Near-Term Pinpoint Landing with an MSL Cruise/EDL Rebuild. D.P. Scharf[1], B. Acikmese[1], and G. T. Chen[1], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, Daniel.P.Scharf@jpl.nasa.gov, Behcet.Acikmese@jpl.nasa.gov, and George.T.Chen@jpl.nasa.gov.

Introduction: To support future sample return missions, access to scientifically compelling terrain, and the goals of the Human Exploration and Operations Mission Directorate, it is shown that *precision landing to 1.5 km 3-sigma* is possible with a rebuild of Mars Science Laboratory (MSL) using a lighter rover and an existing and flyable on-board powered descent guidance algorithm for precision/pinpoint landing (PPL) called G-FOLD (Guidance for Fuel-Optimal Large Divert) [1-3]. With improved knowledge of the attitude, position, and velocity of the entry vehicle at the hand-off between ground-based navigation and on-board navigation – and navigation experiments to do so are being performed with MSL – *sub-kilometer landing accuracy is possible with the MSL EDL system* when combined with G-FOLD and a lighter rover. Lastly, if the MSL landing radar is augmented with Terrain Relative Navigation (TRN) [4], <100 m pin-point landing accuracy is possible.

The enabling idea is that a lighter rover increases the thrust-to-weight ratio (T/W) of the MSL skycrane powered descent vehicle (PDV). In turn, the divert distance – how far the PDV can maneuver laterally once separated from the parachute – scales favorably and nonlinearly with increased T/W.

Capabilities and Limitations of MSL for a PPL Demonstration: Generally speaking, PPL has three major challenges: 1) *knowledge*: knowing where the vehicle is with respect to the target point with sufficient accuracy; 2) *guidance*: being able to calculate a feasible trajectory from the current point to the target point; and 3) *fuel*: having enough to reach the target point. These challenges are inter-related and affected by other system characteristics. For example, simplistic guidance can increase the fuel required, but a smaller entry vehicle dispersion at the start of powered descent or higher T/W reduces the fuel required. This enumeration, however, is convenient for understanding what PPL is possible with an MSL rebuild.

Quantitatively, it is shown via G-FOLD guidance that an MSL rebuild with a 185-kg MER-class rover has enough fuel to divert 8.5 km to pinpoint land. See Figure 1. This divert distance leaves sufficient fuel for the subsequent skycrane and flyaway phases and reserve. However, the nominal, 3-sigma MSL landing ellipse has semi-major and minor axes of 10.6 km and 3.6 km, respectively. To pinpoint land at the center of the MSL ellipse from anywhere within the ellipse, the PDV would have to be able to divert 10.6 km. For a

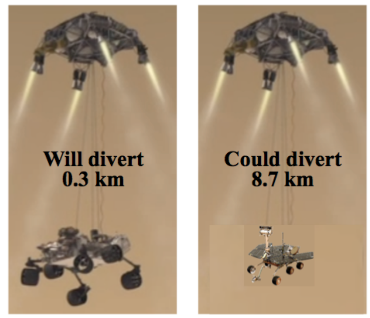

Figure 1. Left: MSL Descent Stage with 900-kg MSL rover will divert 0.3 km to avoid the chute and back-shell. Right: MSL Descent Stage with 185-kg MER rover could divert 8.7 km due to increased thrust/weight ratio resulting from a lighter rover.

10.6 km divert, the rover could not mass more than 75 kg, which may not be practically useful.

Nonetheless, a divert capability of 8.5 km allows PPL 98.5% of the time (integral of the multi-variate Gaussian landing distribution over the intersection of the 3-sigma landing ellipse and a circle of radius 8.5 km). Moreover, G-FOLD is able to find the *fuel-reachable* point closest to the desired target [2]. As a result, even if the center of the MSL ellipse is not achieved, a PPL capability can still demonstrated: the vehicle autonomously calculates and executes a large divert to land at an on-board targeted point.

The main PPL limitation with an MSL rebuild would be knowledge. Assuming nominal MSL performance, inertial propagation from the ground-based navigation hand-off results in a horizontal position knowledge uncertainty of 1.5 km 3-sigma at touchdown. Hence, the center of ellipse could be targeted only within a 1.5 km radius. However, if MSL state initialization accuracy is increased (e.g., attitude from a star tracker or in-flight calibration and position/velocity from differential tracking of MSL and a Mars orbiter), then <1 km horizontal position knowledge is possible at touchdown.

Such improved state initialization would also likely shrink the major axis of the MSL landing ellipse to less than 8.5 km, thereby enabling <1 km precision landing at the center of the 3-sigma landing ellipse from anywhere within it.

In short, a lighter rover would give the existing MSL PDV more ability to maneuver (increased T/W reduces fuel required) and G-FOLD (guidance) would use that maneuverability. If a partner could be found to provide the rover, the mission could conceivably fit within a New Frontiers cap.

Powered Descent Guidance for PPL: G-FOLD is an existing, flyable powered descent guidance algorithm [1-3] that could plan on-board and in realtime trajectories that take a PDV from chute separation to a soft touchdown or the start of an MSL skycrane. The key feature is that the guidance problem has been reformulated and approximated to make it convex. With convexity, a trajectory can be generated in < 1 s on a flight processor. While this is not an inconsequential amount of time, the trajectory would be generated while still on the parachute or during the 2 s of freefall that provides separation between the PDV and parachute/backshell before MSL's powered descent begins.

The approximations necessary to obtain convexity do introduce some sub-optimality, but feasible trajectories are nonetheless found for >8 km diverts that respect constraints on maximum speed, maximum and minimum thrust, and remaining above a glide-slope for terrain clearance. It is this ability to satisfy constraints in realtime that makes the PPL PDG algorithm flyable.

Approach to Demonstrating Divert Capability: A simulation capability has been developed for trade studies with G-FOLD. First, inputs are specified, such as mass properties, descent engine configuration, dynamic constraints, and boundary conditions. The MSL PDV properties are used, but with a lighter rover. The boundary conditions are the position and velocity when the PDV separates from the parachute/backshell (1.5-to-3 km of altitude, 8.5 km from the origin with an MSL 3-sigma high descent rate of 100 m/s) and the altitude and velocity for the start of the Constant Velocity Accordion phase of MSL's landing profile (~150 m altitude and ~30 m/s descent rate). Additional constraints include a maximum speed of 0.8 Mach and thrust limited to 90% of total (the MSL descent engines are throttleable). The remaining 10% of thrust capability is reserved for attitude control and position feedback. Then G-FOLD is run, generating profiles of throttle-level and PDV attitude: the MSL descent engines are not gimbaled, and so the PDV must angle itself to generate a horizontal acceleration. Next, these profiles are fed into a dynamics model to verify the profiles generate trajectories that satisfy boundary conditions and constraints. Finally, the fuel required to fly the rest of the MSL landing profile is calculated.

An 8.5 km divert with an the MSL Descent Stage and 185-kg rover is shown in Figures 2-4. Explanations are given in the captions. The fuel budget includes: descent engine use for the 8.7 km divert; MSL 3-sigma high values for Exo/Entry RCS thruster use, on-chute RCS use, and descent engine use for the Flyaway phase; descent engine use adjusted for the lighter PDV for Constant Velocity Accordion, Constant Deceleration, Skycrane, and Touchdown Accordion phases; the MSL required reserve; and an additional 10 kg reserve for attitude maneuvers and feedback.

Conclusion: With a 185-kg rover and G-FOLD, an 8.5 km divert and MSL skycrane profile could be flown with the MSL fuel loading. Such a divert capability allows <1.5 km precision landing with the MSL Cruise/EDL system. With reasonable assumptions on performance enhancements for ground-based navigation and EDL attitude initialization, the landing error – dominated by uncertainty in inertial propagation of horizontal position knowledge – could be reduced to <1 km. Additional engineering challenges exist, such as correcting radar-measured altitude for a 10 km offset prior to divert, but they have solutions that do not require new technology (e.g., interpolating a coarse-gridly digitial elevation model of the landing site). However, if new technology is considered, then TRN would enable <100 m accuracy. These landing accuracies are with respect to the G-FOLD-targeted point, which 98.5% of the time would be the center of the ellipse. However, even should G-FOLD have to forgo the center of the ellipse and target a fuel-reachable point closest to the center, an advanced PPL capability would have been demonstrated with a cost-effective build-to-print of the MSL Cruise/EDL system.

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References: [1] Acikmese B. and Ploen S.R. (2007) *JGCD, 30,* 1353–1366. [2] Blackmore L. et al. (2010) *JGCD, 33,* 1161-1171. [3] Carson III J. M. et al. (2011) *IEEE Aerospace Conf.* [4] Mourikis A. et al. (2009) *IEEE Trans. Robot. Autom*., 25, 264-280.

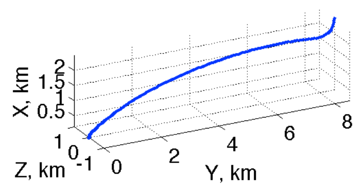

Figure 2. 8.5 km divert. X-axis is vertical. Chute separation is at 2.5 km. Terminal point above origin is at ~150 m altitude. Solution is planar since initial velocity is vertical, but arbitrary velocities can be handled.

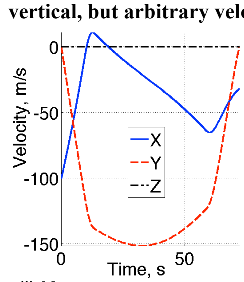

Figure 3. Time history of velocity components during divert. PDV travels from +8.5 km along Y-axis to origin. Initial thrusting balances 1) vertical impulse to "buy time" for high-speed horizontal coast and 2) horizontal impulse to generate large horizontal speed for divert.

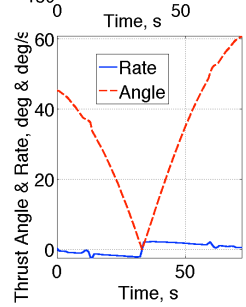

Figure 4. PDV angle from vertical and angular rate during 8.5 km divert. The PDV must tip over 45 deg to impart the balanced vertical/horizontal impulse noted in Figure 3. Imporantly, note that constraints on the angular rate ensure the attitude profile generated by the PDG algorithm can be followed by the PDV.