Autonomous Robotic Systems for Mars Exploration

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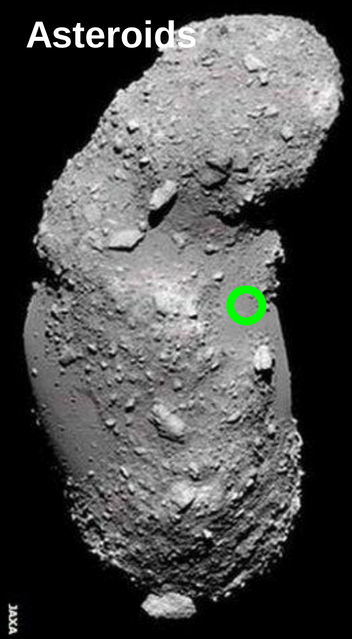
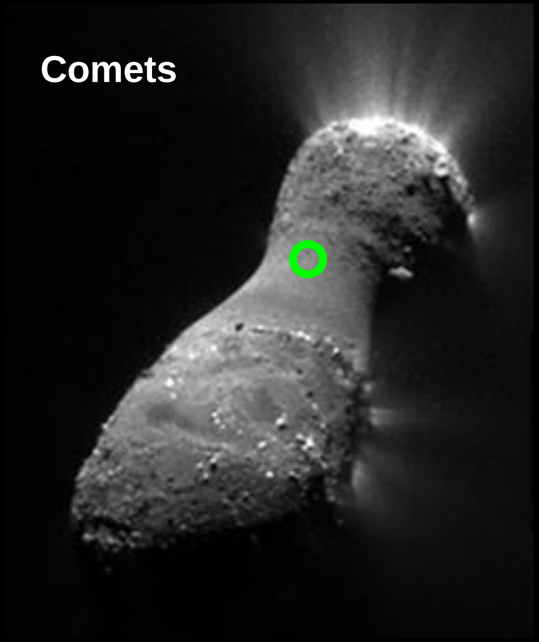
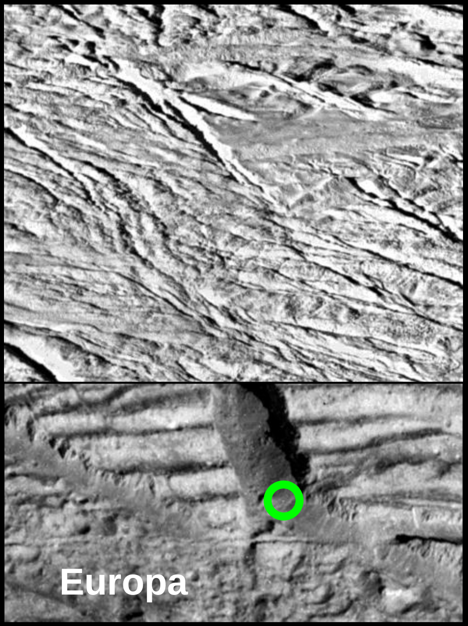
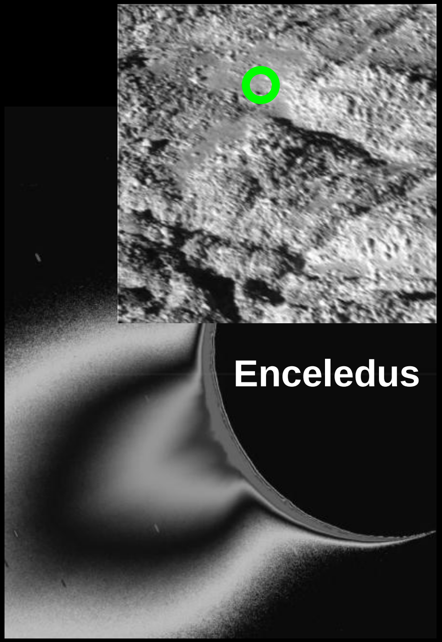
Science versus Safety

- The highest science return is often in very challenging terrain for landing.
- Current landing systems cannot access these sites because of the high risk

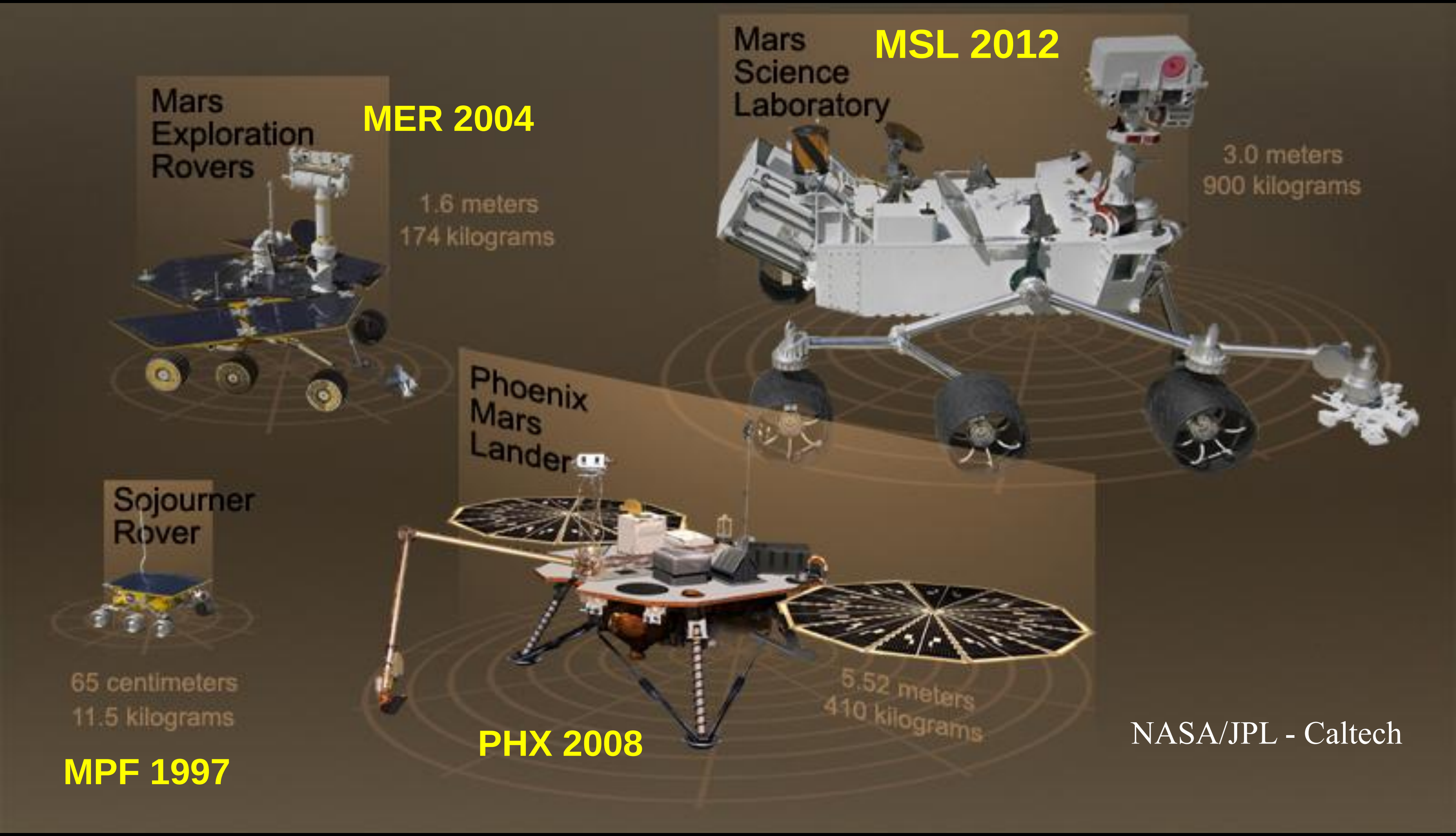








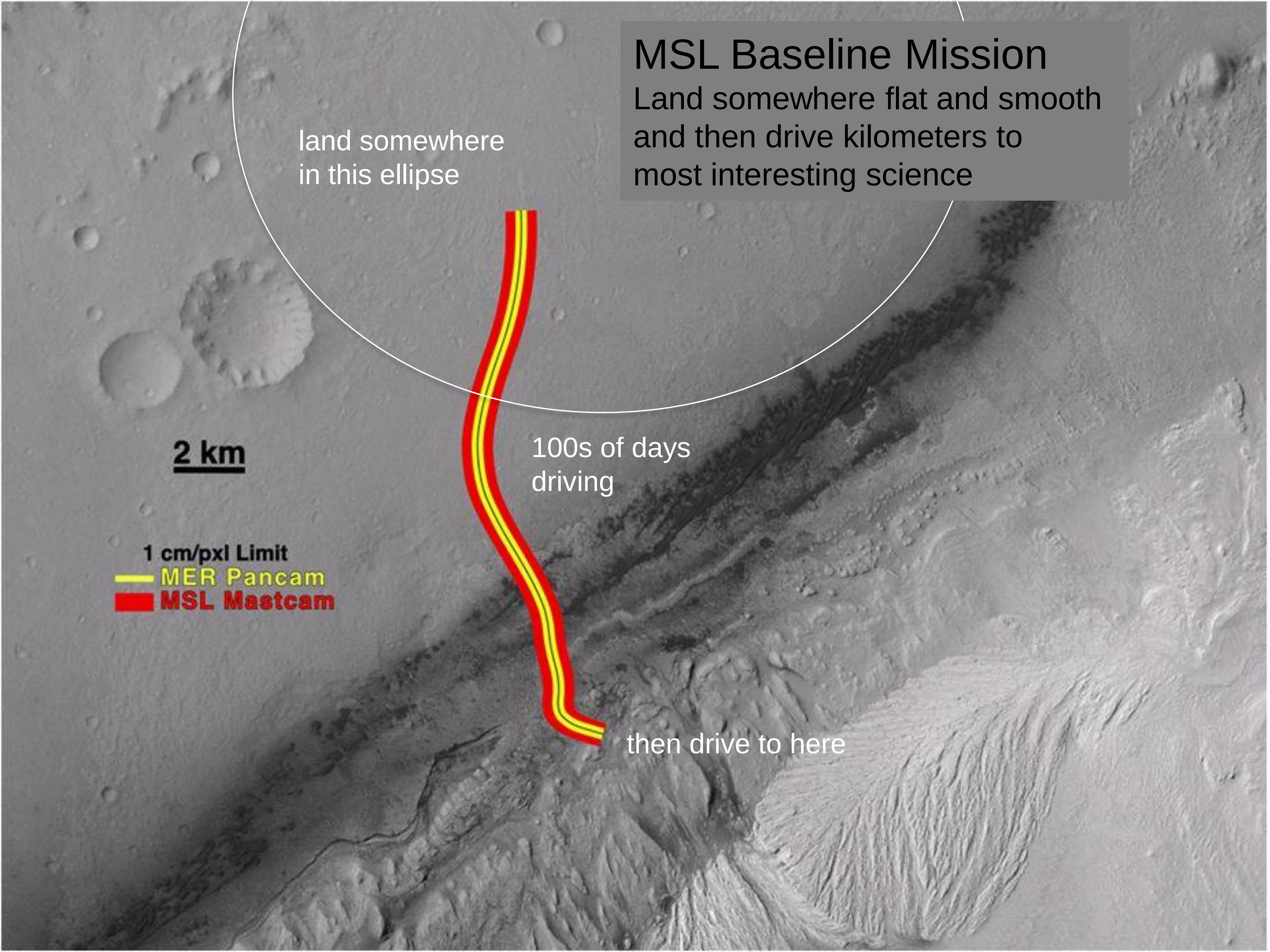
Recent NASA Mars Surface Vehicles

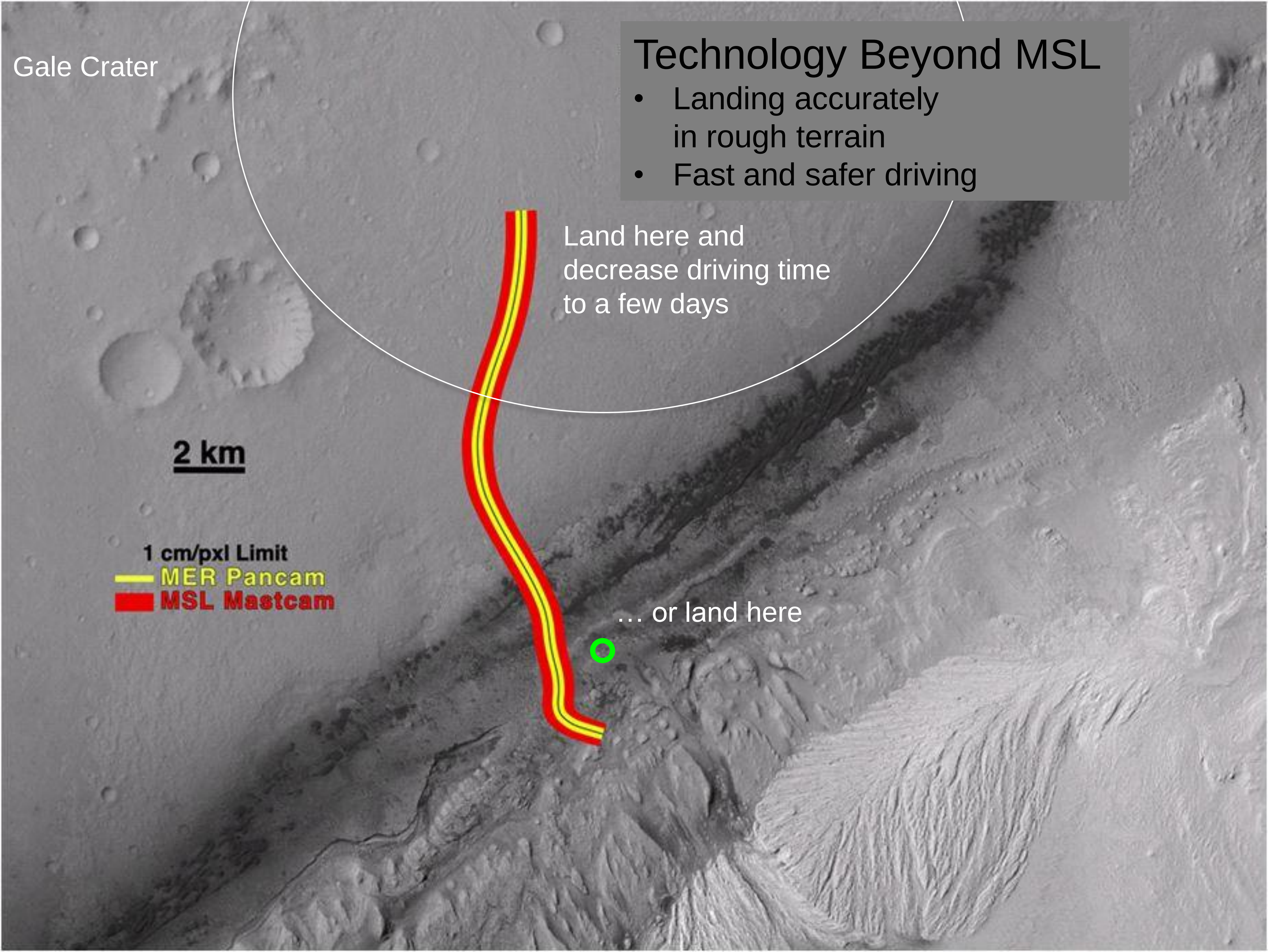


Development Challenges for MSL

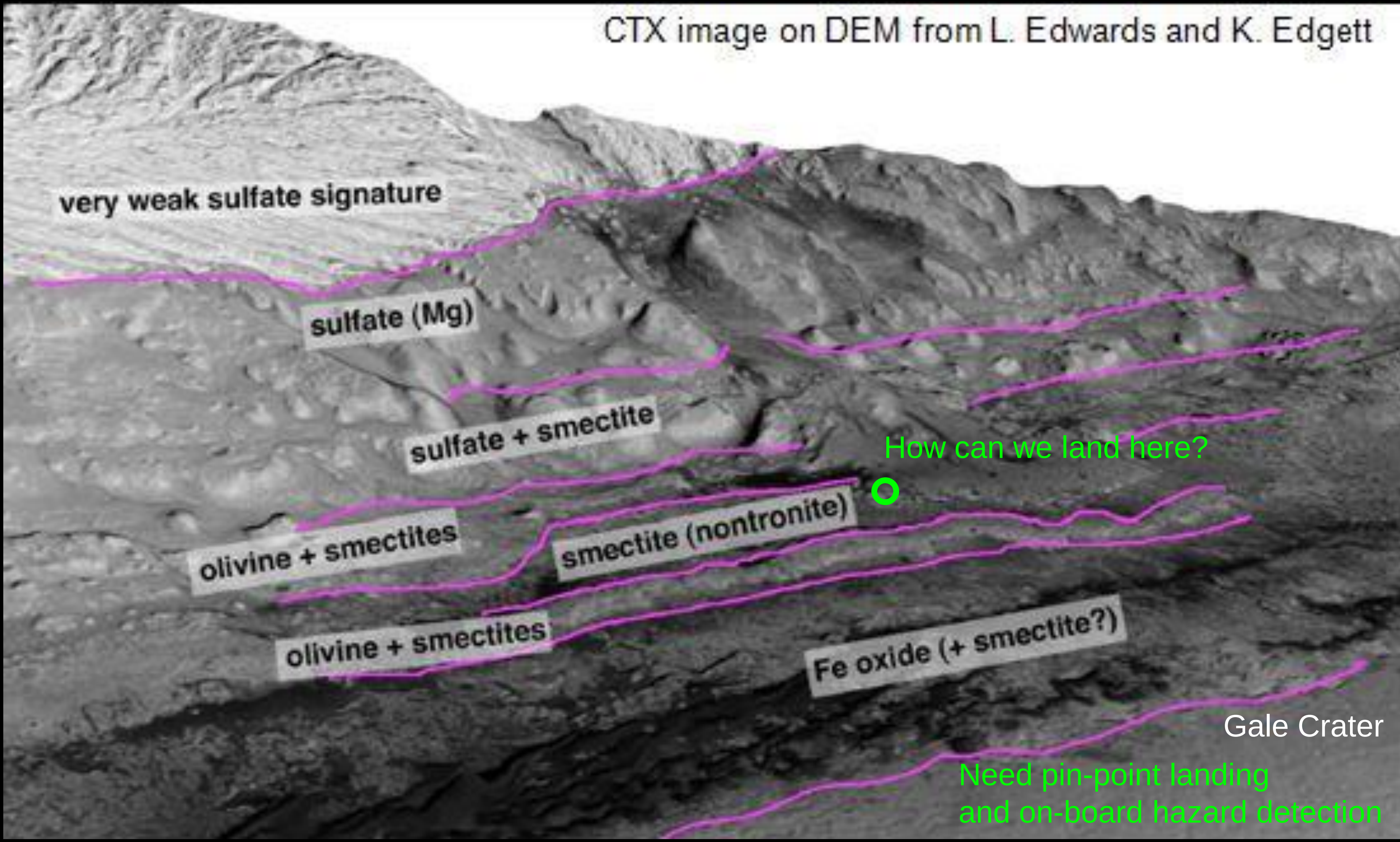
MSL Baseline Mission

Land somewhere flat and smooth and then drive kilometers to most interesting science




Gale Crater
Technology Beyond MSL
• Landing accurately in rough terrain
• Fast and safer driving
Land here and decrease driving time to a few days
2 km
1 cm/pxl Limit
MER Pancam
MSL Mastcam
… or land here

Safe and Precise Landing



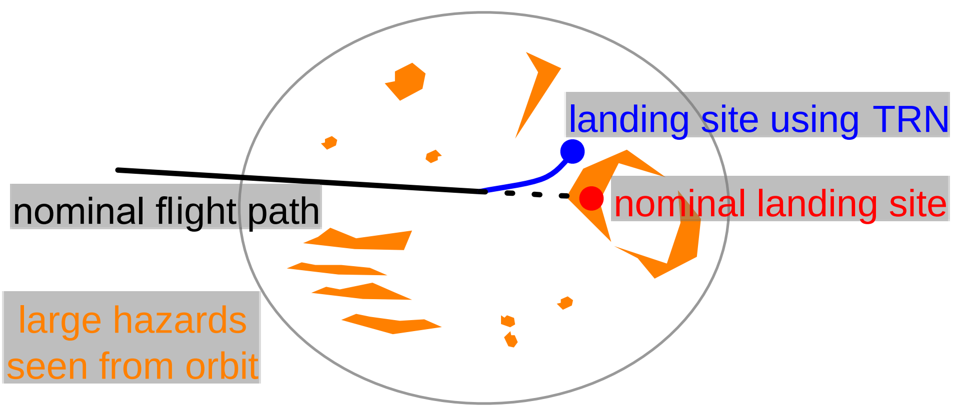
Two Landing Problems to Solve

Terrain Relative Navigation (TRN)

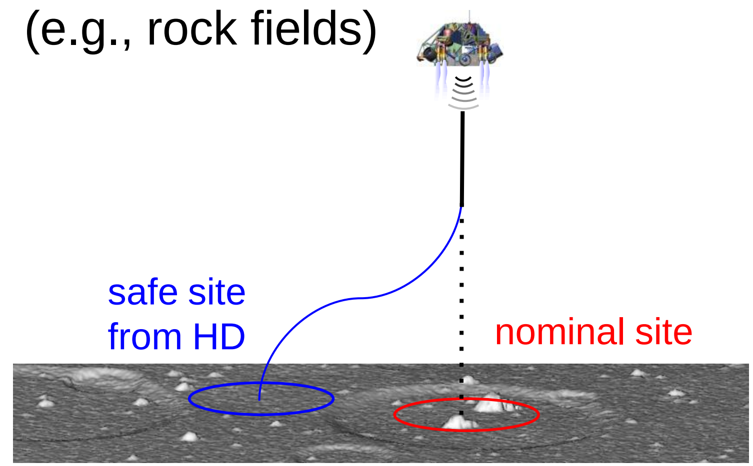
- Avoids known large hazards seen from orbit through on-board map relative position estimation
- Allows selection of landing ellipses with large hazards (e.g., hills, craters)

Hazard Detection (HD)

- Avoids unknown small hazards (rocks, scarps) through on-board terrain mapping during landing
- Allows selection of landing ellipses with a large number of small hazards (e.g., rock fields)



25km x 20km landing ellipse



local terrain around touch down

TRN and HD

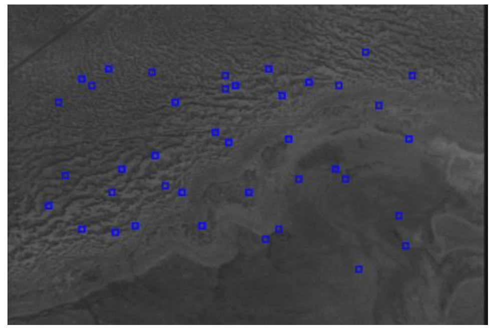
- are complimentary and use different technology
- increase number of selectable landing sites
- reduce mechanical complexity of the landing system

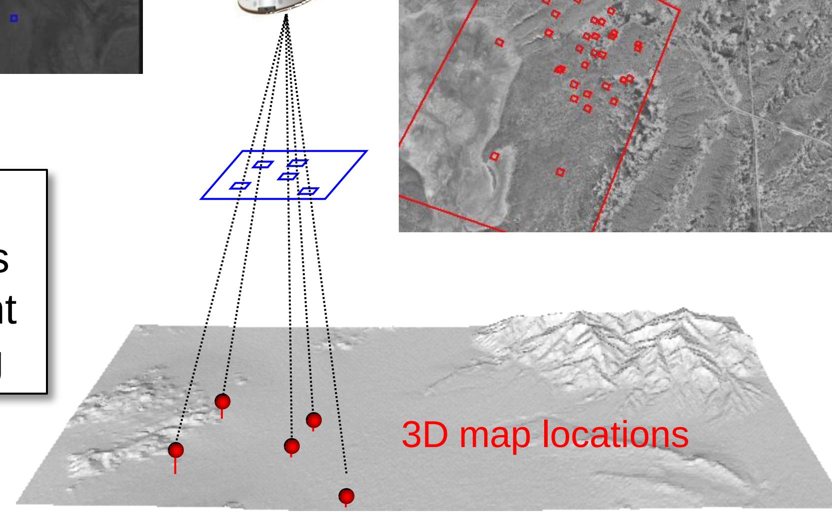
Terrain Relative Navigation (TRN)

Terrain relative navigation combines inertial measurements with (1) landmark matches between a descent image and a reference map and (2) features tracks through a stream of images to estimate map relative position attitude and velocity.

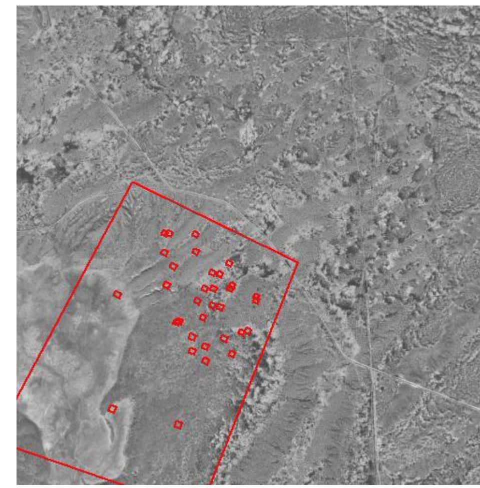
TRN Algorithms

(1) Features tracked in descent imagery



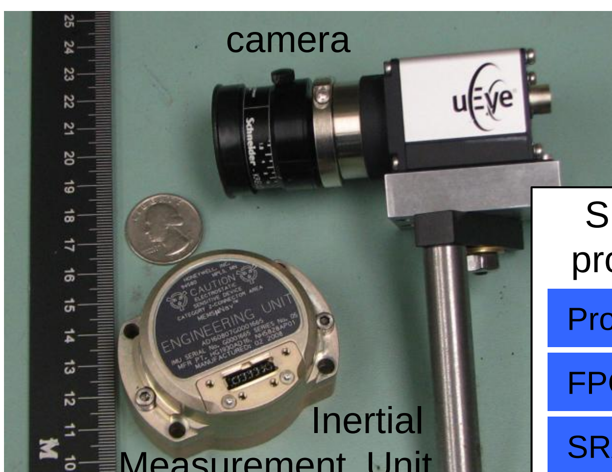


(2) landmarks matched to reference map



TRN enables pin-point landing

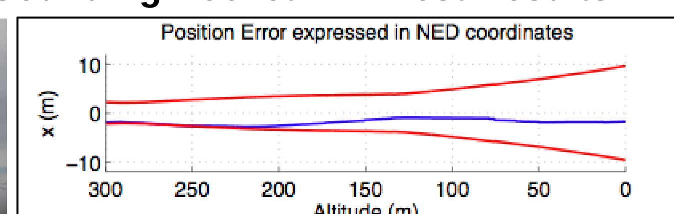
TRN Hardware



Single board processor card

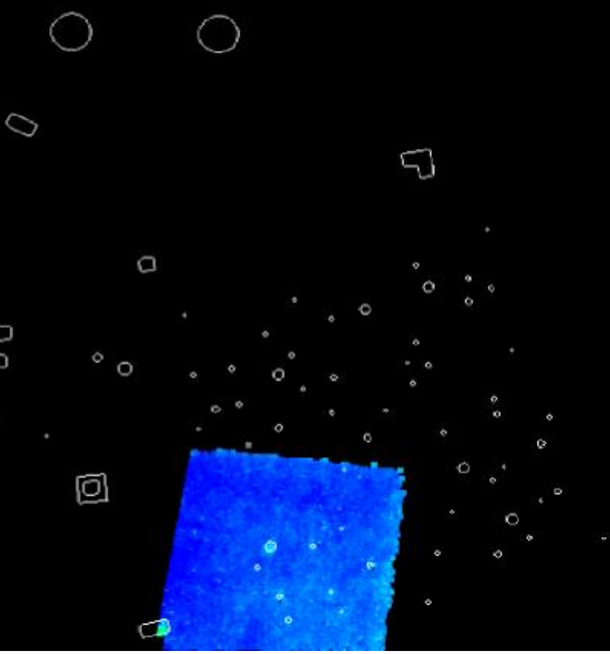
- Processor
- FPGA
- SRAM Memory

Sounding Rocket TRN Test Results



Landing Hazard Detection (HD)

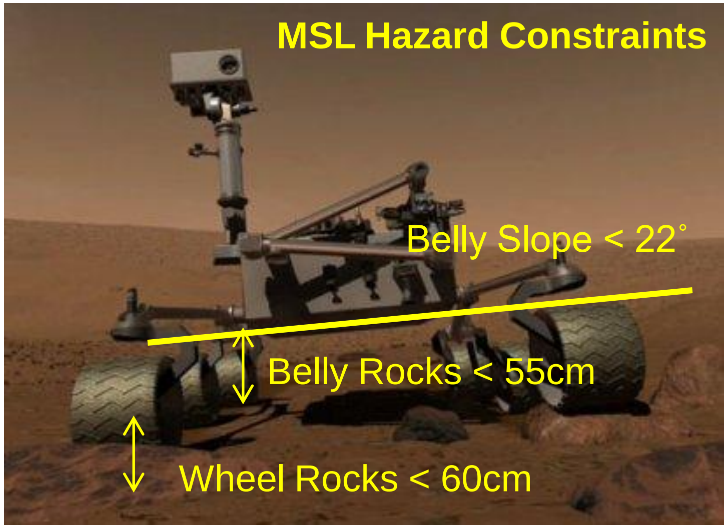
HD builds an elevation map from on-board lidar data, computes a safety probability across the map and directs the lander to target the safest reachable landing site



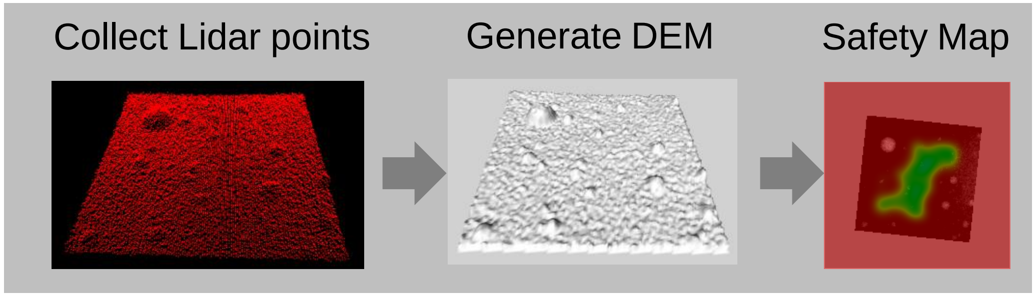
HD Components

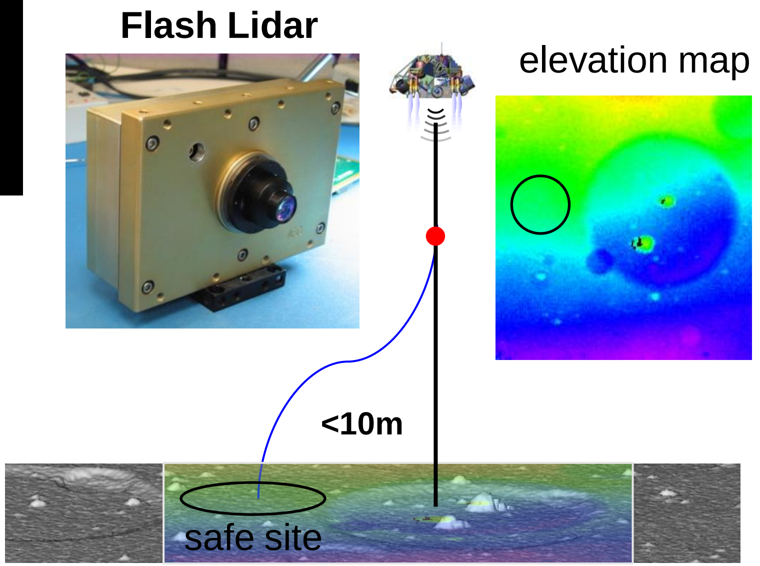
– **HD lidar** generates an elevation map from one image

– **HD algorithm** identifies safe sites free of rocks and slopes



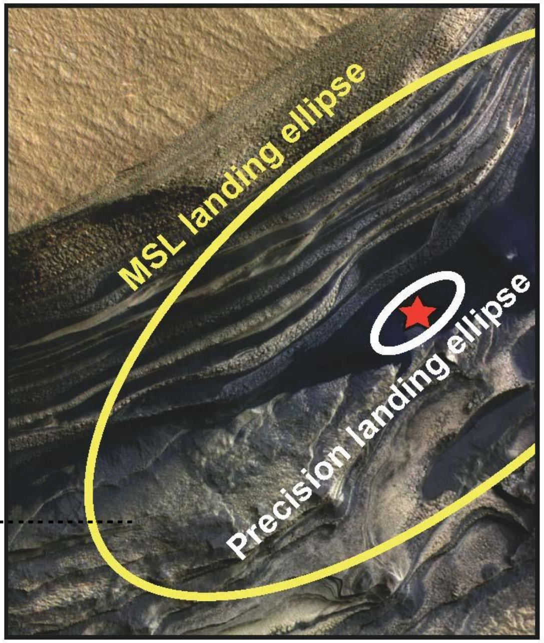
HD Algorithm

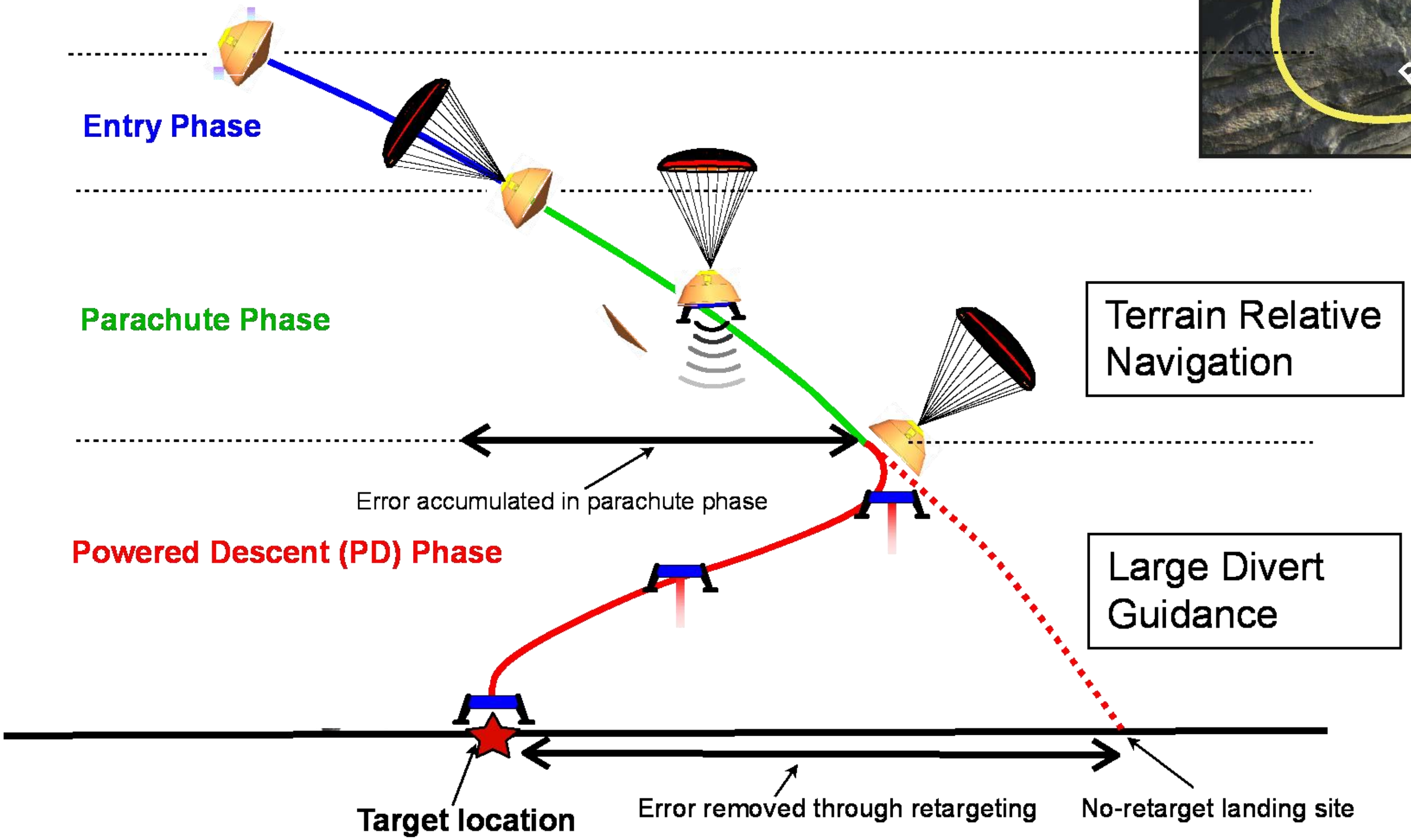




Large Divert Guidance (LDG)

- Large divert guidance computes the fuel optimal trajectory to a target kilometers away while satisfying constraints on off nadir attitude and altitude.
- On-board algorithm enables pinpoint landing or large hazard avoidance.

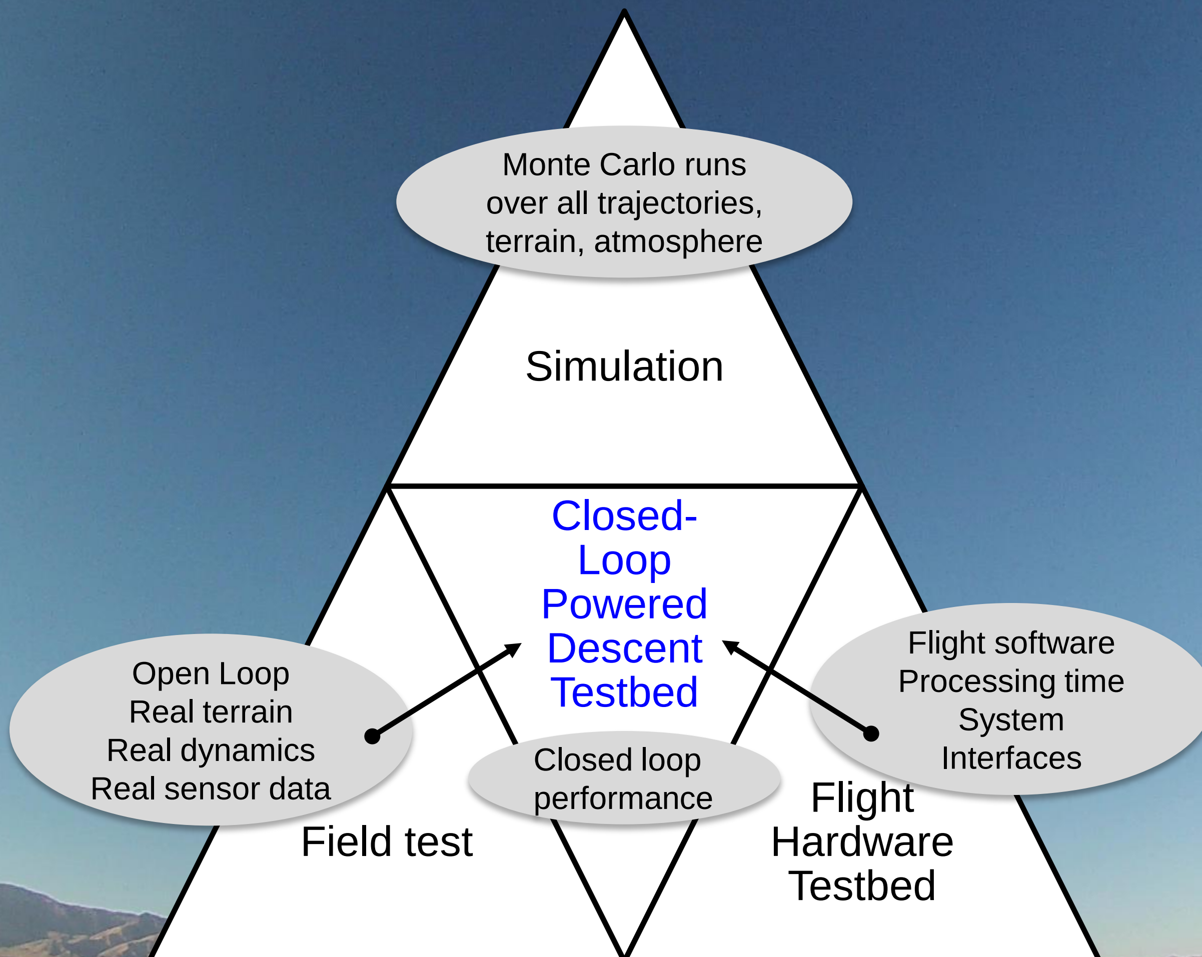




Behcet Acikmese

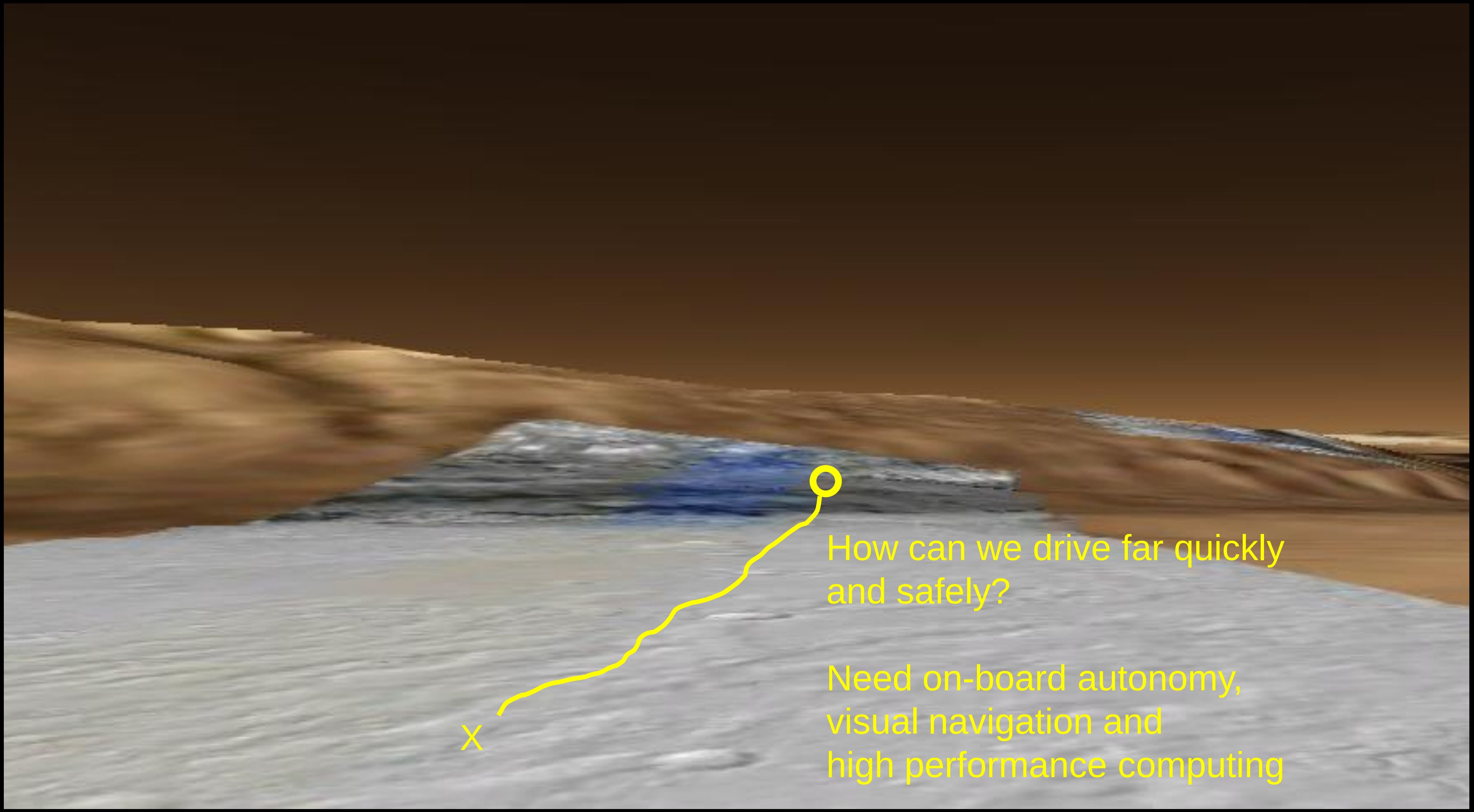
Closed Loop Testing for Landing

Terrestrial Propulsive Free-Flyer



vehicle and movie from Masten Aerospace

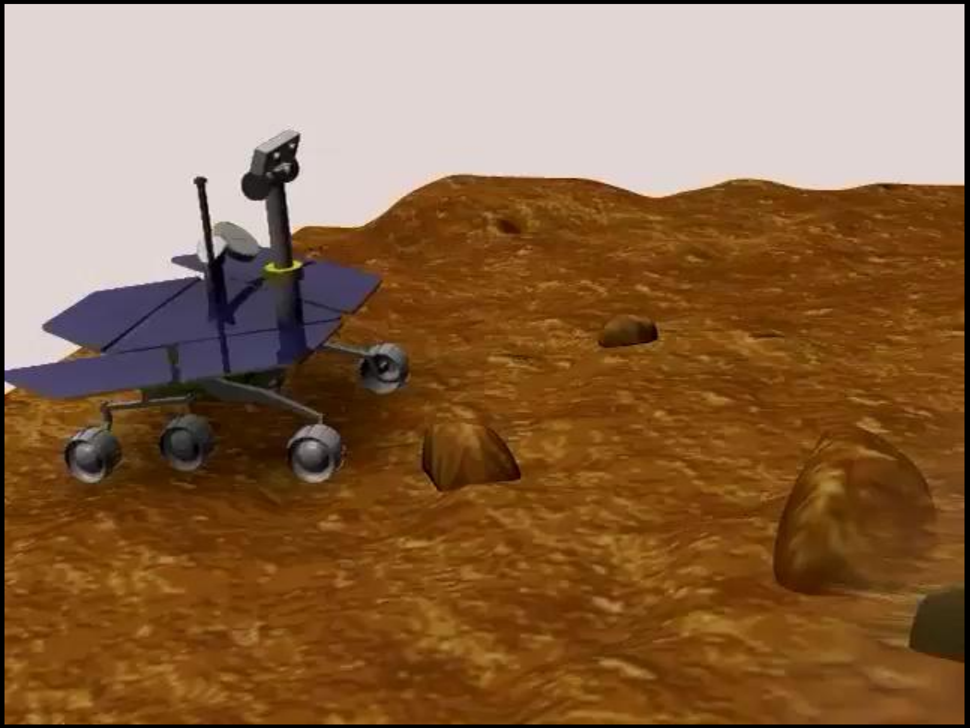
Fast Rover Traverse



Rover Hazard Avoidance (AutoNav)

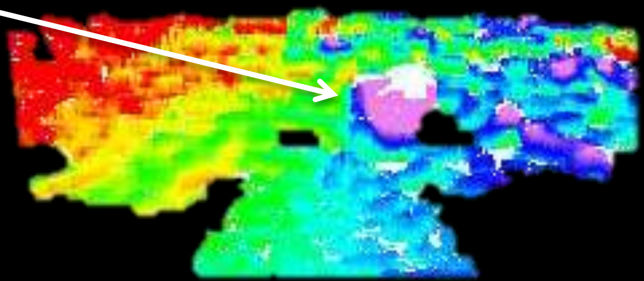
Stereo vision based hazard avoidance (Autonav) enables autonomous rover traverse in rough and/or unknown terrain

- Over the horizon driving
- Navigating in rock field with rover slip



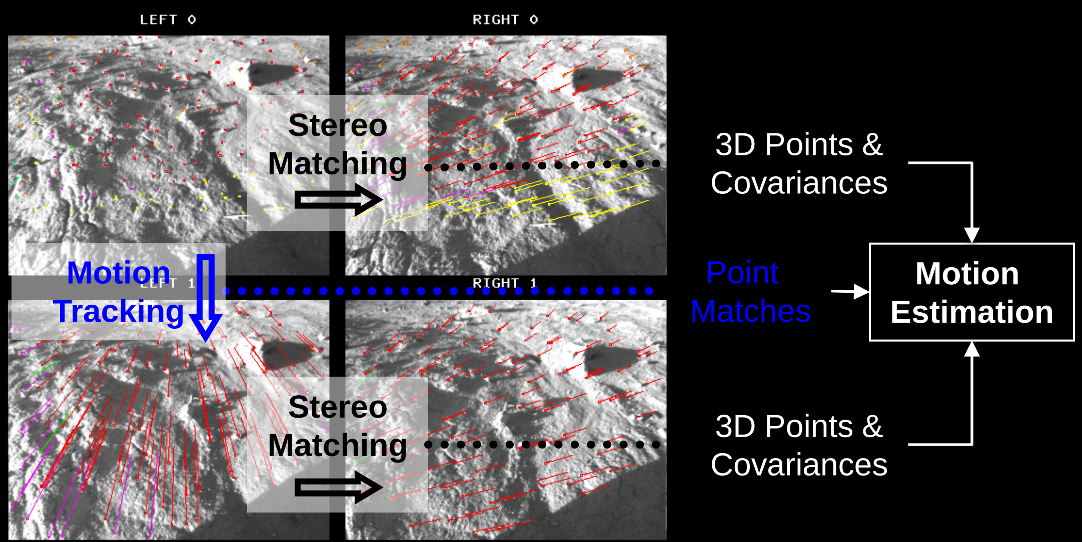
HazCam image

Elevation map



Mark Maimone

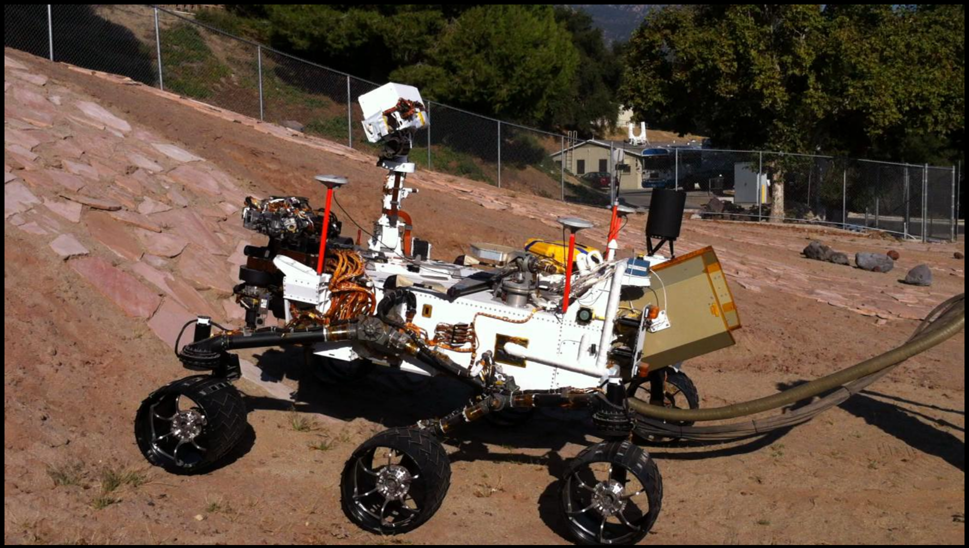
Rover Visual Odometry (VO)

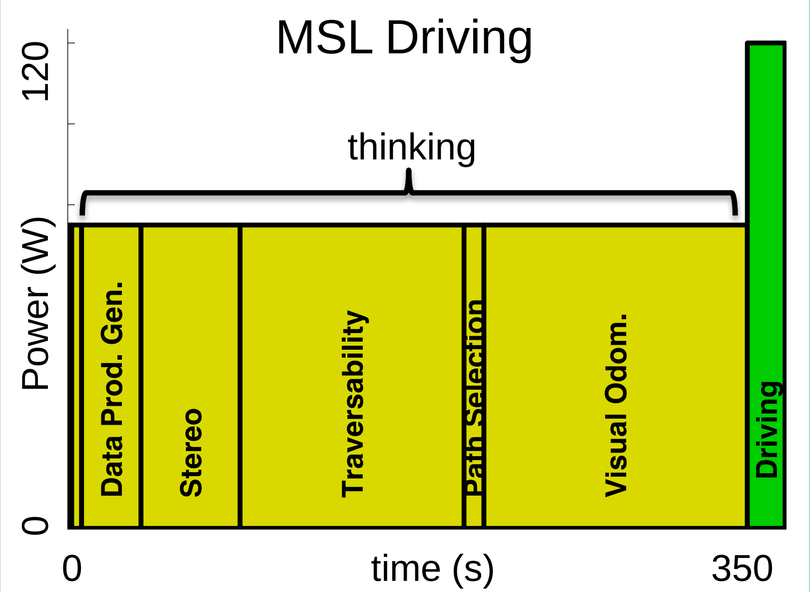


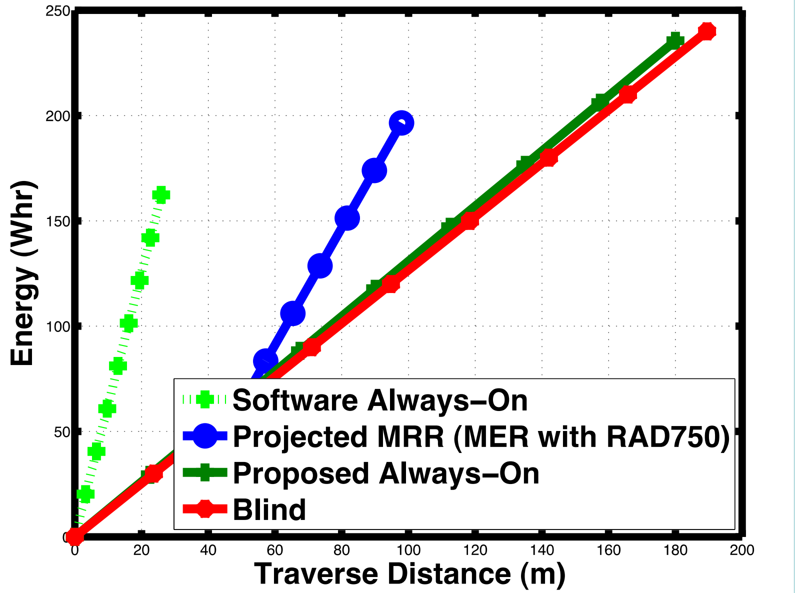
Visual Odometry enables precise position estimates even when the rover slips

- navigation in complicated terrain
- check on rover slip to prevent digging rover into hole

Faster Driving is Safer and More Energy Efficient

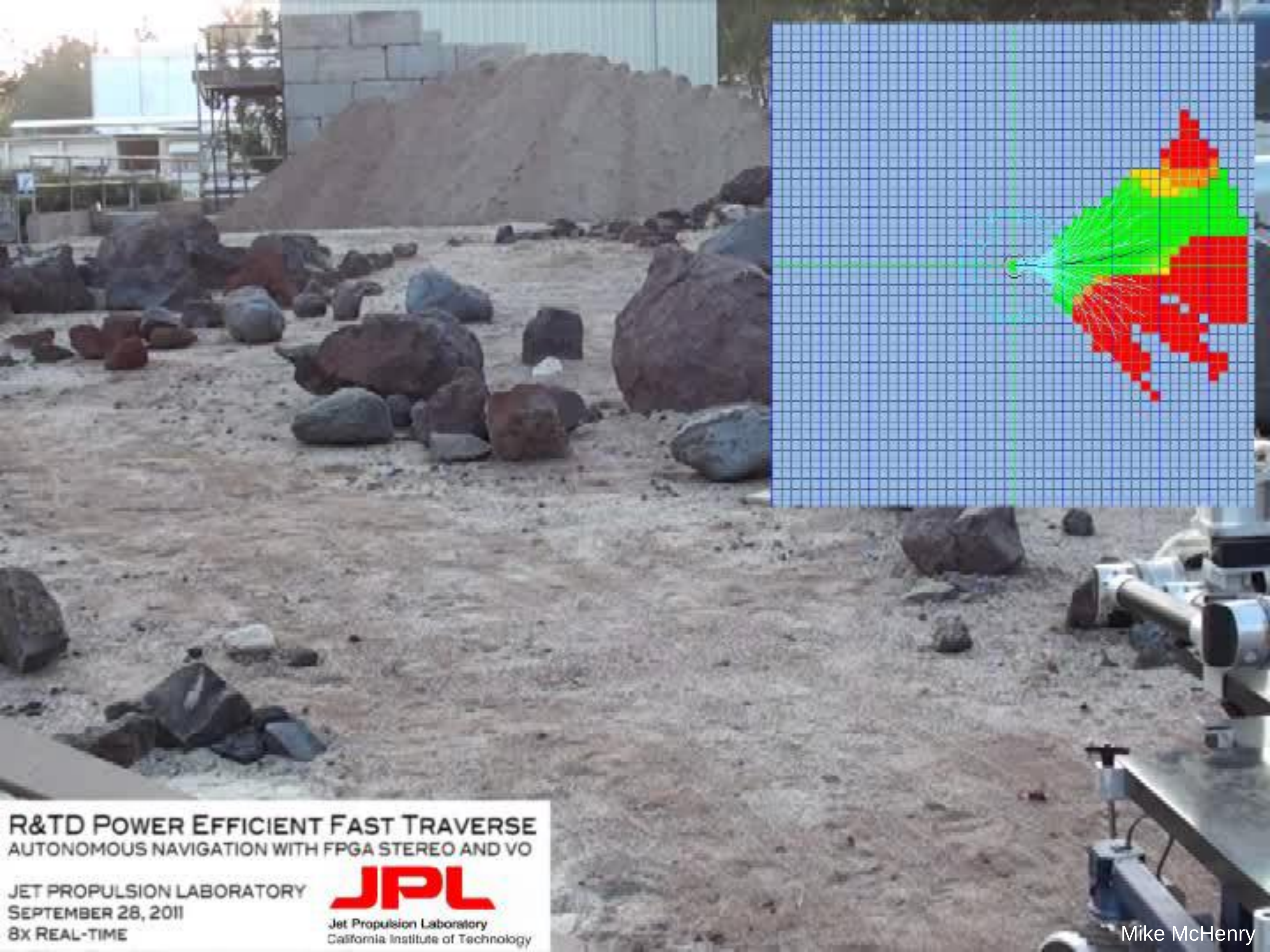






- The MSL rover drives slowly and must stop to process imagery.
- If VO &Autonav are "always on" driving is:
  - **Faster:** Eliminate the need for the rover to stop and 'think'
  - **Safer:** AutoNav hazard avoidance and VO slip checking
  - **More Efficient:** Eliminate energy wasted while 'thinking'

Mike McHenry


R&TD POWER EFFICIENT FAST TRAVERSE
AUTONOMOUS NAVIGATION WITH FPGA STEREO AND VO
JET PROPULSION LABORATORY
SEPTEMBER 28, 2011
8X REAL-TIME
JPL
Jet Propulsion Laboratory
California Institute of Technology
Mike McHenry

Open Questions

- Technology adds risk to a mission
  - What methods do you use to promote technology in the face of this risk?
  - Are there risk categories?
  - Can the risks be quantified?
- Technology must be validated before use
  - Do you cover the entire operational/usage envelop?
  - What methods do you use (e.g., sim, field testing)?
  - What is the right mix of methods?
  - How do the methods cross check each other?
  - When is there sufficient validation (cost versus risk)?
- Human vs Machine
  - What is the right balance between autonomy and human control?
  - How do we prove a fully autonomous spacecraft will do what we want?
  - Do we have to prove this before flying one?