinkage relationships developed by Bekker, Reece, and Wong to determine wheel-soil stresses [1]. To model wheel-soil interactions on non-deformable surfaces, Artemis uses wheel contact as a constraint and utilizes a velocity-based friction model to calculate static and dynamic forces of friction [1]. Quantities such as wheel slip, wheel torque, and shear and normal stresses are then calculated. Terrains are generated from orbital or rover-based data. A full range of drive types can be modeled, including forward and backward drives, turns in place, arc drives, blind drives, and drives using visual odometry for course correction. The Artemis Curiosity model can be used in a predictive manner to advise on path planning and also as a "virtual instrument" to sense terrain properties.

Artemis is used to simulate drives of Curiosity, a six-wheel drive, four-wheel steered 989kg rover with a rocker bogie suspension system. Fig. 1 shows the Curiosty model, which was developed using MSC-ADAMS software. To validate and calibrate the Curiosity model, simulations were compared to a series of rover drives on Earth. The purpose of this abstract is to present results from modeling test rover drives on deformable and hard surfaces and to discuss present and future uses of the Artemis Curiosity model.

Validation of Deformable Soil Model: To validate the deformable soil model, a number of representative Curiosity drives were simulated and compared with telemetry data from test rover traverses. Test rover traverses were conducted in the Mars Yard in the Jet Propulsion Laboratory on a series of slopes covered with cohesive and cohesionless soils [2]. These drives were modeled and simulated 3D rover slip as a function of pitch was compared with telemetry. Test results were shown to be statistically indistinguishable from model results. On cohesive soil, simulated slip is relatively constant at low (<10 degree) slopes before increasing nonlinearly between 10 and 25 degrees, consistent with a transition to slip-sinkage at higher slopes (Fig. 2). On cohesionless soils, simulations yield low, linearly increasing slip at low pitch angles (<10 degrees), increasing nonlinearly between 10 and 15 degrees before approaching 100% slip (Fig. 2).

Additional rover testing was performed in the Mojave Desert, California on cohesionless sand in the Dumont Dunes and at Tecopa, a hard-packed dissected lakebed. A representative Dumont Dunes simulation yielded slip approaching 100% at 20 degree pitch, consistent with test telemetry. Additionally, Artemis results suggest that softer sands are present near the dune crests, consistent with in situ measurements. Additional simulated quantities including wheel torque, roll, and pitch are compared with telemetry in figures 3, 4, and 5, respectively. A representative drive at Tecopa was modeled by adjusting the lateral shear deformation modulus k_x, a parameter which controls the longitudinal shear stress and hence affects wheel traction and the amount of wheel slip. A nominal value of $k_x = 8$ was found for Tecopa, which is considerably lower than the value of $k_x = 29$ found in modeling MER test rover drives in the Dumont Dunes [1]. A lower k_x value is consistent with the minimal wheel sinkage experienced in the hard-packed surfaces of Tecopa. Results show that rover-based tests on deformable surfaces can be simulated with Artemis.

Validation of Non-Deformable Soil Model: To validate the non-deformable soil model, representative Curiosity drives over non-deformable (i.e. bedrock) terrains are simulated and compared with telemetry data from test rover traverses. The Dyamic Test Model (DTM) and Scarecrow, Curiosity test rovers, were driven over a series of bedrock-covered slopes ranging from 0 to 30 degrees [2]. Drives were simulated using the non-deformable contact model on a series of slopes ranging between 0 and 30 degrees with coefficients of static and dynamic friction of 0.577 and 0.450, respectively. Simulations yield low, linearly increasing slip between 0 and 15 degrees of pitch, increasingly nonlinearly before approaching 100% at ~30 degrees of pitch, consistent with DTM test results (Fig. 6). Results show that rover-based tests on non-deformable surfaces can be simulated with Artemis.

Future Work: Artemis is currently used to model Curiosity traverses to yield information about terrain properties [3]. To sense terrain properties, coefficients in the Wong and Reece pressure-sinkage relationships are adjusted iteratively and simulated 3D rover slip is compared with telemetry to find a best fit set of parameters [1]. Because many quantities such as soil density and cohesion are known to good approximation, and because slip is almost solely affected by k_x, only k_x is modified to make a slip comparison. A limitation of this technique is that simulations are computationally expensive; a single minute of simulated drive time typically requires more than an hour of computation time. In the future, this issue may be circumvented by modeling dozens of drives in parallel using a Windows HPC to cover the full range of possible k_x values before comparing results using chi-square minimization to find a nominal set of soil parameters.

As Curiosity continues the journey to Mount Sharp, Artemis will be used to simulate rover drives and gather information about martian terrain properties.

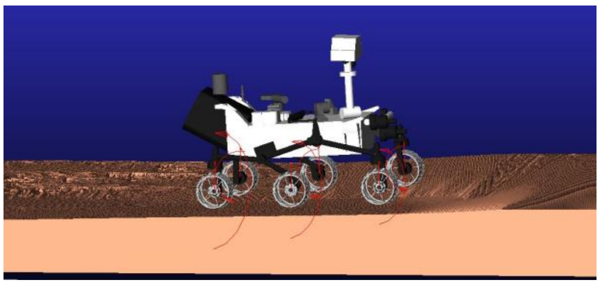

Fig. 1: View of Curiosity Model on a representative terrain.

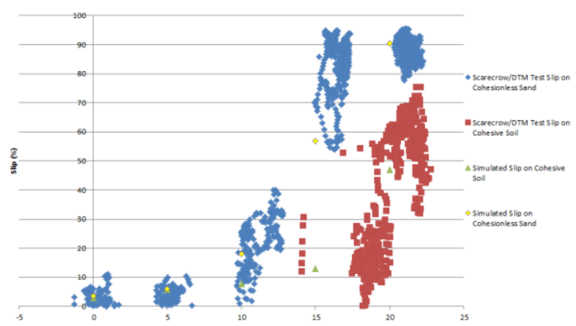

Fig. 2: Simulated and measured rover slip as a function of pitch for drives over cohesive soil and cohesionless sand.

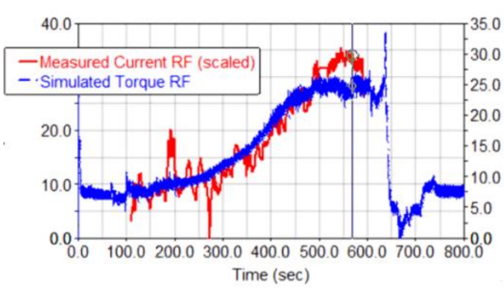

Fig. 3: Simulated torque and measured wheel current for the right front wheel for a Dumont Dunes test drive backwards and down slope. Simulated wheel torque scales with actuator current, as expected.

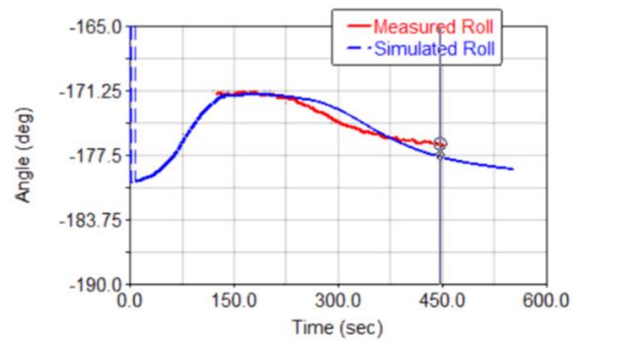

Fig. 4: Simulated and observed roll for the same drive shown in Fig. 3. The terrain was generated from a 3D terrain scan.

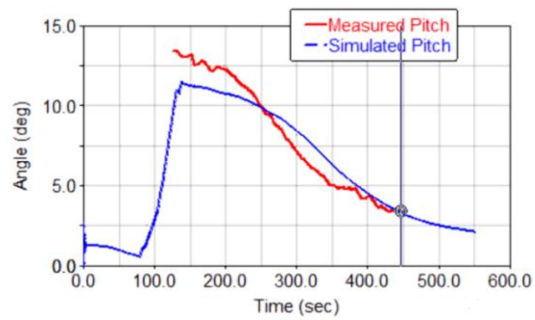

Fig. 5: Simulated and observed pitch for the same terrain in Fig. 4.

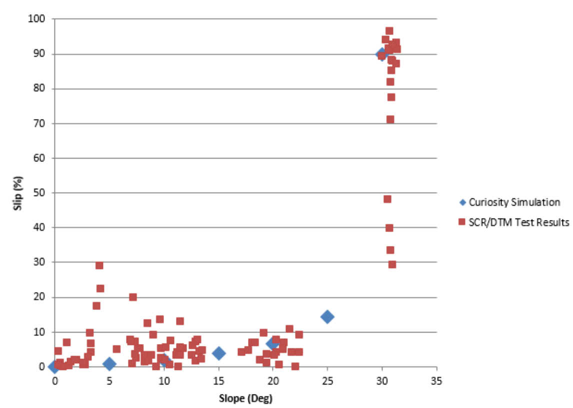

Fig. 6: Simulated and observed 3D rover slip as a function of slope for drives over bedrock.

References: [1] Zhou, F. et al. (2014) *J. Field Robotics.* doi: 10.1002/rob.21483: 1-20. [2] Heverly, M. et al. (2013) *J. Field Robotics.* Doi: 10.1002/rob.21481. 835-846. [3] Arvidson, R. E. et al. (2014) *JGR Planets*, submitted.