RELATIONSHIPS BETWEEN REMOTE SENSING DATA AND SURFACE PROPERTIES OF MARS LANDING SITES. M. P. Golombek[1], A. F. C. Haldemann[2], R. A. Simpson[3], R. L. Fergason[4], N. E. Putzig[5], A. Huertas[1], R. E. Arvidson[6], T. Heet[6], J. F. Bell III[7], M. T. Mellon[8], and A. S. McEwen[9], [1]Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, [2]ESA/ESTEC, Noordwijk, Netherlands, [3]Stanford University, Stanford, CA 94305, [4]U.S. Geological Survey, Flagstaff, AZ 86001, [5]Southwest Research Institute, Boulder, CO 80302, [6]Washington University, St. Louis, MO 63135, [7]Cornell University, Ithaca, NY 14853, [8]University of Colorado, Boulder, CO 80309, [9]University of Arizona, Tucson, AZ 85721.

Introduction: Understanding the relationships between orbital remote sensing data and "ground truth" is essential for safely landing spacecraft and for correctly interpreting surface physical and material properties globally on Mars. Here we use the investigations at the six successful Mars landing sites to establish those relasionships [e.g., 1 and references therein].

Surface Materials: All landing sites that have been investigated on Mars are composed of a combination of rocks, outcrops, eolian bedforms, and soils, many of which have been cemented to varying degrees [2]. Rocks, typically appear as float and are common at all landing sites except Meridiani. Outcrops have been observed at three of the landing sites. The cumulative fractional area covered by rocks and outcrop varies from about 3% to 30% at VL (Viking Lander) 1, VL2, MPF (Pathfinder), Phoenix, and different portions of the cratered plains investigated by Spirit [3, 4, 5, 6]. For these five sites, the size-frequency distribution of rocks show a characteristic exponential decrease in fractional area covered by larger rocks in accord with fracture and fragmentation theory [4]. These rocks appear largely as dense volcanics (~2800 kg m^{-3}) and have an effective thermal inertia of about 2500 J m^{-2} K^{-1} $s^{-1/2}$. Clastic rocks in the Columbia Hills and layered sulfate evaporites at Meridiani have lower thermal inertia and lower density based on Mini-TES measurements [7], RAT grind energies, and susceptibility to erosion.

Soils studied at the six landing sites can be distinguished by their mechanical properties, which are generally similar to moderately dense soils on Earth [2, 8, 9, 10]. Crusty and cloddy soils have weak cohesion (1-4 kPa) and moderate angles of internal friction (30-40°), likely due to mild cementation. Blocky and indurated soils have higher cohesion (3-10 kPa) and moderate friction angles (25-33°). Bulk densities inferred from their friction angles are 1100-1600 kg/m^3 and 1200-2000 kg/m^3, and thermal inertia estimates from their bulk densities, particle sizes and cohesions are 200-326 J m^{-2} K^{-1} $s^{-1/2}$ and 368-410 J m^{-2} K^{-1} $s^{-1/2}$ for crusty-to-cloddy and blocky-indurated soils, respectively. Eolian deposits at the landing sites include drift, sand dunes, ripples, and wind tails. Drift material is weak, porous, high-albedo, very-fine-grained dust (~3 µm) that has settled out of the atmosphere. It has very low bearing strength, small angles of internal friction (15-21°), very low bulk densities (1000-1300 kg/m^3), and very low thermal inertias (40-125 J m^{-2} K^{-1} $s^{-1/2}$) [2]. Dunes and other eolian bedforms are dominantly fine sand (160 µm), with friction angles of ~30°, densities of 1100-1300 kg/m^3, and thermal inertia of ~200 J m^{-2} K^{-1} $s^{-1/2}$ [7] consistent with those expected for wind-sorted cohesionless sand.

Thermophysical Properties: Soils and rocks observed at the landing sites and their relative abundances can be related to their orbital (generally kilometer-scale) signatures in thermal inertia and albedo data. Successful landers have sampled two of the three major units of combined thermal inertia and albedo [11] that cover most of Mars (Figure 1). Regions of moderate to high thermal inertia and low albedo (unit B) are relatively dust free and composed of dark eolian sand and/or rock (e.g., Opportunity). Regions of moderate to high thermal inertia and intermediate to high albedo (unit C) are dominated by crusty, cloddy, and blocky soil (duricrust), with some dust and variable rock abundance (e.g., VL1, VL2, Spirit, Phoenix, and MPF, which has higher thermal inertia). Along with variations in rock abundance, these two units represent the majority of surfaces that are likely to be safe for landing spacecraft on Mars. The third unit (A), with very low thermal inertia and high albedo is likely dominated by dust deposits that may be neither load bearing nor trafficable. Comparisons of soils and rocks covering the landing sites indicate that the main contributor to the bulk thermal inertia is the degree of induration or cementation (and grain size) of the soils or fine component, rather than rock, which generally cover less than one quarter of the surface [11].

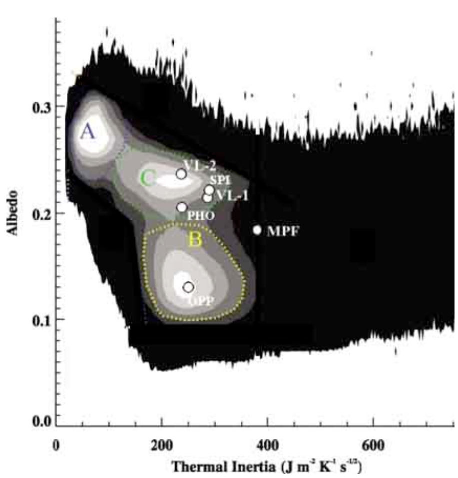

Figure 1: Global TES thermal inertia versus albedo showing the six landing sites and modes (units A, B, and C) that make up 80% of the surface area of Mars. Adaped from Putzig et al. [11]

The site with the highest thermal inertia, MPF, has the highest fine-component thermal inertia due to a preponderance of pebble-rich, cloddy, blocky, and indurated soils [8]. The bulk thermal inertia of VL1 and Spirit are lower due to greater amounts of low thermal inertia drift deposits, and that of VL2 is lower still due to thin drift deposits and the lower thermal inertia of its cloddy soils, which also dominate the Phoenix landing site [10]. The Opportunity site has very little rocky fraction and its bulk inertia is dominated by uncemented (or very poorly cemented) sand and granular ripples [12].

The fraction of dust and drift deposits at the landing sites (and thus their influence on thermal inertia) can also be related to the albedo of the sites. The site with the highest albedo, VL2, also has the greatest area (~40%) covered by drift deposits, followed by VL1 with 18-30% drift cover [3]. At the Spirit site, dusty areas such as the rim of Bonneville crater, have high albedo, and areas in dust devil tracks that have been swept clean of dust have lower albedo. The Opportunity landing site in Meridiani Planum has the lowest albedo of any landing site and is essentially dust free [12].

Rock abundance derived from thermal differencing techniques applied to orbital data essentially matches that determined from rock counts at the surface, and varies from ~3% at Opportunity to 7% (average) at Spirit to 16-19% at VL1, VL2 and MPF [13, 1]. The size-frequency distributions of rocks >1.5 m diameter, fully resolvable in HiRISE images of the landing sites, are continuous with exponential models developed from lander measurements of smaller rocks indicating both are part of the same population [14, 6].

Radar Data: Radar data have been used to infer surface roughness at the scale of the radar wavelength (diffuse scattering) as well as at 10-100 times the radar wavelength (specular), which have been compared favorably with slopes derived from stereogrammetry and photoclinometry of MOC and HiRISE images and with estimates of relief within the returned MOLA pulse over the 75 m laser spot. Radar reflectivity has also been used to estimate the bulk density of the surface materials, which can be used to infer whether the surface is load bearing and trafficable.

The diffuse scattering data measured at wavelength scale at the VL1 and VL2 sites have been successfully modeled using the observed rock populations [15]. Radar reflectivity suggest a bulk density of 1500 kg/m^3, consistent with the blocky soil at VL1. RMS slopes of 4.5° at VL1 are consistent with moderately high MOLA pulse spread and interpolated 100 m slopes. MPF radar results are similar to those of VL1. The cratered plains at Gusev have lower radar-derived RMS slopes than at VL1 or MPF, correspondingly lower MOLA pulse spread and interpolated 100 m slopes, and comparable diffuse scattering from the moderately rocky but pebble-rich surface. The low radar RMS slope at Meridiani Planum agrees with the low slopes estimated from MOLA altimetry and pulse spread.

Slopes and Relief: The slopes and relief at three length scales important to landing safety (1 km, 100 m, and several meters) were also estimated and compared at the six landing sites using MOLA altimetry, MOC stereogrammetry and photoclinometry, and radar backscatter. Results from these data are in accord with each other and with what was found at the surface. Of the six landing sites, Meridiani Planum is the smoothest, flattest location at all three length scales, consistent with the very smooth, flat plain traversed by Opportunity. At the other extreme, the MPF site is roughest at all three length scales, which agrees with the undulating ridge and trough terrain and the more distant streamlined islands with greater relief that are visible from the lander. The other three landing sites are between these extremes at the three length scales, with VL2, Phoenix and portions of Gusev fairly smooth at the 100 m and 1 km scale, VL1 slightly rougher at all three length scales, and VL2 and portions of Gusev (such as the Columbia Hills) intermediate in roughness at the several meter length scale. All of these observations are consistent with the relief observed at the surface.

Conclusions: The six landing sites sample surfaces with moderate to high thermal inertia and low to high albedo (but not those with low thermal inertia and low albedo); these surfaces are representative of almost 80% of the planet. The close correspondence between surface characteristics and material properties inferred from orbital and Earth-based remote sensing data and those found at the landing sites allows the landing sites to be used as "ground truth" for interpreting remote sensing observations of the surface at other locations.

References: [1] Golombek M. et al. (2008) Ch. 21 in *The Martian Surface*, J. Bell ed., Cambridge. [2] Christensen P. & Moore H. (1992), Ch. 21 in *Mars*, H. Kieffer et al. eds., U AZ Press. [3] Moore H. & Keller J. (1990) Rep. Plan. Geo/Geophys. Prog.-1989,1990, NASA Tech. Mem. 4210, 4300, 533–535 & 160–162. [4] Golombek M. et al. (2003) *JGR 108*, 8086, doi:10.1029/2002JE002035. [5] Golombek M. et al. (2006) *JGR 111*, E02S07, doi:10.1029/2005JE002503. [6] Heet T. et al. (2009) LPSC XL, abs., this volume. [7] Fergason R. et al. (2006) *JGR 111*, E02S21, doi:10.1029/2005JE002583. [8] Moore H. et al. (1999) *JGR 104*, 8729–8746. [9] Sullivan R. et al. (2007) *LPS XXXVIII*, abs. #2084. [10] Arvidson R. et al. (2009) LPSC XL, abs. #1067. [11] Putzig N. et al. (2005) *Icarus 173*, 325–341. [12] Golombek M. et al. (2005) *Nature, 436*, doi:10.1038/nature03600. [13] Christensen P. (1986) *Icarus, 68*, 217-238; Nowicki S. & Christensen P. (2007) *JGR 112,* E05007, doi:10.1029/2006JE002798. [14] Golombek M. et al. (2008) *JGR 113*, E00A09, doi:10.1029/2007JE003065. [15] Baron J. et al. (1998) *JGR 103,* 22695-22712.