LIDAR-based Hazard Avoidance for Safe Landing on Mars

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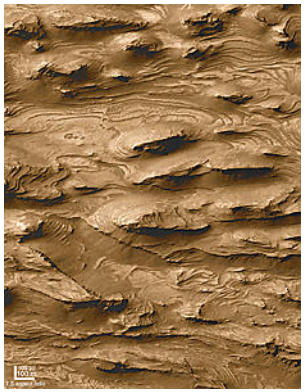
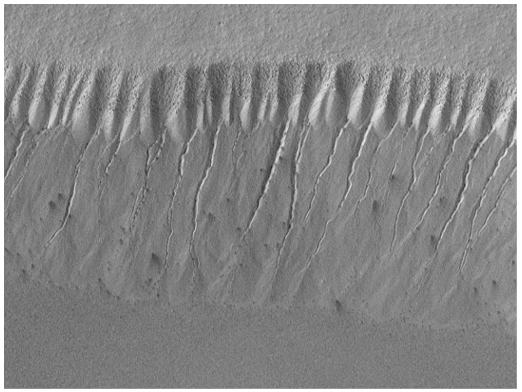
Motivation

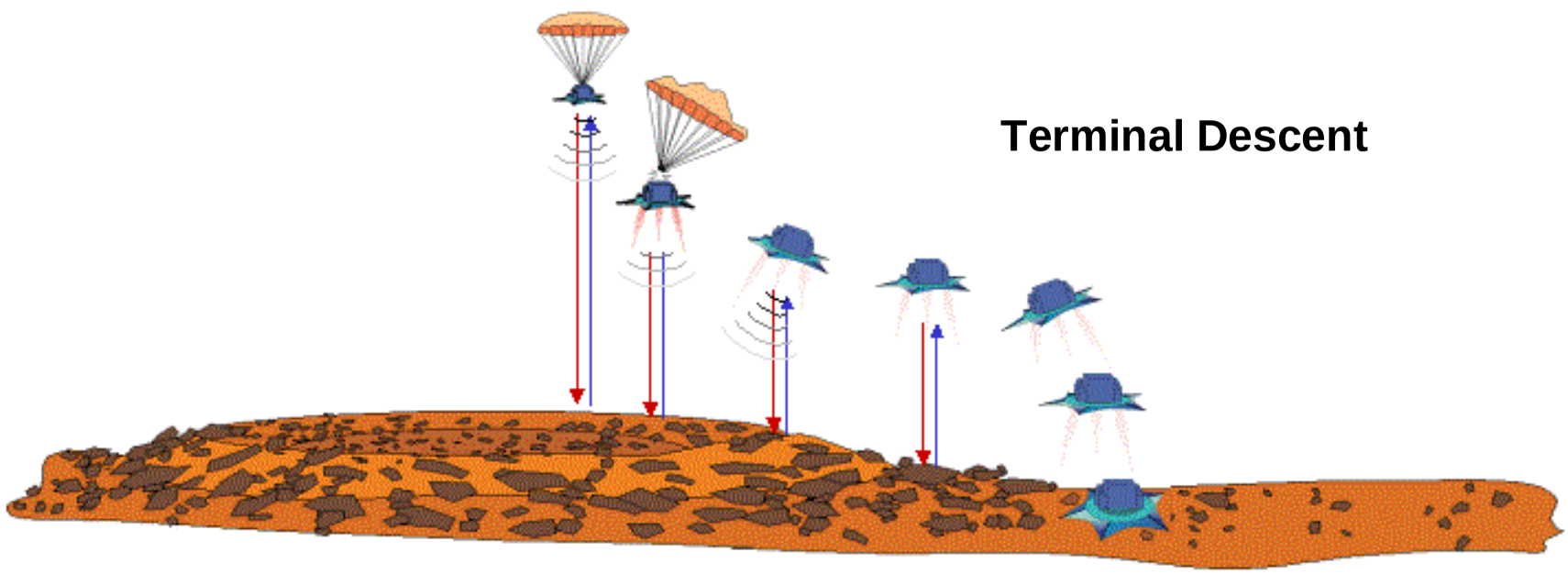
- Landing sites for past missions to Mars have been located in relatively benign terrain
  - Dictated by guidance system inaccuracy and inability of landing system to accommodate extreme rocky or sloped areas
- Recent discoveries of exposed sedimentary rocks and possible near-surface water have ignited interest in exploring more complicated Martian terrain
  - requires improved landing accuracy and robustness over current lander systems.





Next Generation of Landers

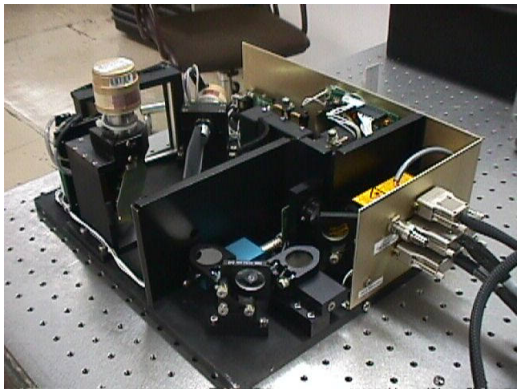
- Will employ a precision soft-landing capability which will enable exploration of hazardous terrain
- Will include a fully-autonomous hazard detection and avoidance safe landing system
  - Maps landing zone with terrain sensor, identifies hazards, and guides vehicle to a safe landing site



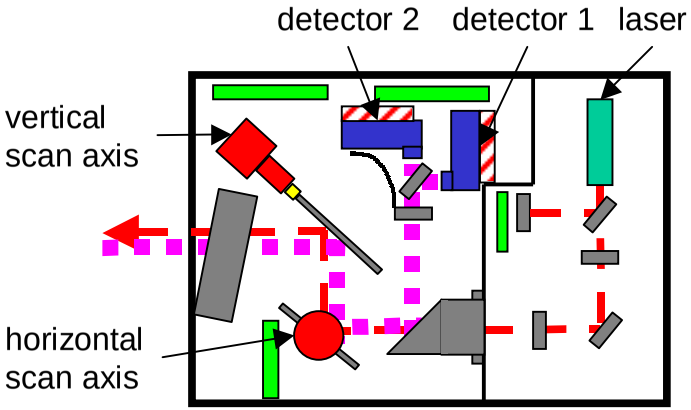
Terrain Sensor

- Scanning LIDAR – LIght Detection and Ranging
  - time of flight, 8000 Hz PRF, 2 mRad divergence
  - 500 m max range, 2 cm range resolution
  - Raster scan, 10º x 10º, 100 x 100 samples
  - Horizontal resolution of 1 m @ 500 m, 10 cm @ 50 m

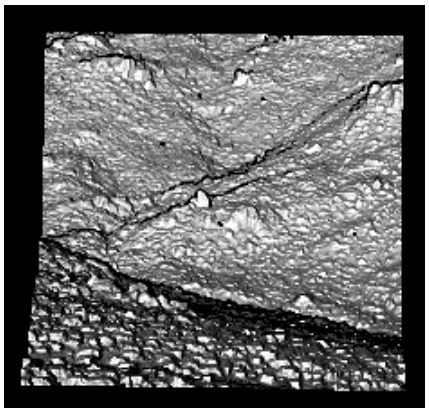
Optech LRI



Optical Layout

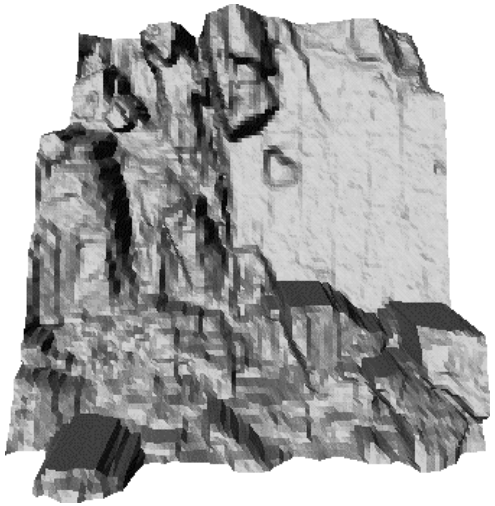


Terrain Map

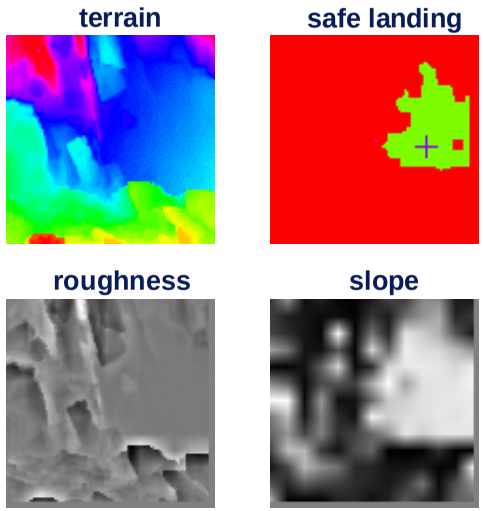


Hazard Detection and Avoidance

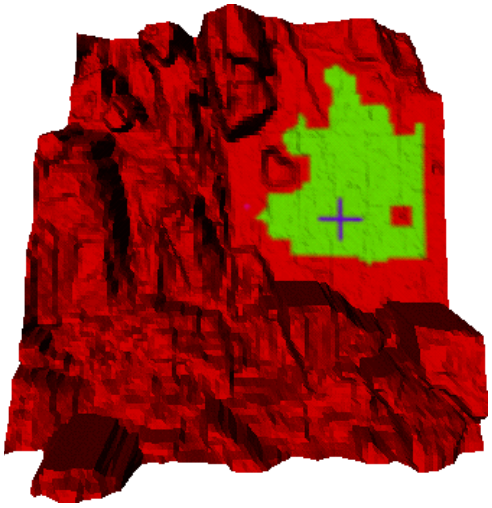
LIDAR Scan: Cliff



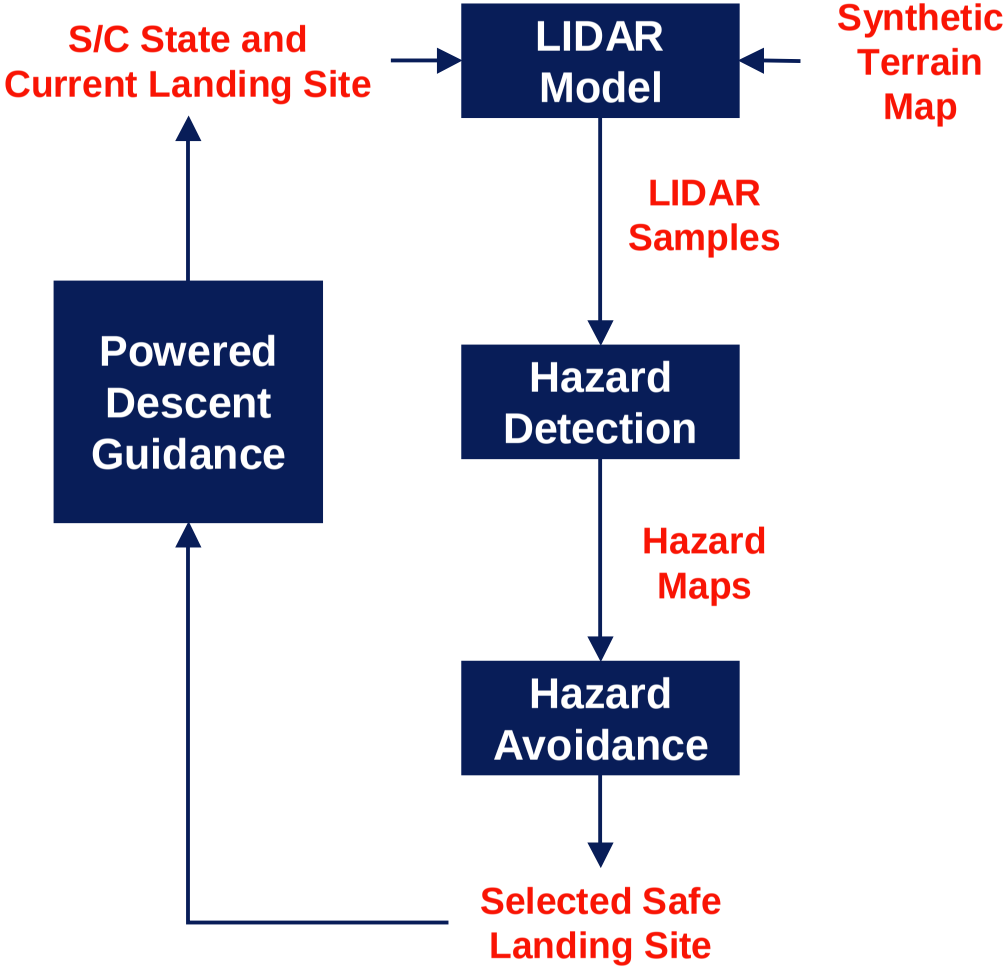
Parameter Maps

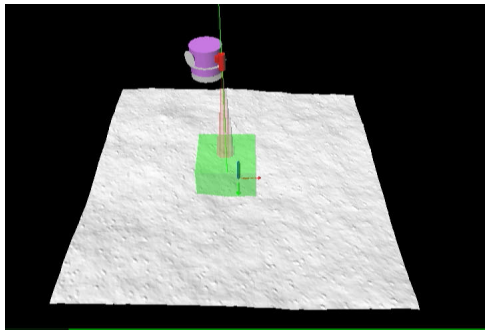


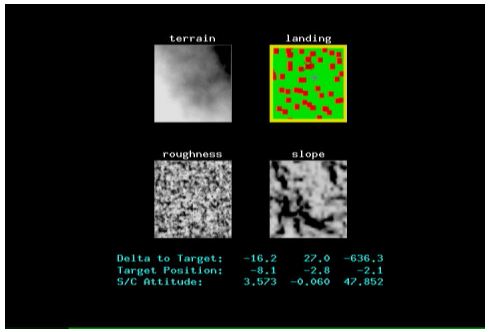
Selected Safe Landing Site

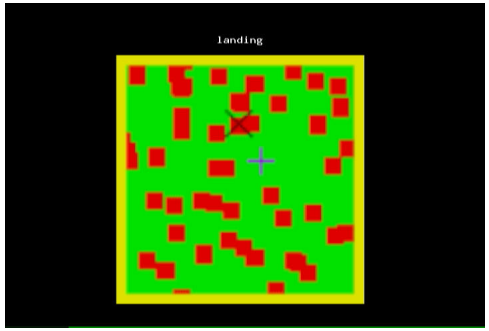


Simulation Overview



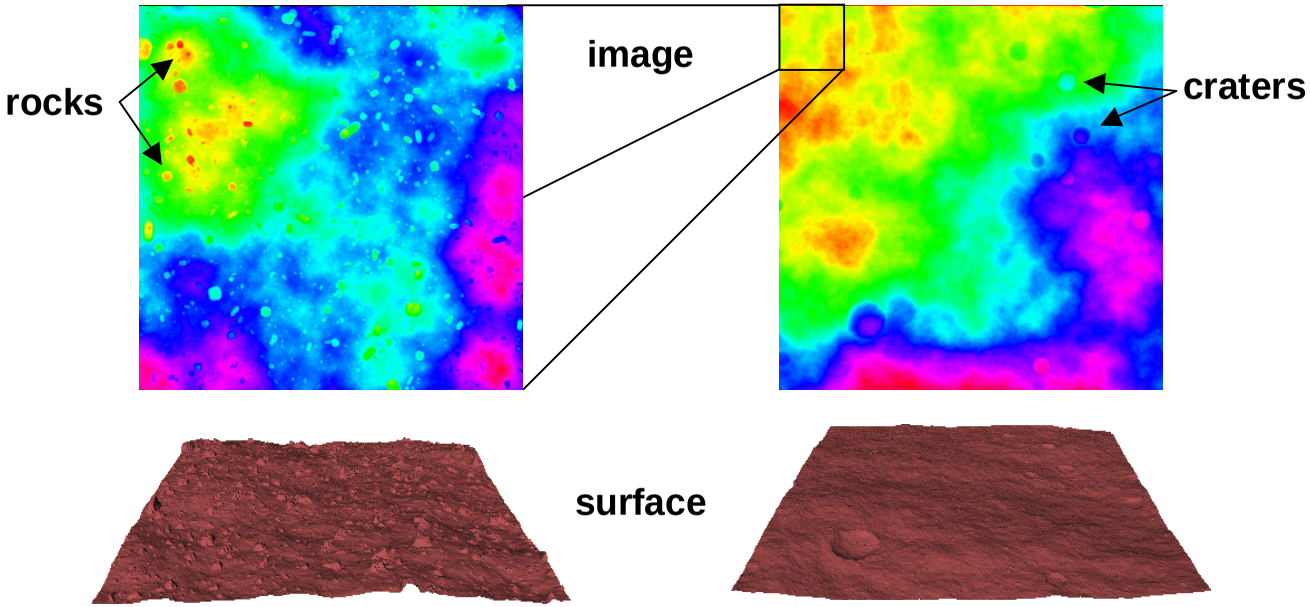






Terrain Map Generation

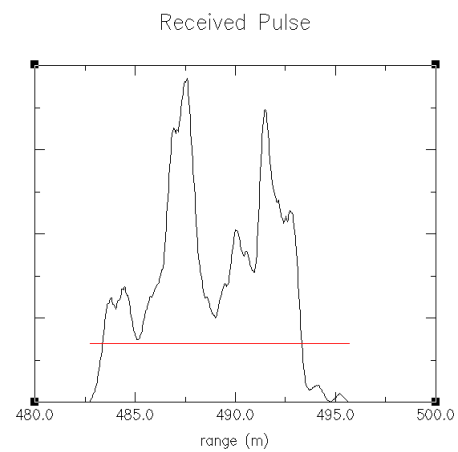
- Realistic topographic data is needed to model hazards
  - based on geophysical processes (Gaskell 1993)
  - initial surface comes from coarse orbiter topography data
  - filled in with fractal terrain
  - populated with rocks and craters
  - models the aging of the Martian surface.

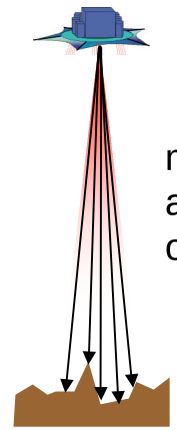


LIDAR Model

- range sensing errors
  - detector noise
  - pulse stretching
  - efficient ray tracing
- pointing errors
- real-time simulation
  - 50 μs/sample

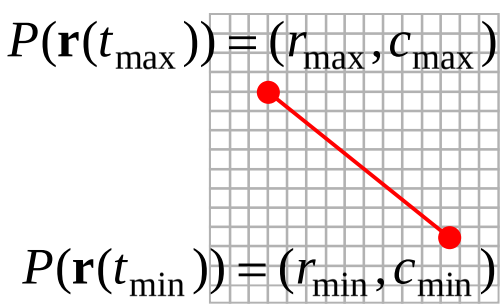
Pulse Stretching

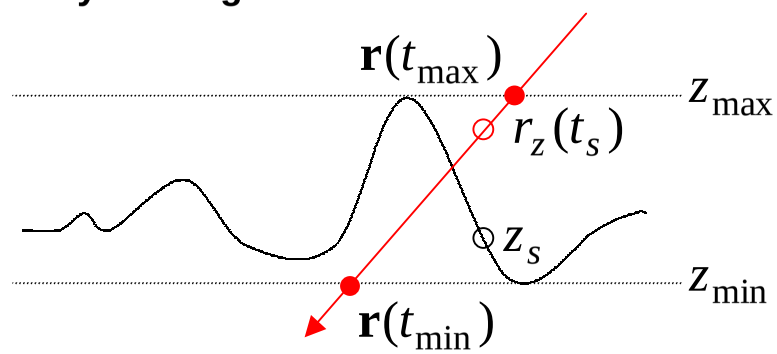




model pulse as bundle of rays

Efficient Ray Tracing

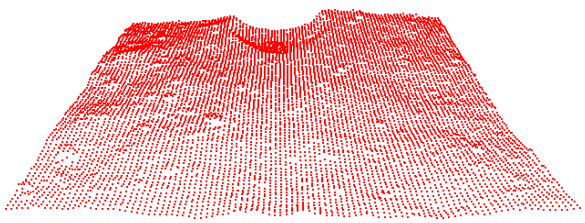




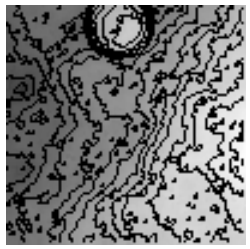
Elevation Map Generation

- Create elevation map *Z(r,c)* from LIDAR samples
  - set bounds and grid cell size based on LIDAR scan
  - project *(x,y,z)* to *(r,c,z)* using bilinear interpolation
  - fill holes with modified grassfire transform

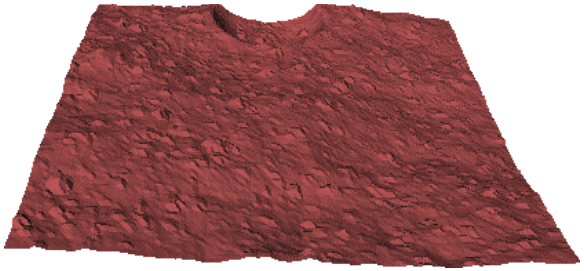
samples



elevation map (contour image)



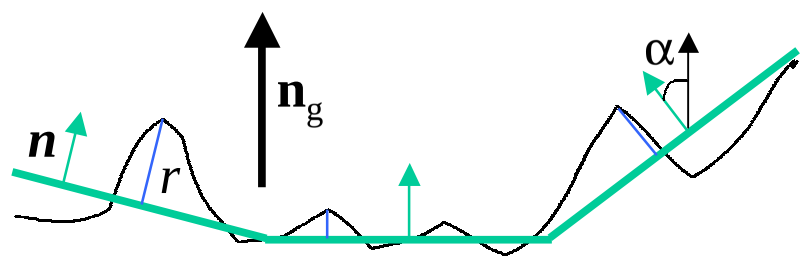
elevation map (3-D surface)



Hazard Map Generation

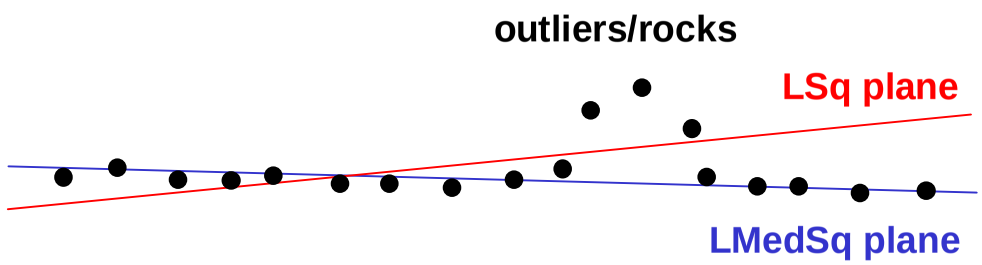
- Detect hazards in elevation map
  - fit robust plane $(\mathbf{n},d)$ to local regions of $Z(r,c)$
  - generate smooth underlying elevation map $Z_s(r,c)$
  - compute landing incidence angle map $A(r,c) = \alpha$ using global normal $\mathbf{n}_g$
  - compute roughness map $R(r,c) = | Z(r,c) - Z_s(r,c)|$
  - Use coarse grid and bilinear interpolation to decrease computation

$$\alpha = \mathrm{acos}(\mathbf{n}_g \cdot \mathbf{n})$$
$$r = \max_i(\mathbf{n}\mathbf{x}_i + d)$$



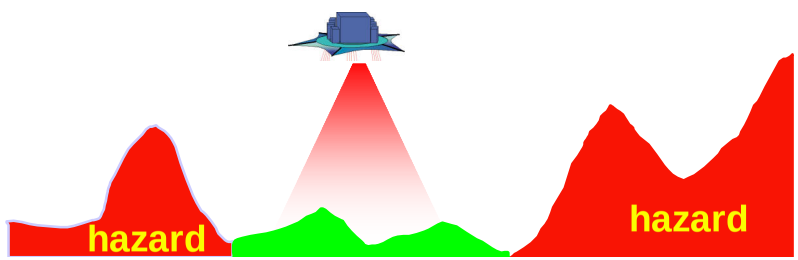
Robust Plane Fitting

- Mars hazard detection
  - underlying surface is desired for slope computation
  - rocks are outliers
- Least Median Square (LMedSq) plane fitting
  - robust plane fitting to 3-D points with outliers
    - repeat for multiple triples
      - select random triple of points and fit plane
      - if median of square plane error is minimum keep as best
    - throw out points that are far from plane
    - fit Least Square (LSq) plane to remaining points



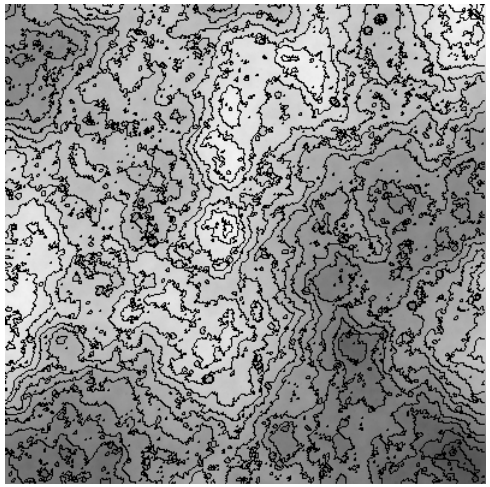
Hazard Avoidance

- Philosophy: land at the safest place that is far from hazards
- Lander hazard tolerance places constraints on landing
  - max roughness R_{max} and max landing incidence angle α_{max}
- Generate landing cost map $C(r,c)$ that combines constraints
  - Define determine hazard cells where $R(r,c) > R_{max}$ or $A(r,c) > \alpha_{max}$
  - if (r,c) is within the lander size of a hazard cell then $C(r,c) = 1$
  - else $C(r,c) = R(r,c)*A(r,c)/(R_{max}*\alpha_{max})$
- Smooth $C(r,c)$
- Select landing site as (r,c) the minimizes $C(r,c)$

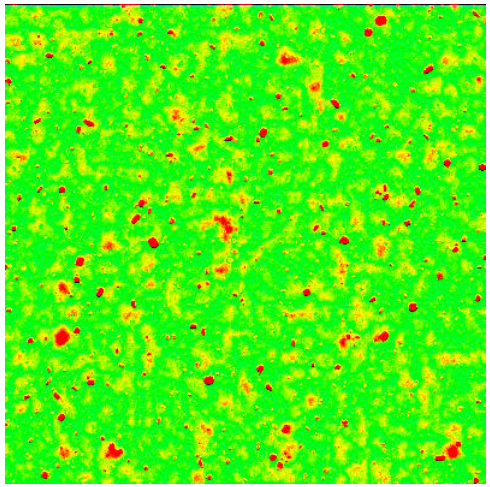


Hazard Avoidance Example

Elevation

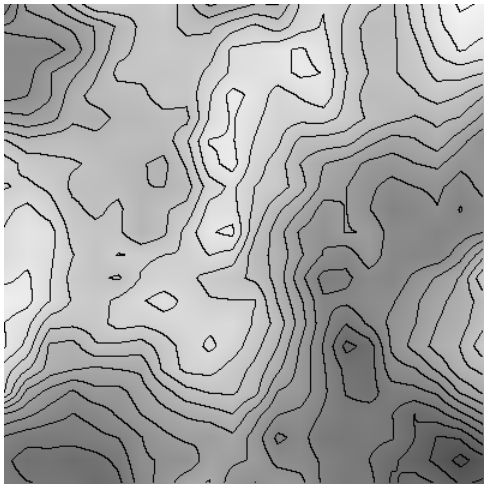


Surface Roughness

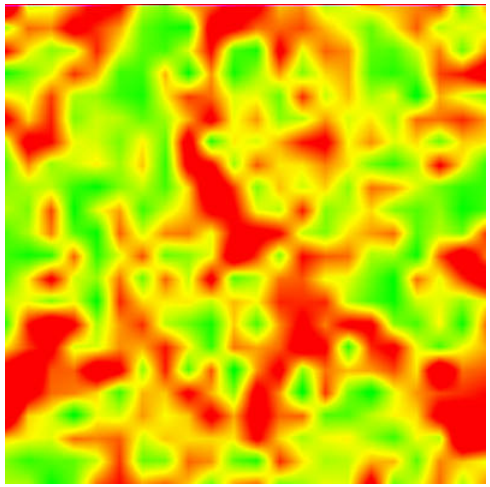


Cost

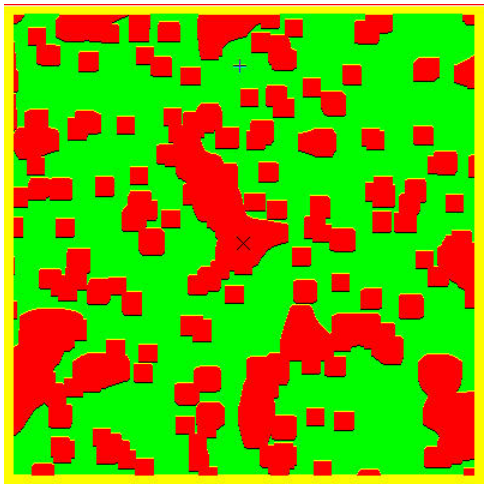
Smooth Elevation



Incidence Angle



Safe Landing

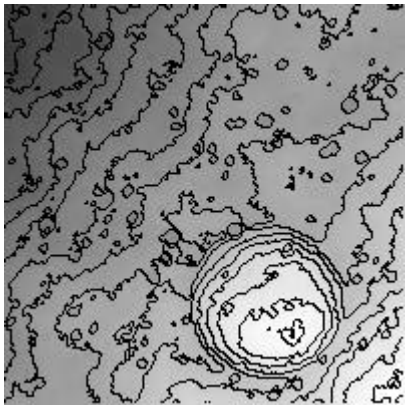


Powered Landing Guidance

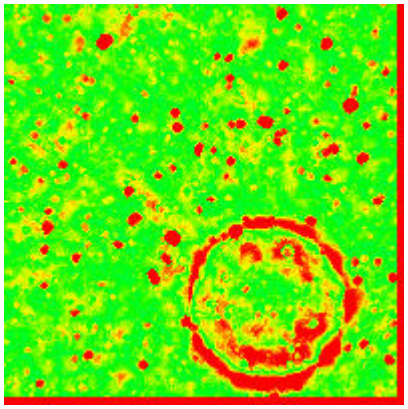
- Adapted from that flown on Apollo
  - Retarget at any time
- Transfers lander from current position and velocity to touchdown in two phases
  - approach (down to 5-10 meters above surface)
  - vertical descent (down to landing)
- Each phase has a target point where the position, velocity, and acceleration are all specified.
- Guidance algorithm solves a two-point boundary-value problem.
  - initial and target position and velocity
  - solved by polynomial fitting

Simulation

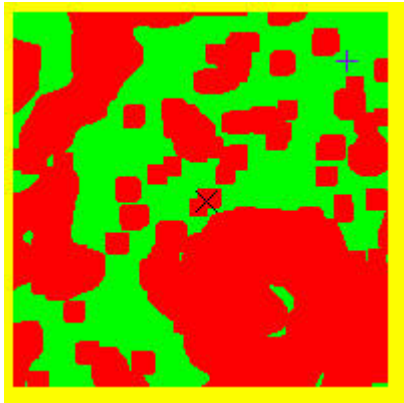
Elevation



Surface Roughness

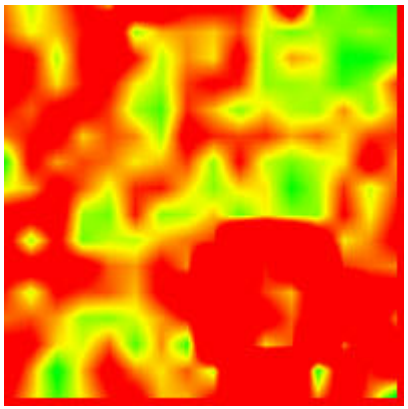


Safe Landing

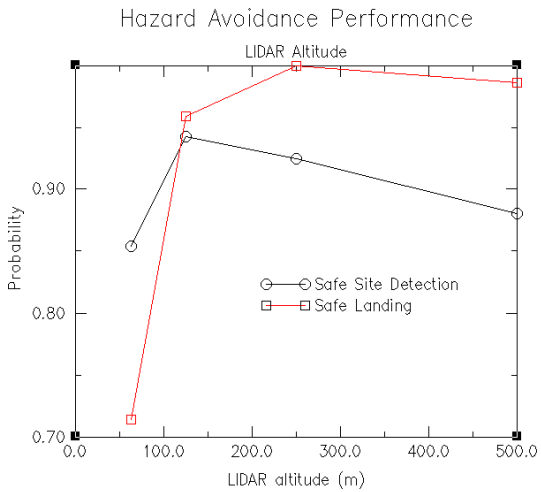


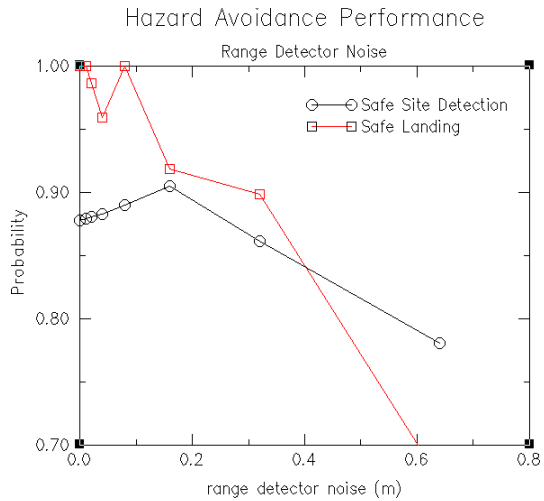
Smooth Elevation

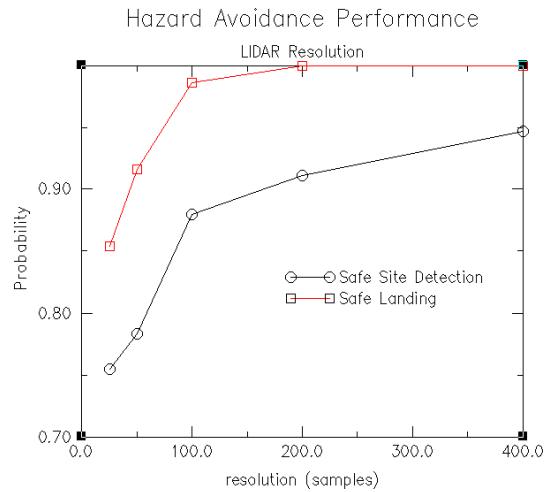
Incidence Angle



Preliminary Monte Carlo Results







	Rock Density		
	0.10	0.15	0.20
Safe Landing Probability	1.00	0.98	0.93

Future Work

- Incorporate into complete terminal guidance and control simulation for safe landing
  - POST
  - Darts/DSHELL
- Monte Carlo simulations to for mission design
  - LAMP requirements
  - Mars Smart Lander requirements
- Incorporate fuel consumption into safe site selection