MARS EXPLORATION ROVER OPPORTUNITY TERRAMECHANICS ACROSS RIPPLE COVERED BEDROCK IN MERIDIANI PLANUM. R. E. Arvidson[1], L. van Dyke[1], K. Bennett[1], F. Zhou[1], K. Iagnemma[2], C. Senatore[2], R. Lindemann[3], B. Trease[3], S. Maxwell[3], P. Bellutta[3], A. Stroupe[3], F. Hartman[3], V. Verma[3], K. Ali[3]
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Introduction: Opportunity has been traversing the Meridiani plains since January 2004 and after reaching Santa Maria crater on December 16, 2010 had traveled over 26.5 km (based on wheel odometry). With acquisition of stereo imaging before, during, and after drives, together with monitoring wheel turns and currents, suspension angles, and rover attitudes, an extensive data set has been collected to evaluate mobility and to also retrieve terrain and soil properties using basic terramechanics approaches. This abstract summarizes Opportunity's drives across the plains since leaving Victoria crater, issues associated with high slippage and sinkage during traverses, and soil and terrain properties retrieved from modeling the drives and the wheel-soil interactions.

Mobility Campaign: Opportunity's mobility system consists of a rocker-bogie suspension configuration with six-wheel-drive capability. In addition the outer four wheels have azimuthal actuators to allow arc turns. Opportunity's right front steering actuator failed on sol 433, leaving the wheel rotated inward by an ~8 degree angle. The vehicle has primarily been driven backwards during the mission period covered by this paper, in part to minimize wheel actuator current spikes, and because this mode was found to permit Opportunity to cross ripples with minimal mobility difficulties.

Drives have been accomplished using a blind mode for regions relatively close to the rover for which terrain meshes could be constructed from stereo imaging and for which mobility obstacles were judged to be minimal. Terrain avoidance procedures in which Opportunity used its stereo imaging capabilities to search for and avoid obstacles have also been employed. Visual odometry (VO) uses repeated stereo imaging to track the vehicle's position and attitude on-board and to adjust the path accordingly. VO has been used extensively to determine slippage along traverses, with upper limits designed to stop traverses before embedding (Fig. 2).

After completion of the Victoria crater campaign the next long-term destination for Opportunity was the rim of the Noachian-aged Endeavour crater, located ~15 km (straight line) to the southeast. Traverses needed to be done across rather large aeolian ripple fields (3 to 4 m wide and 10 to 30 cm high) that have relatively low thermal inertias (from THEMIS) indicative of loose, poorly sorted sands (Fig. 1). Largest ripples were avoided and many traverses took place from north to south along inter-ripple corridors. Crossings took place for regions in which relatively low ripples could be found. By ~sol 2350 Opportunity arrived at a new terrain type in which ripples were much smaller and thermal inertias higher (Fig. 1).

A detailed analysis of slippage based on visual odometry data collected during drives (short bumps left out) shows that all the traverses were dominated by relatively low slippage (~5%) (Fig. 2). High slippage and wheel sinkage values occurred when the rover crossed or straddled large ripples in the area with low thermal inertia. High slippage values also occurred when Opportunity ascended a relatively high slope (~10 deg) to get to the Santa Maria crater rim (Fig. 2). In this case the thin soil over bedrock precluded much wheel sinkage. The high slip periods provide information on how the rover's mobility system performs during less than nominal conditions. Variations in slippage and sinkage also provide retrievable information on terrain and soil properties.

Modeling High Slip Events: Crossing or straddling large ripples has dominated high slippage and wheel sinkage events while traversing across ripple covered plains (Figs. 2-4). To provide a quantitative evaluation of these mobility difficulties a dynamical model of Opportunity was constructed in software, including wheel-soil interactions with wheel sinkage and slippage into deformable soils. Normal and shear stresses between the wheels and soil were modeled using the classical Bekker-Wong terramechanics expressions that describe relationships among normal and shear stresses, applied wheel torque, wheel slippage and wheel sinkage as a function of soil properties and terrain slope. The complete rover and wheel-soil model was needed, rather than a single wheel model, because of the complex feedback mechanisms between the driven wheels, the suspension system, and the terrain and soils. Lateral and longitudinal stresses, bull-dozing, and skidding were included in the model.

Models show that increased wheel sinkage due to increased weight over a given wheel led to increased contact area between the wheel and soil and increased compaction resistance, thereby increasing the amount of slippage for a driven wheel as motor torques are increased to compensate. As slippage increased, additional sinkage occurred as soil was moved in the direction of the spinning wheel. This further increased motion resistance as the wheel came in contact with additional soil during sinkage. At some point the maximum soil shear stress before failure was reached and slippage became effectively 100% in some cases, causing longitudinal motion to cease (e.g., Fig. 3). Models run with real terrain topography derived from stereo image coverage and soil properties dominated by loosely consolidated, poorly sorted sands replicate the main elements of slippage and sinkage (measured from images) and provide validation of the overall modeling approach.

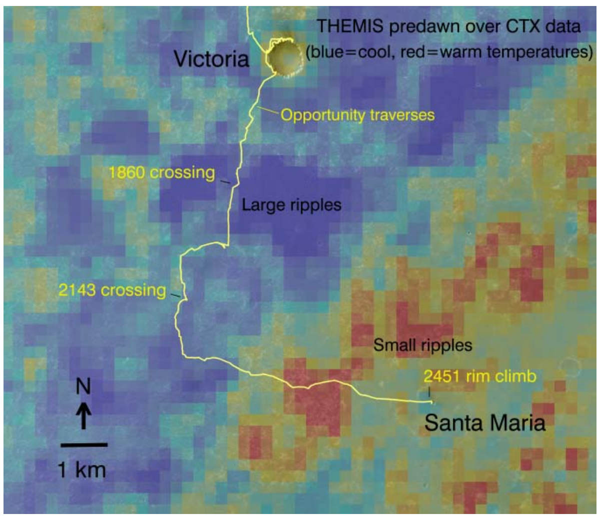

Fig. 1 – Regional-scale view showing Opportunity's traverses between Victoria and Santa Maria craters. Sols are labeled for which detailed discussion of high slip drives is included in text. Cool temperatures in THEMIS predawn TIR correspond to low inertia, large ripples. This is where Opportunity experienced high slippage and sinkage.

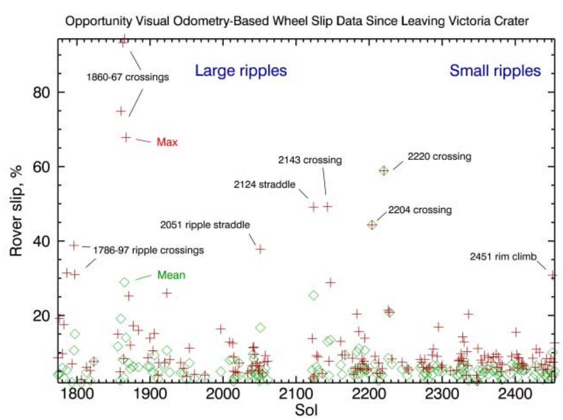

Fig. 2 – Plot of VO-based slip as a function of sol since leaving Victoria and arriving on the western rim of Santa Maria craters. Highest wheel slippage occurred when crossing or straddling relatively large ripples dominated by poorly consolidated and sorted sands.

Fig 3 – Front Hazcam view acquired on sol 1865 showing left front wheel deeply sunk into the flank of a ripple. This was a high slip event in which Opportunity recovered by backing out onto the inter-ripple surface.

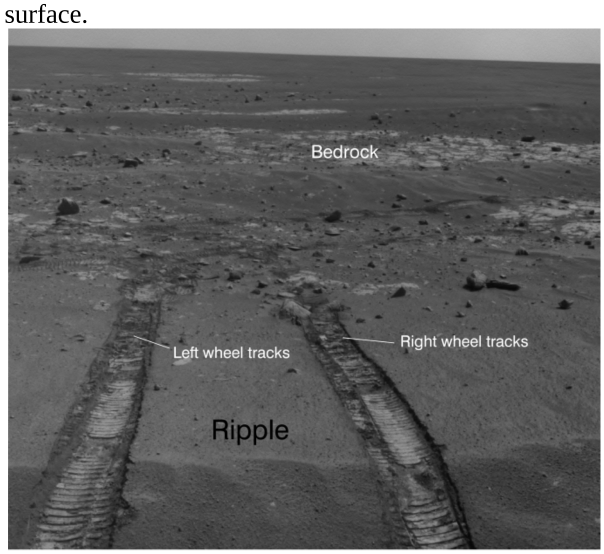

Fig. 4 – Navcam view from sol 2143 taken after Opportunity crossed a ripple and encountered modestly high slippage and sinkage. Note bedrock exposures. Opportunity drove backwards during the crossing.

Future Work: Detailed simulations are underway to further validate the model and retrieve terrain and soil properties. We expect to be able to simulate traverses of possible ascents of the soil-covered outer rim of Endeavour crater. The ascents will occur after Opportunity leaves Santa Maria and traverses the ~6 km across the plains to get to the Cape York rim segment. Model runs will be used to help define best approaches for ascent, thus minimizing risks to Opportunity's health and safety.