LUNAR ENTRY DOWNMODE OPTIONS FOR ORION

KELLY SMITH & JEREMY REA

NASA JOHNSON SPACE CENTER

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BALLISTIC ENTRY

- Concept: Spin a lifting capsule vehicle at some constant spin rate such that the integrated effects of aerodynamic lift are approximately nulled.

- With an infinite spin rate, the only net forces acting on the vehicle would be gravity and aerodynamic drag ("ballistic").

- Ballistic Entry used in Mercury flights, and retained as backup emergency entry system for Gemini and Apollo. Also used in historical Mars EDL missions (excluding Curiosity).

- Requires only attitude rate information (gyroscope) and functional control system.

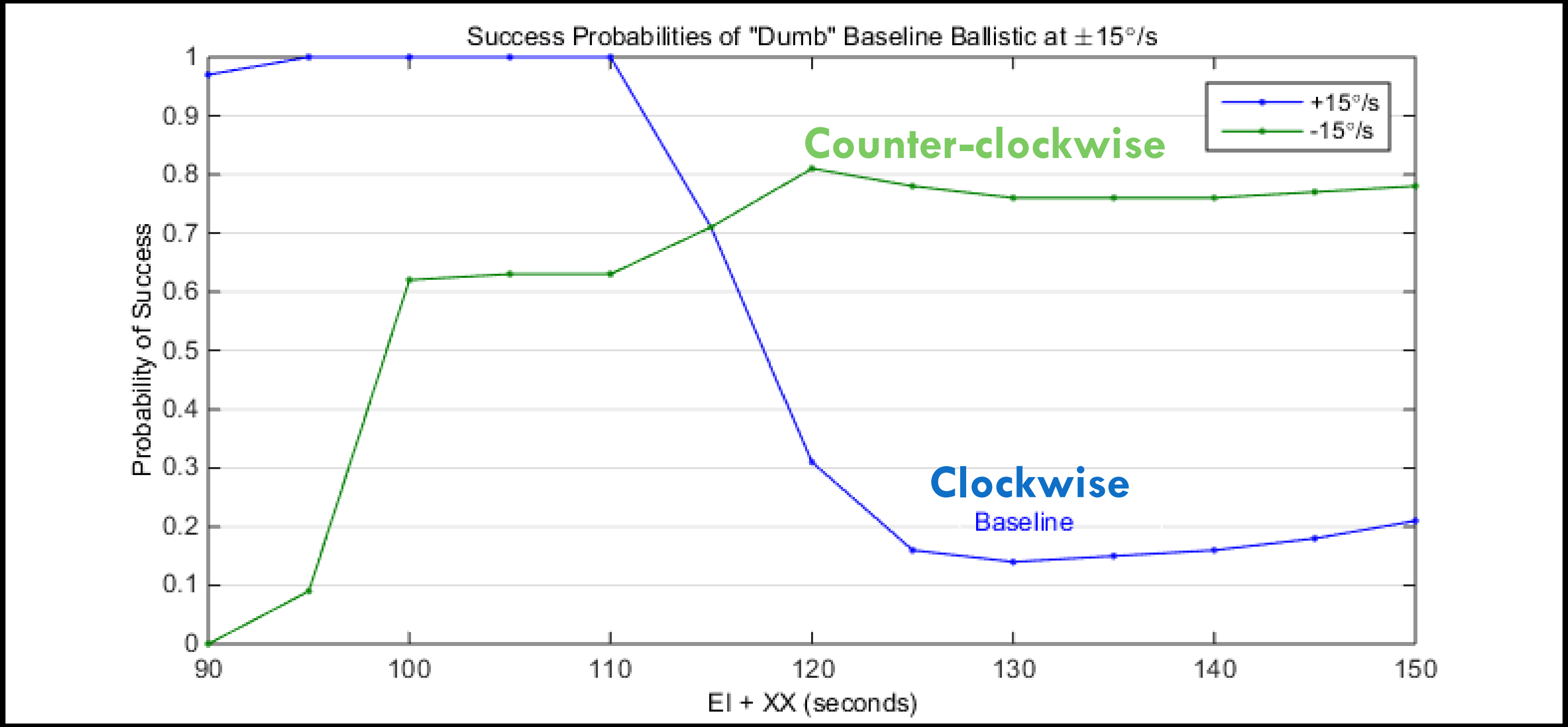
LUNAR RETURN CONDITIONS

- Typical Entry Interface conditions:
  - Inertial Velocity > 36,000 ft/s
  - Equivalent energy to a Nimitz-class aircraft carrier at *260* mph.
  - Average energy dissipation during entry would power 7.5 million 60W light bulbs

BALLISTIC ENTRY & LUNAR RETURN

- Guided entry will attempt to steer the vehicle onto a skip trajectory toward the landing site.
- For crewed missions, it's required to have continuous abort capability during entry.
- Initiating Ballistic Entry before Entry Interface is OK.
- Initiating Ballistic Entry after Entry Interface can result in a catastrophic atmospheric skip-out, if you do it at the wrong imte.
  - "catastrophic" = not landing within lifetime of Orion power consumables.

HOW BAD IS IT?



Success Probabilities of "Dumb" Baseline Ballistic at ±15°/s
+15°/s
-15°/s
Counter-clockwise
Clockwise
Baseline
Probability of Success
EI + XX (seconds)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
90
100
110
120
130
140
150

WHAT CAUSES THIS?

- Generally, this period of skip-out coincides with the timing of the first bank reversal.

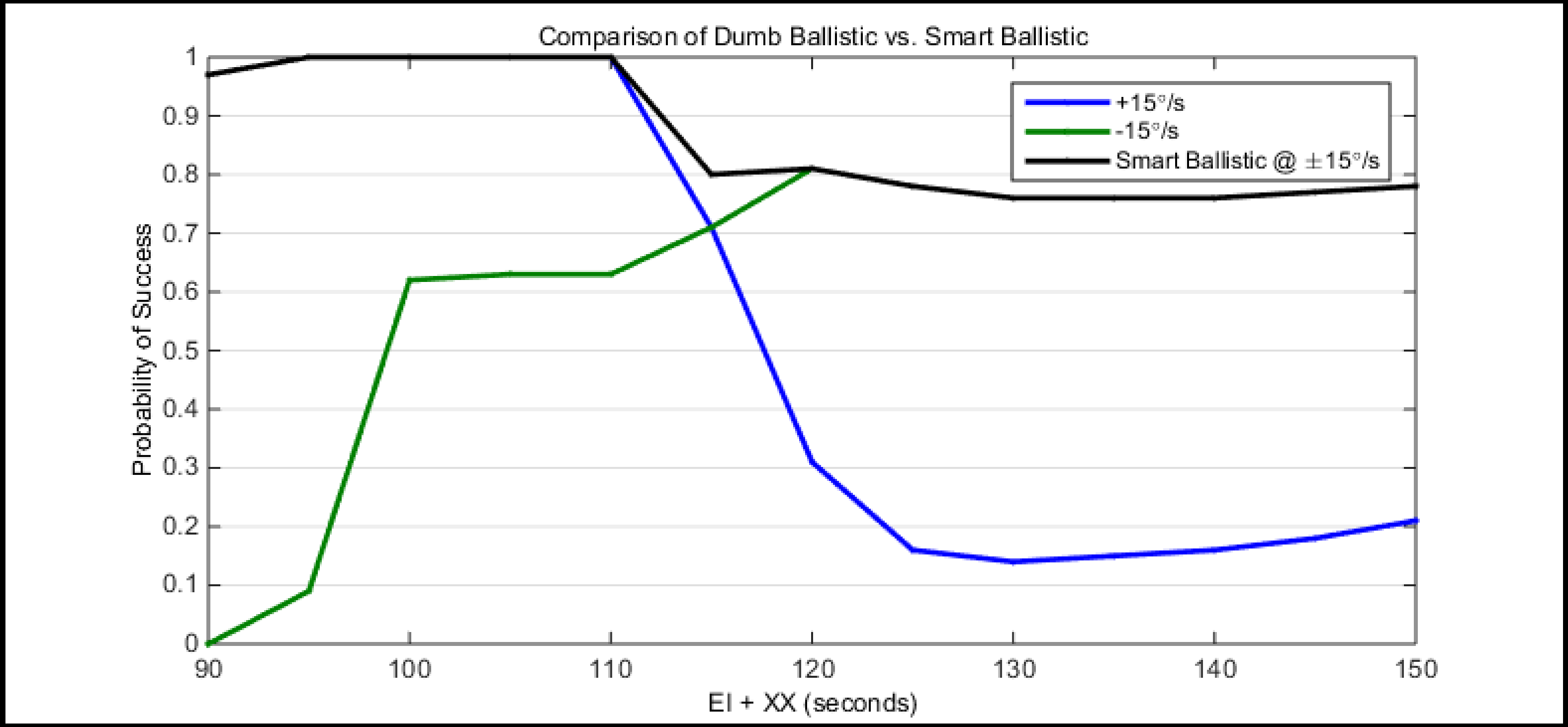
- During this interval:
    - Dynamic pressure is building
    - Flight path angle is positive
    - Counter-clockwise bank reversal is beginning

- In the middle of a counter-clockwise bank reversal, a clockwise ballistic spin-up maneuver begins, resulting in lift directed mostly upwards during this transient.

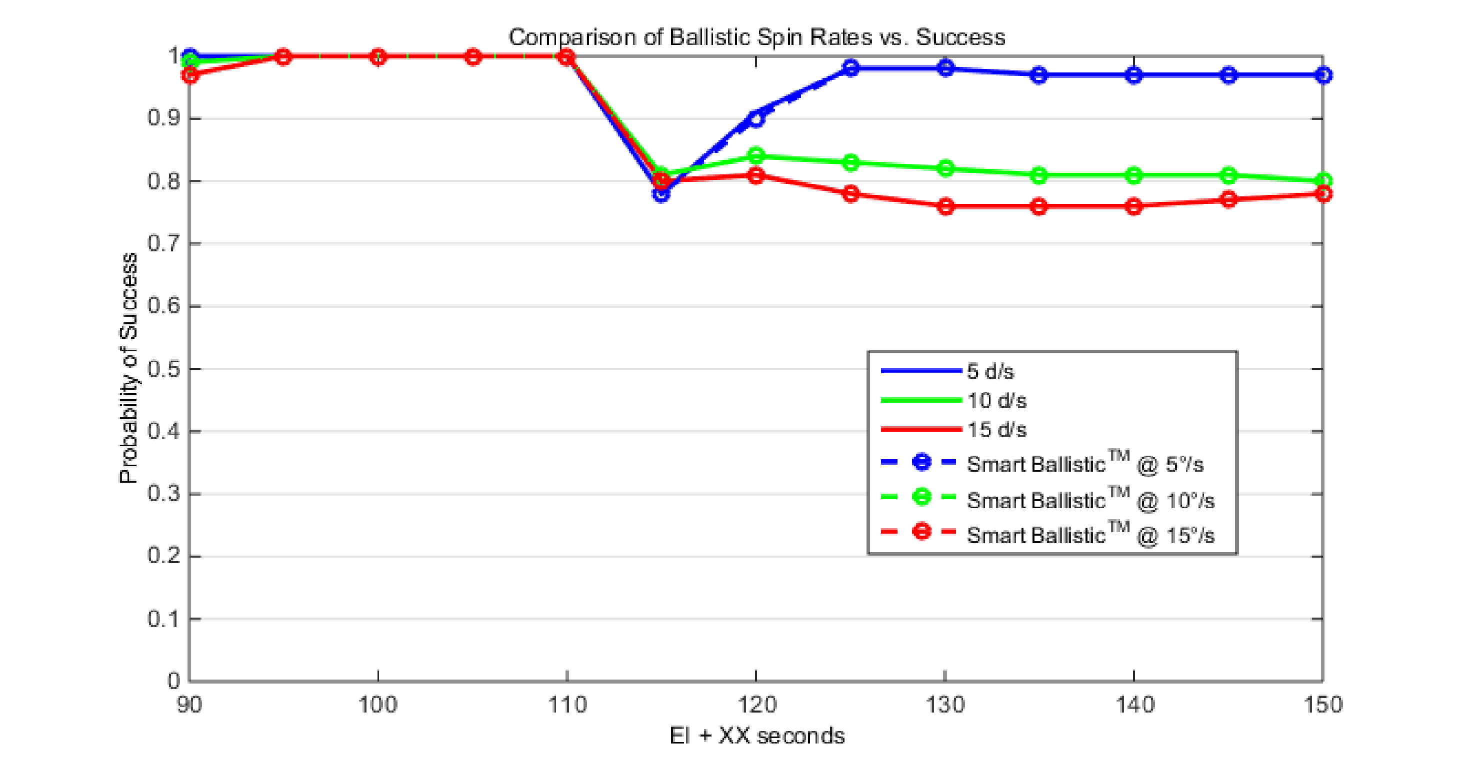
- This transient is enough to cause catastrophic skip-out.

SMART BALLISTIC

- Don't always spin clockwise. Choose the best spin direction that minimizes the time to the lift-down attitude.



SPIN RATE EFFECTS



LINGERING PROBLEM

- Using a “smart” spin-up and slowing the spin rate increases the time spent lift-down.
- Using a constant spin rate approach will never entirely eliminate the problem.
- A different approach is needed to solve the problem.

CHARACTERISTICS OF IDEAL SOLUTION

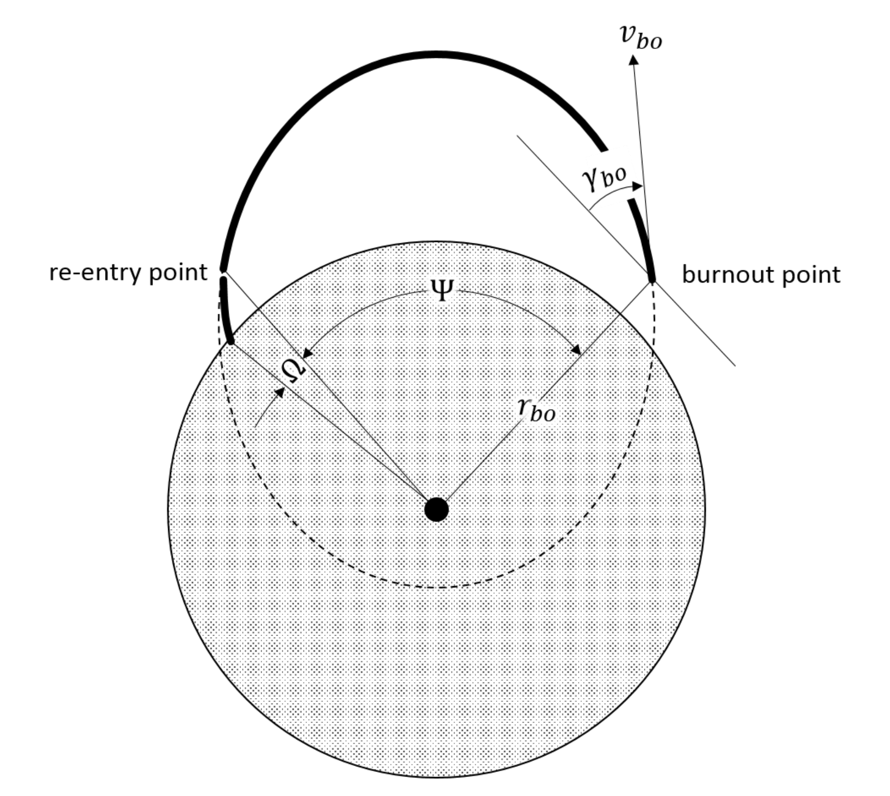
- Conceptually simple
- Computationally inexpensive
- Insensitive to navigation errors
- Eliminates the ballistic skip-out problem

CONCEPT

- Hold lift down attitude until atmospheric capture is assured.
- Then, fly some other attitude profile to lessen heating and loads.

2-BODY ORBITAL MECHANICS (IN-PLANE)

Given (r, v, Ψ), compute γ.



$$\gamma_{bo} = \frac{1}{2}\left[sin^{-1}\left(\frac{2-Q_{bo}}{Q_{bo}}sin(\Psi/2)\right) - \Psi/2\right]$$

$$Q_{bo} = \frac{v_{bo}^2 r_{bo}}{\mu}$$

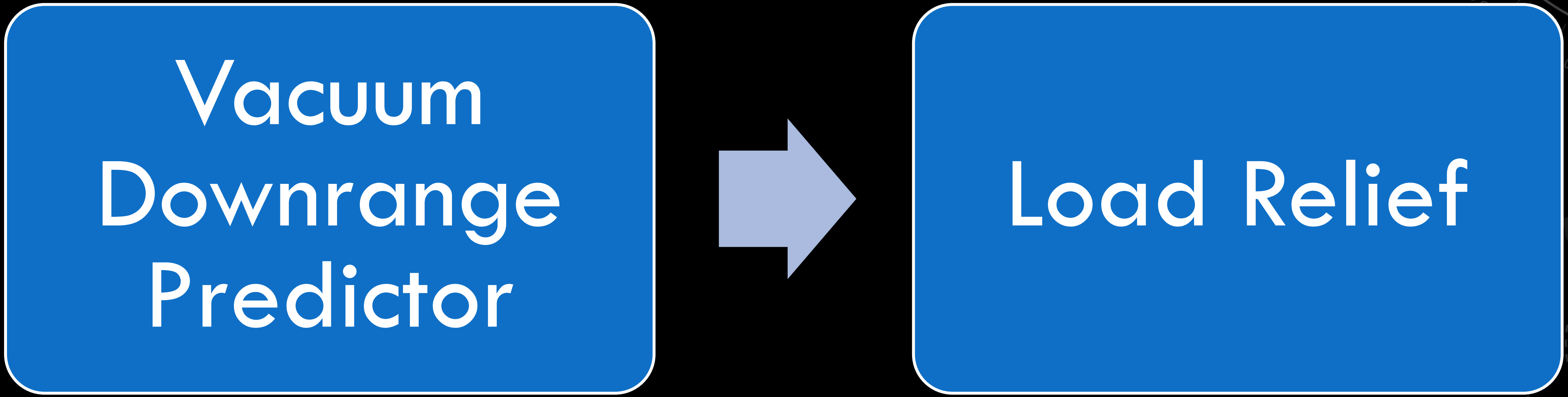
```
IF (FPA > FPA_Vacuum) THEN
    Bank = Pi;
ELSE
    Bank = 0;
END
```

Predict vacuum range flown.

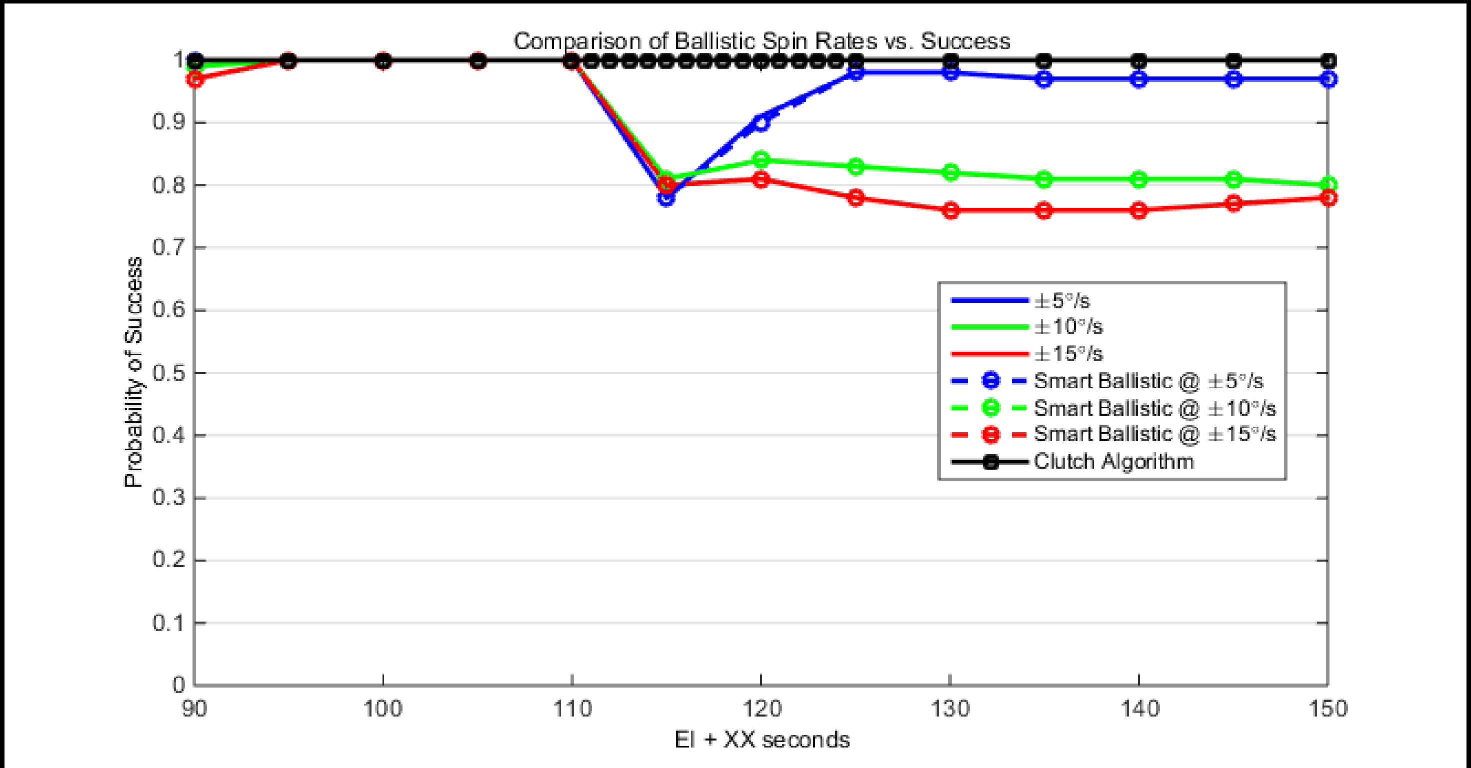
LOAD RELIEF

- The conservative capture strategy will produce unsurvivably high g-loads.
- To mitigate the excessive peak loading issues, the load relief algorithm from FNPEG (Lu 2014) was utilized.
- Load relief overrides the bank command to prevent violation of a load constraint.

CLUTCH

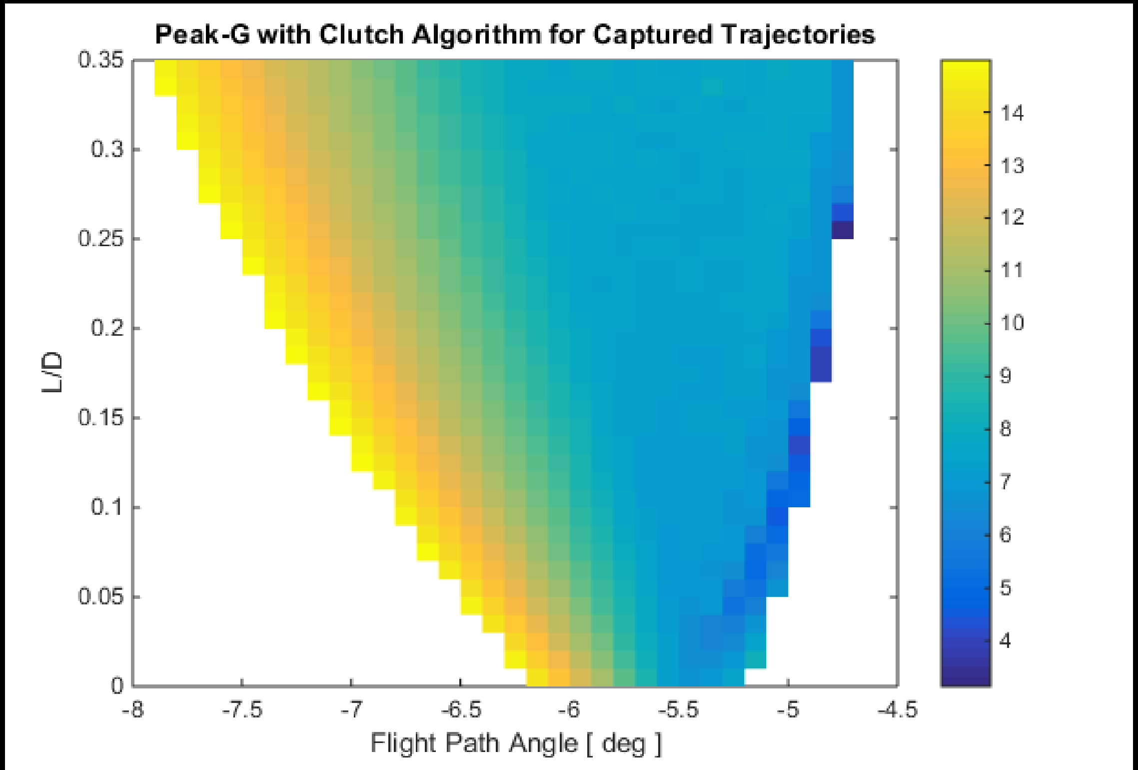


COMPARISON OF CLUTCH TO EARLIER APPROACHES



Clutch eliminates the ballistic skip-out problem.

ENTRY CORRIDOR



SUMMARY

- Traditional ballistic entry does not scale well to higher energy entry trajectories.
- Clutch algorithm is a two-stage approach with the capture stage and load relief stage.
- Clutch may offer expansion of the operational entry corridor.
- Clutch is a candidate solution for Exploration Mission-2's degraded entry mode.