Approach and Entry, Descent, and Landing Operations

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…didn’t this thing land itself?

Jet Propulsion Laboratory, California Institute of Technology
…it did land itself, but needed a little help first

*Three primary objectives for approach/EDL operations:*

- Get the spacecraft ready to do EDL
- Get to the right place at the right time
- Tell the spacecraft what it needs to know
Getting the Spacecraft Ready

- Layered EDL preparation activities on top of “normal” cruise activities during the last month

- Performed hardware checkouts: radar, throttle valves, etc.

- Conducted cold boot activities
  - Cleared flash memory and perform cold processor resets of both strings
  - Intended to match ground test conditions in flight

- Loaded flight parameters: EDL and early surface

- Started power and thermal conditioning for EDL
  - Charged batteries
  - Warmed up propulsion system
Getting to the Right Place at the Right Time

- Although MSL has guided entry, it’s still sensitive to delivery error
  - Entry guidance control authority isn’t unlimited
  - Altitude and landing precision impacted
  - Can increase cruise stage recontact risk

<table>
<thead>
<tr>
<th>Error</th>
<th>EDL System Impact</th>
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<tbody>
<tr>
<td>Steep Flight Path Angle</td>
<td>• Reduced entry guidance control authority</td>
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<td></td>
<td>• Increased guidance prediction error</td>
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<td>• Risk of guidance saturation</td>
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<tr>
<td></td>
<td>• Loss of altitude/timeline margin</td>
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<td></td>
<td>• Reduced testing experience</td>
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<tr>
<td>Shallow Flight Path Angle</td>
<td>• Reduced entry guidance control authority</td>
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<tr>
<td>Reduced Crosstrack Bias</td>
<td>• Increased cruise stage recontact risk</td>
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- Also, closer to target = closer to majority of tested/simulated conditions
TCM Risk Balancing

- Trajectory Correction Maneuvers (TCMs) during approach are used to put the spacecraft back on target.

- Executing TCMs incurs operational risks:
  - Potential for human error, spacecraft hardware failures, etc.
  - Need to consider spacecraft health and flight team readiness in evaluating TCM risk.
  - Typically not a function of maneuver size.

- EDL risks increase non-linearly with delivery error.
Getting to the Right Place on August 5th, 2012

- Conditions leading up to TCM-4 at E-8 days made the decision relatively simple
  - Clearly outside of established TCM criteria
  - Stable navigation solutions
  - Healthy spacecraft and well rested operations team

- Excellent TCM-4 execution and exceptional stability of navigation solutions afterwards made subsequent decisions simple
  - No further TCMs needed

- Very little residual delivery error for EDL to fly out
Telling the Spacecraft What It Needs to Know

- Inclusion of entry guidance significantly increases the importance of good onboard state knowledge
  - Vehicle propagates from ground provided initial state
  - "Lying" to entry guidance directly impacts precision performance

- Best estimate of initial state from ground based navigation evolves with number of measurements, time, and proximity

- State errors usually result in shifts in landing ellipse, which may increase failure risk

- Team was prepared to build and uplink late state updates, if needed
As Flown Parameter Updates

- Navigation solutions were extremely stable following TCM-4, 8 days prior to entry

- Team was prepared to make all planned parameter updates, only one parameter load after TCM-4 was necessary

- State estimate uplinked to vehicle six days prior to entry only ~200 m from post flight reconstructed state!
Conclusion

- Flight team achieved its primary approach/EDL operations goals in weeks and days leading up to August 5
  - Vehicle readied for entry
  - TCM and parameter update decisions made using pre-gamed criteria

- Key decisions balanced spacecraft operational risk with future risk to be incurred during EDL

- Exceptional TCM execution and navigation performance greatly simplified approach activities
  - Team was prepared for much worse

- Executing the operations plan put in the spacecraft in a good position to succeed