LUNAR ENTRY DOWNMODE OPTIONS FOR ORION

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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 time.
  • “catastrophic” = not landing within lifetime of Orion power consumables.
HOW BAD IS IT?

Success Probabilities of "Dumb" Baseline Ballistic at ±15°/s

- Counter-clockwise
- Clockwise
- Baseline
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.
Given \((r, v, \Psi)\), compute \(\gamma\).

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

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

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

Vacuum Downrange Predictor

Load Relief
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.