Brief Summary of EDL GNC

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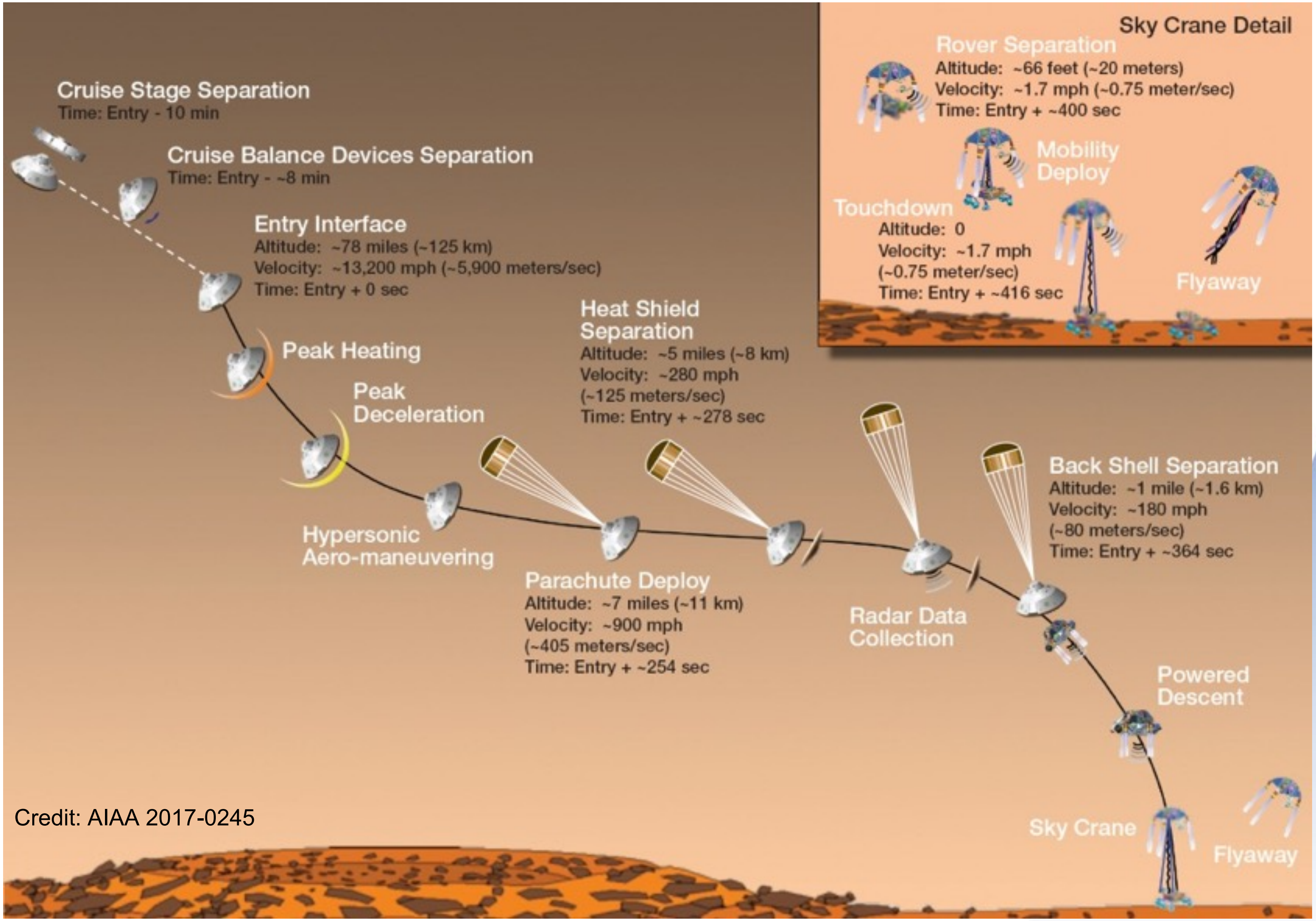
National Aeronautics and Space Administration

Outline

- Entry, Descent, and Landing and the need for control
- Guidance
- Navigation
- Control
- Other aeroassist missions

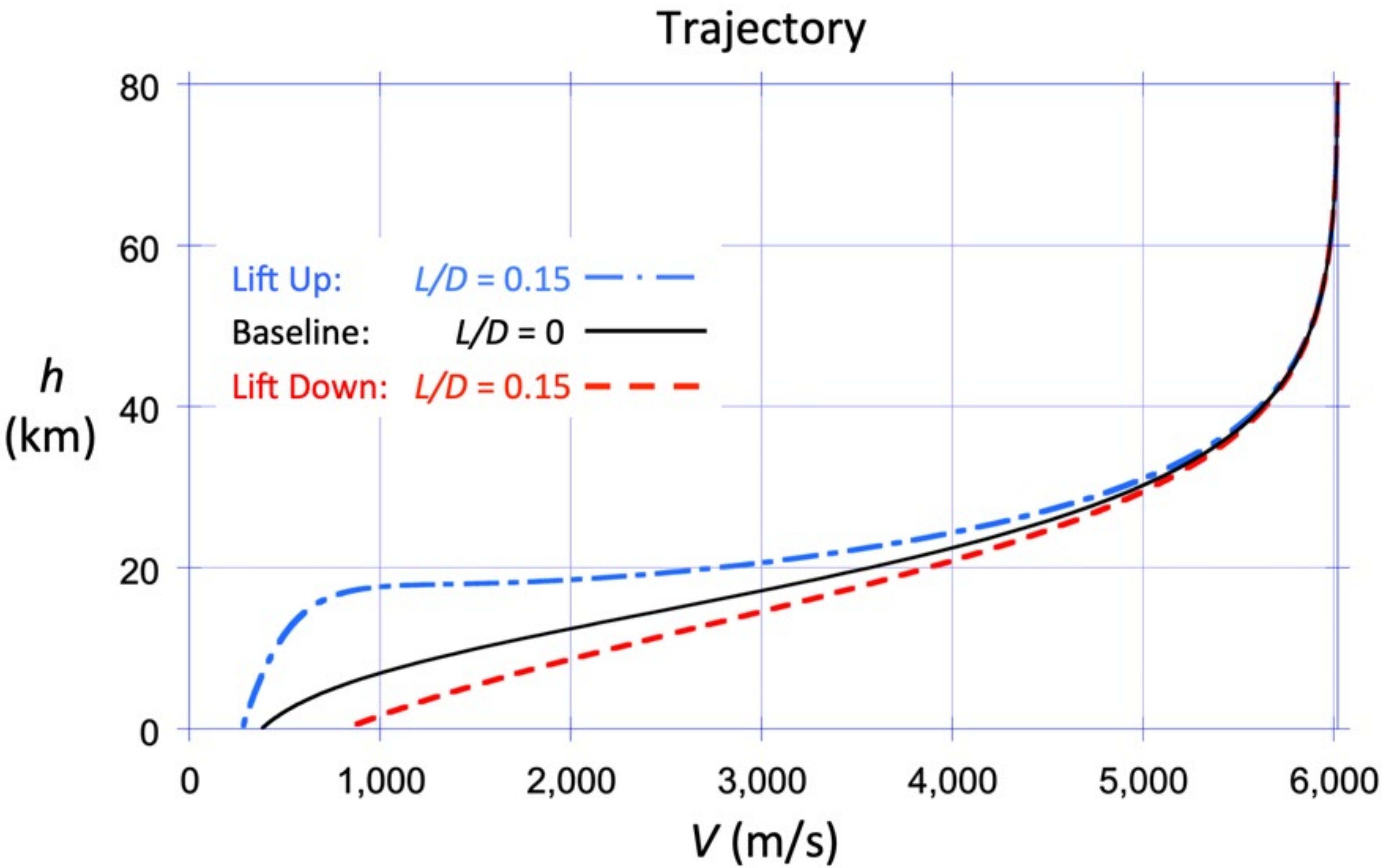
EDL AND THE NEED FOR CONTROL

Entry, Descent, and Landing Concept of Operations



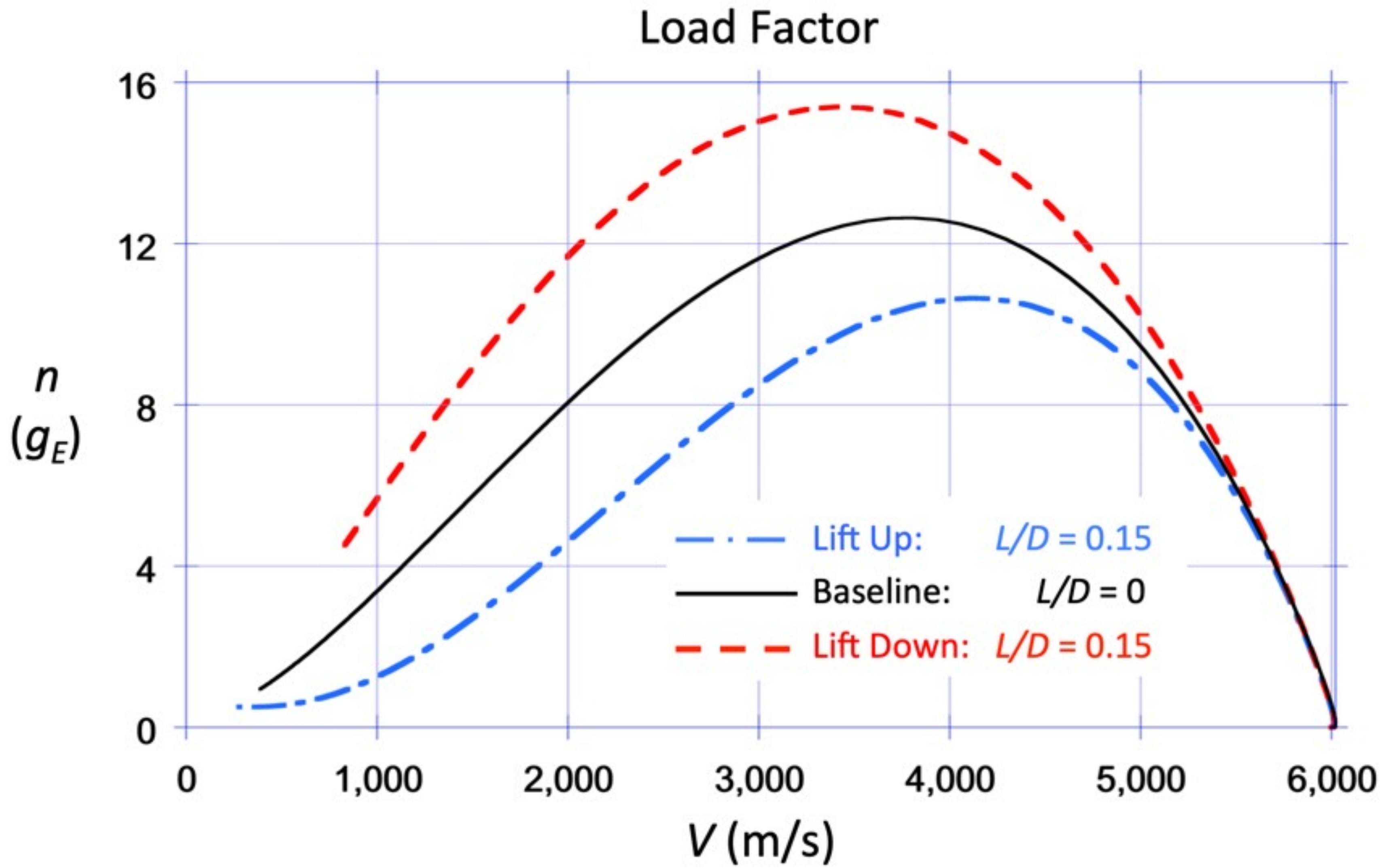
Effect of Lift on Trajectory

Credit: Borrowed from Cruz et al. Summer Lecture "Introduction to Trajectories"



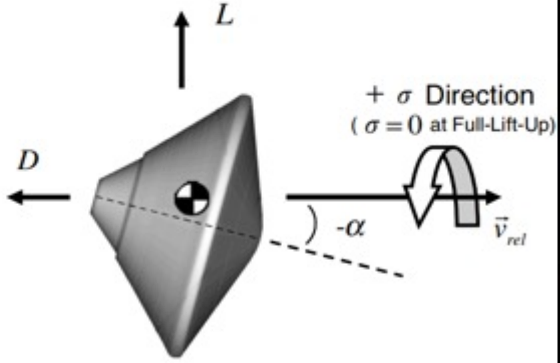
Effect of Lift on Max Acceleration

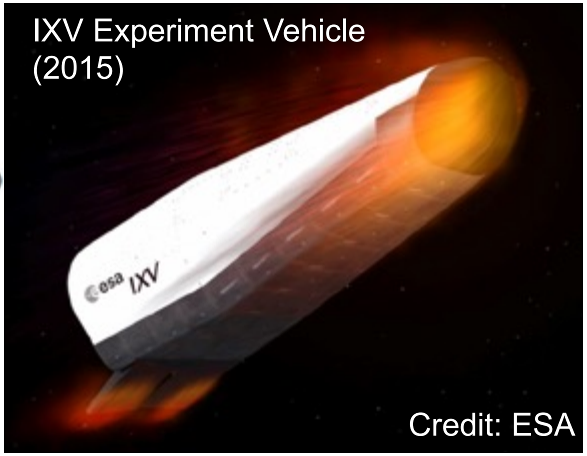
Credit: Borrowed from Cruz et al. Summer Lecture “Introduction to Trajectories”



Lift in an EDL Vehicle

Credit: AAS 19-221





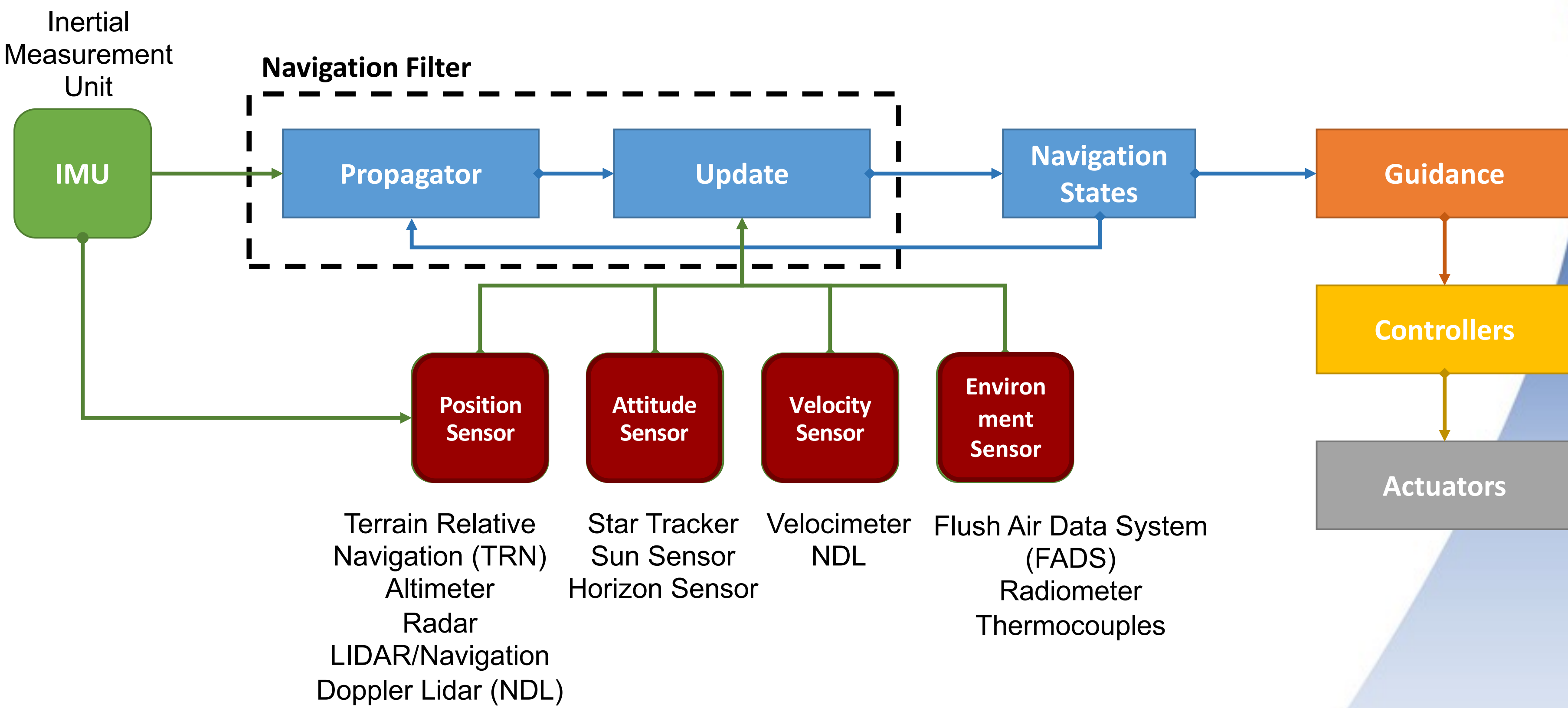
Blunt Bodies
- Low L/D Vehicles (<0.5)
- Drag dominates
- Positive lift generated at negative angles of attack

Mid L/D Vehciles
- Mid L/D Vehicles (0.5-0.8)
- Trim at higher angle of attack (~55 deg)

Higher L/D Vehicles
- L/D around 1

Guidance, Navigation, and Controls Relationship

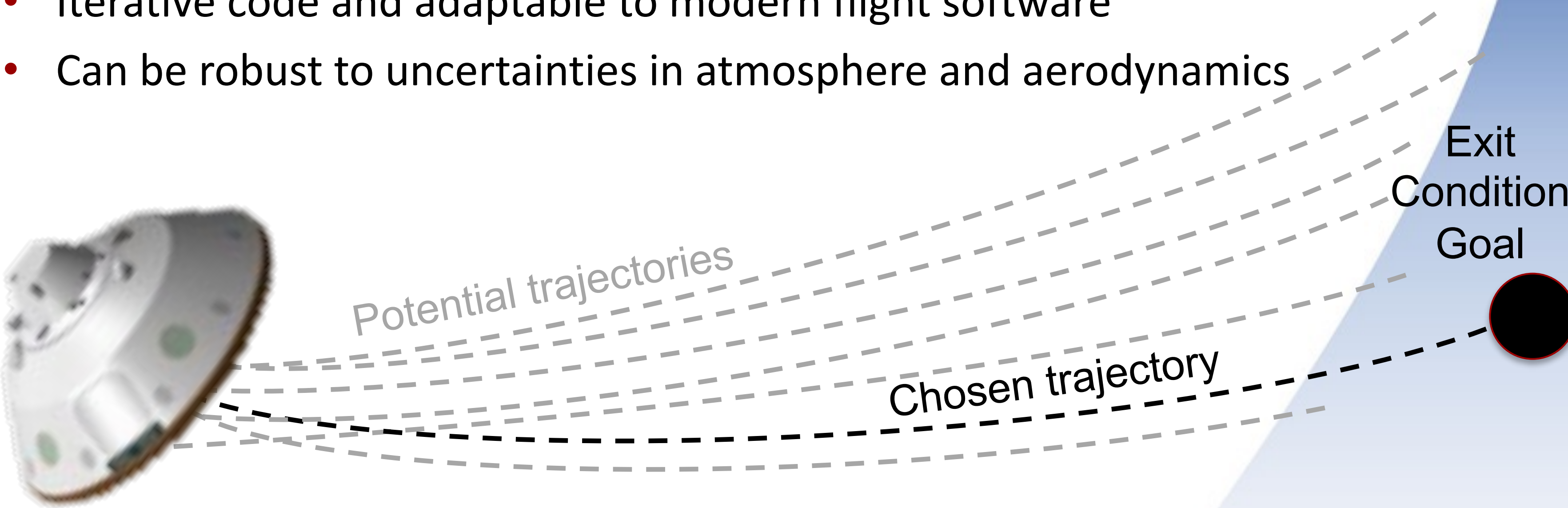
Credit: Adapted from AIAA 2022-0609



GUIDANCE

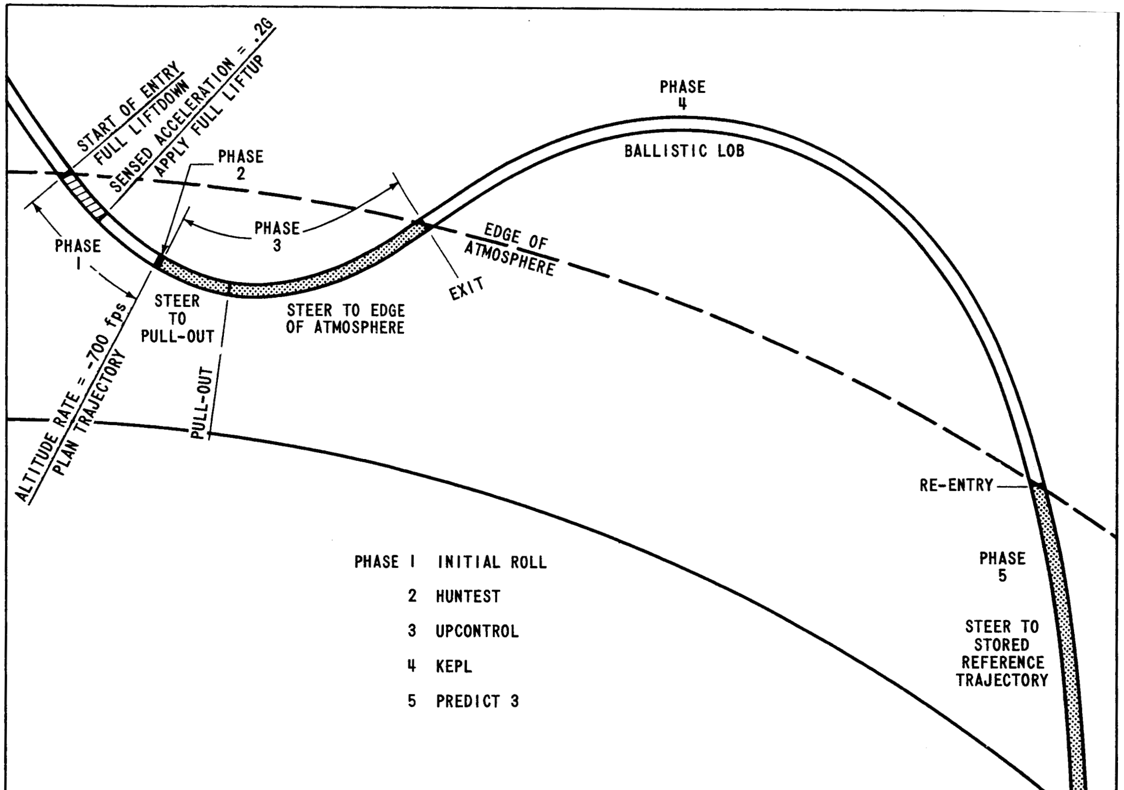
Types of Entry Guidance Schemes

- **Analytic schemes**
  - Gains for guidance based on pre-generated reference profiles
  - Non-iterative and efficient code
- **Numerical predictor-corrector (NPC) schemes**
  - Numerically integrates equations of motion on-the-fly
  - Iterative code and adaptable to modern flight software
  - Can be robust to uncertainties in atmosphere and aerodynamics



Aeroshell Credit: AIAA 2017-0245

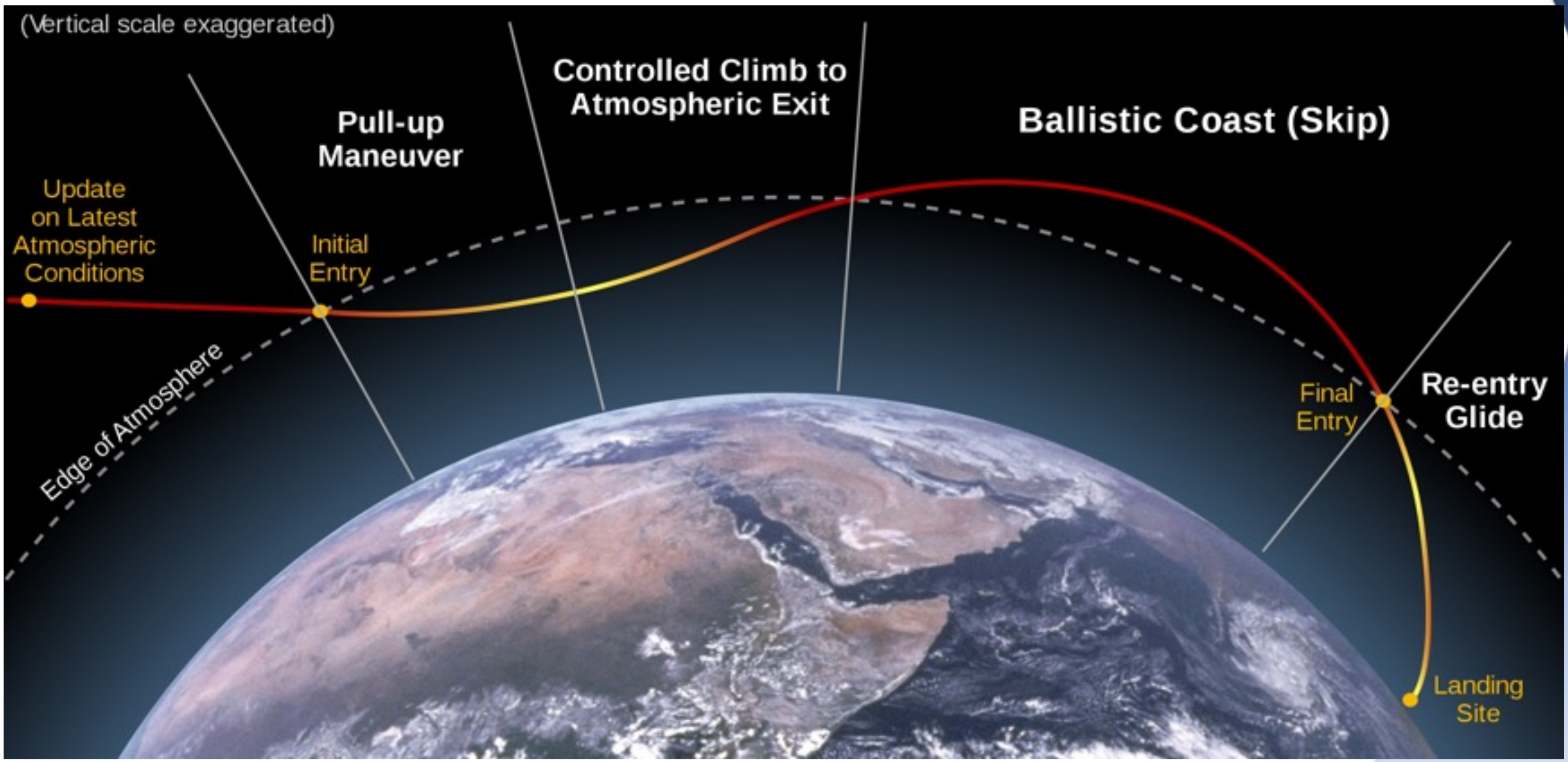
Apollo Guidance



Credit: NASA CR-110924

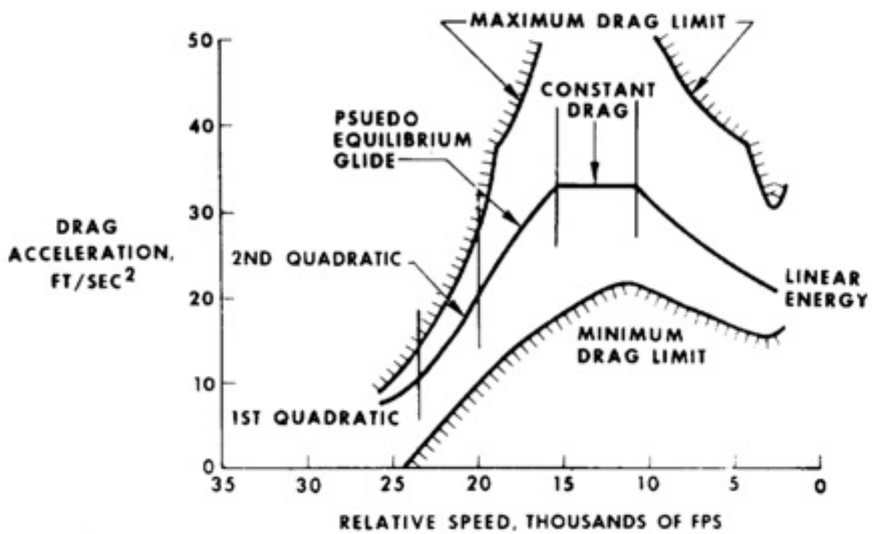
- Reference-following
- Bank angle modulation

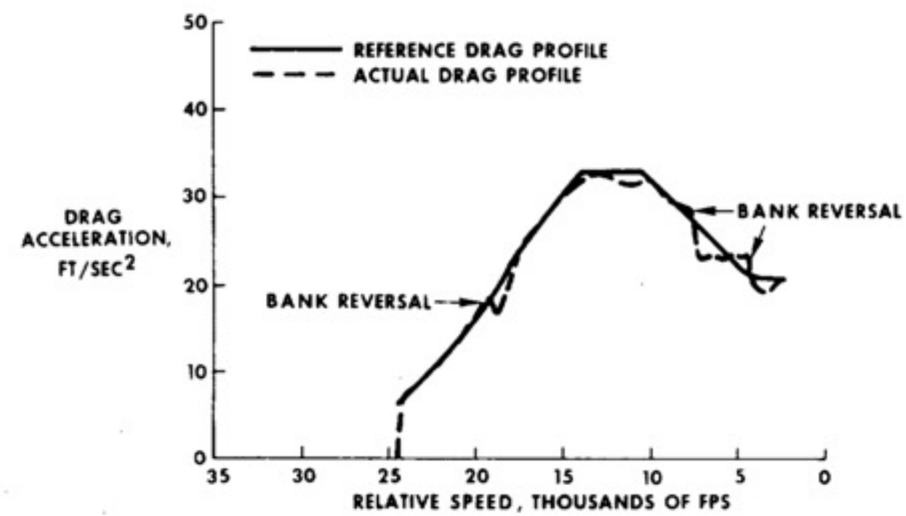
Skip-Rentry



- Use L/D to provide lift to skip out of the atmosphere and extend range
- Effectively the system used by Apollo and other lunar return missions

Space Shuttle Guidance

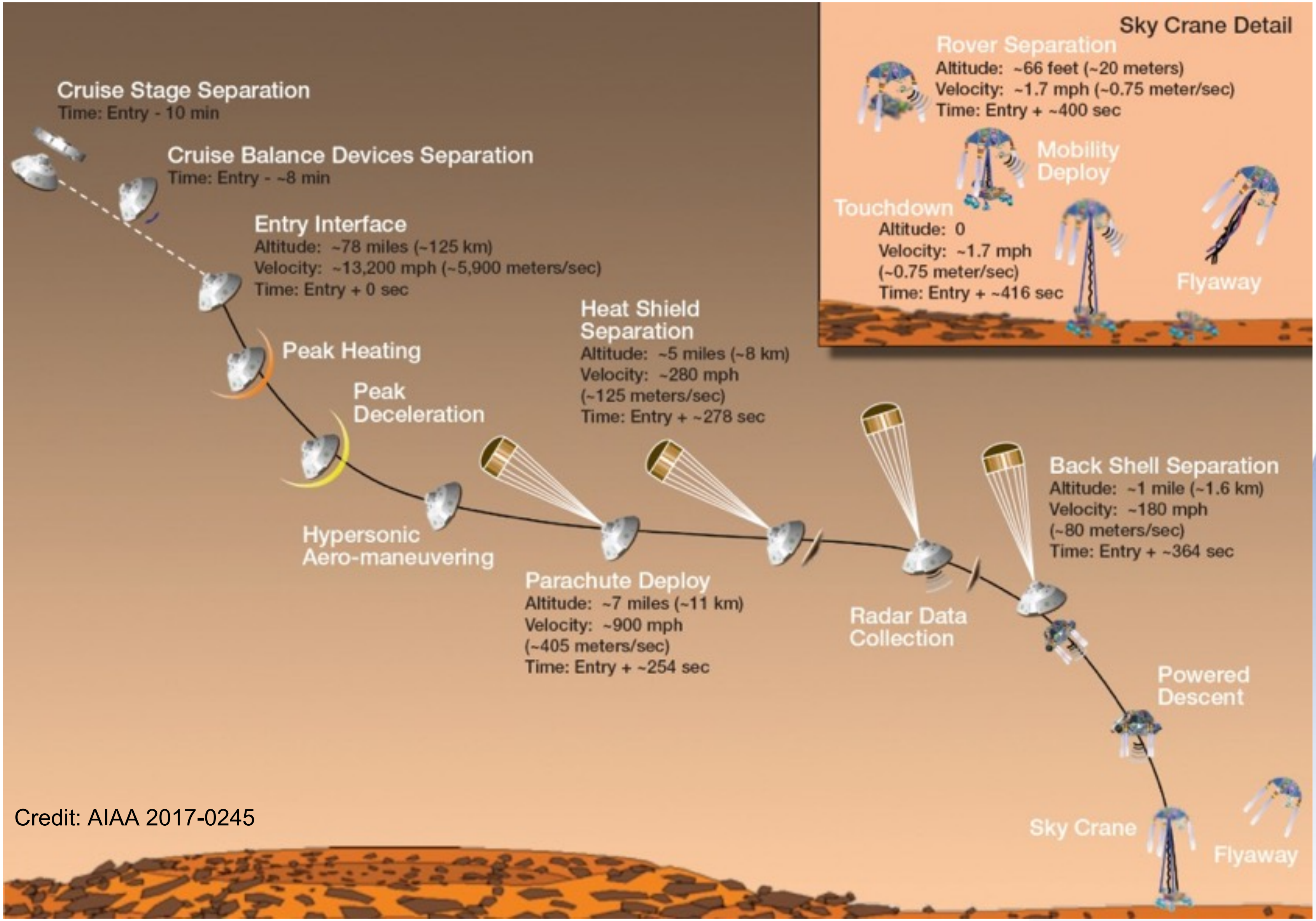




Credit: NASA TM-79949

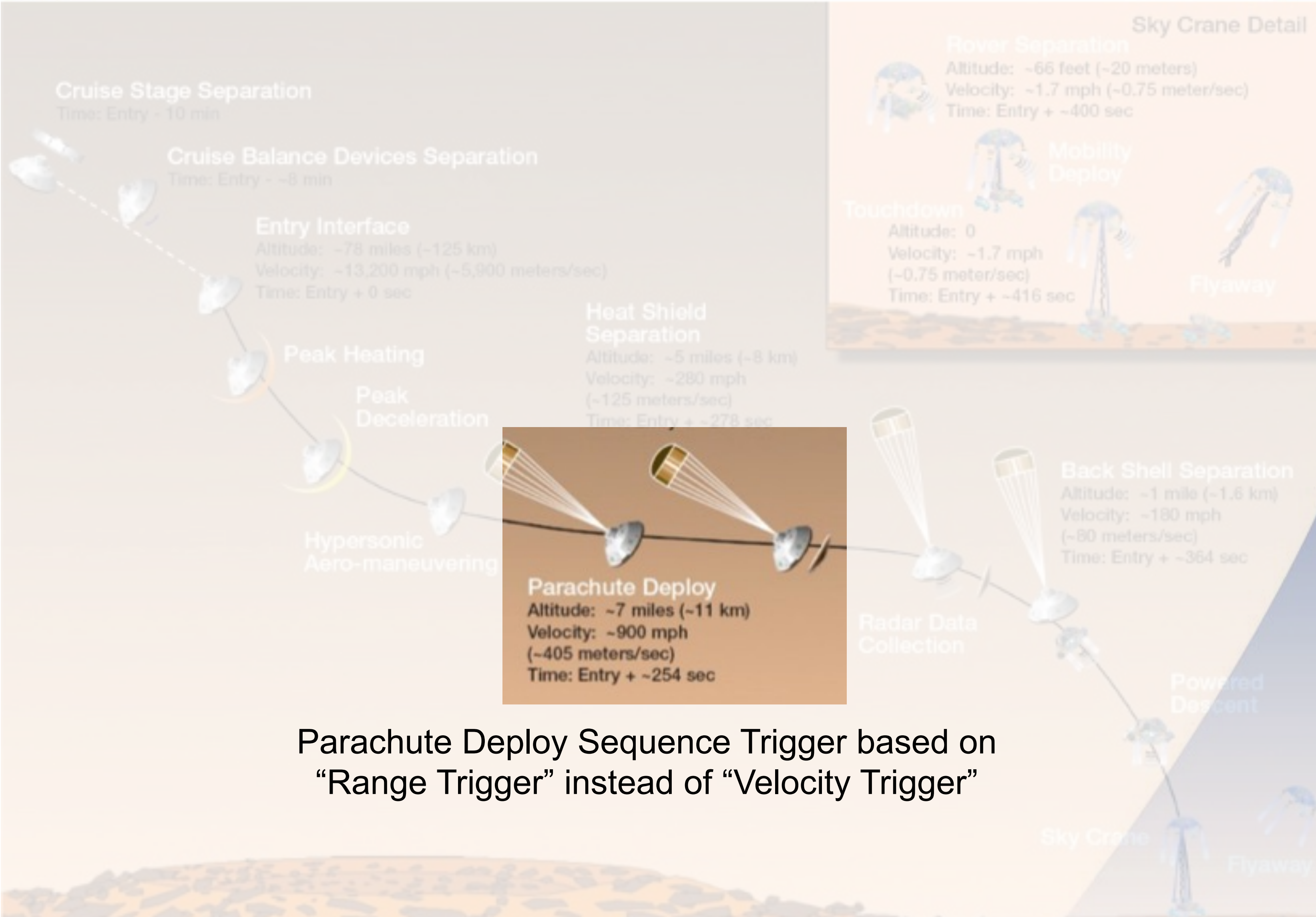
- **Reference-following**
- **Bank angle modulation**

Guidance for Mars Missions



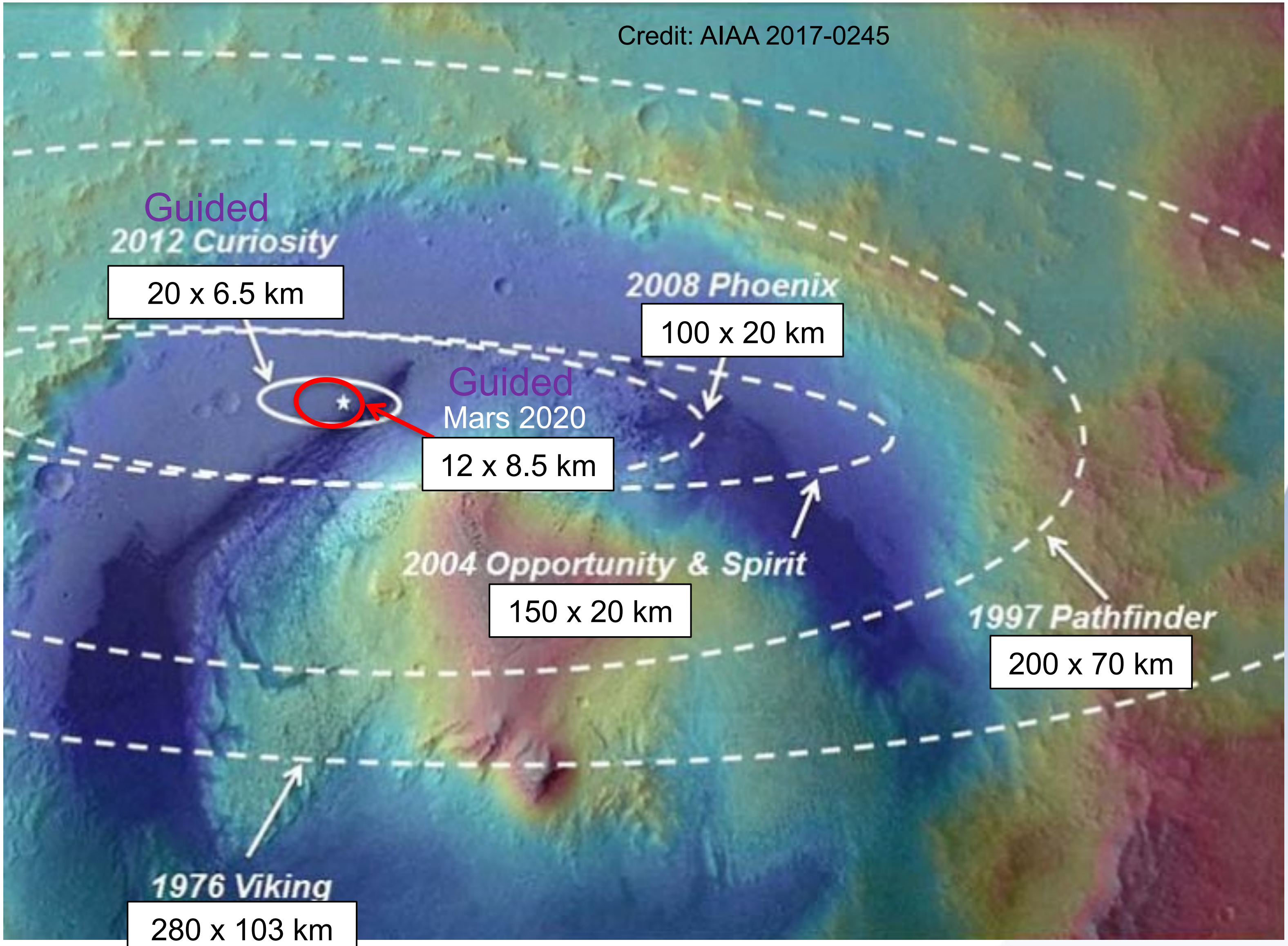
Credit: AIAA 2017-0245

Guidance for Mars Missions

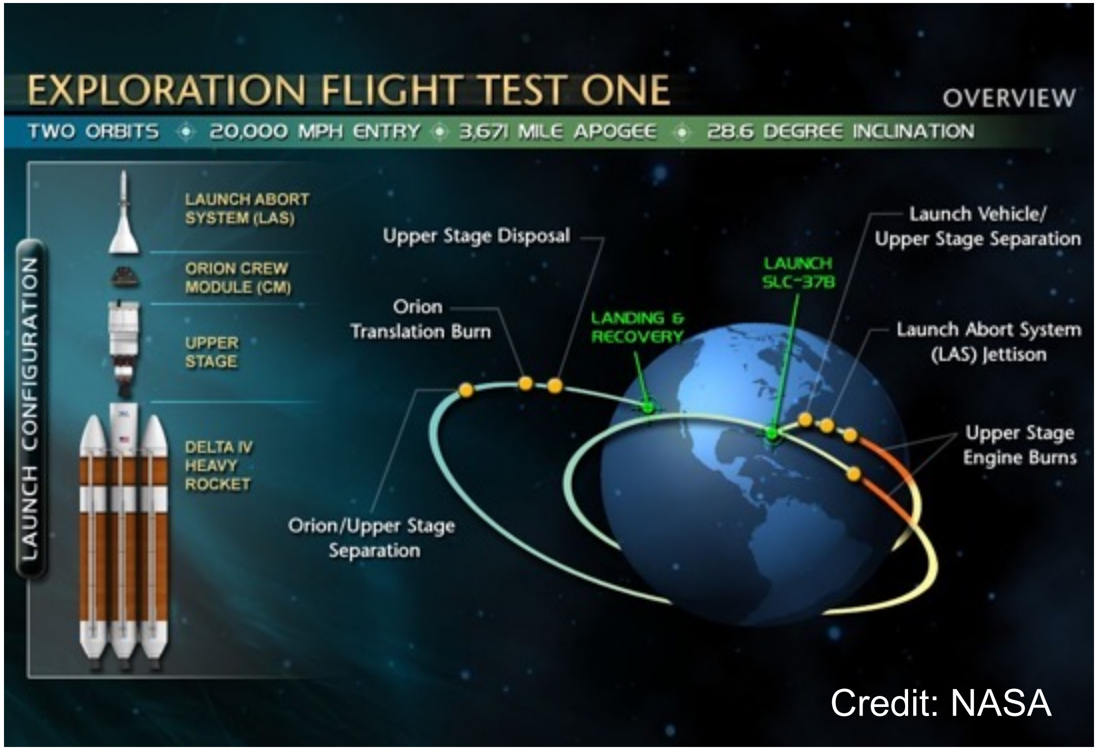


Parachute Deploy Sequence Trigger based on “Range Trigger” instead of “Velocity Trigger”

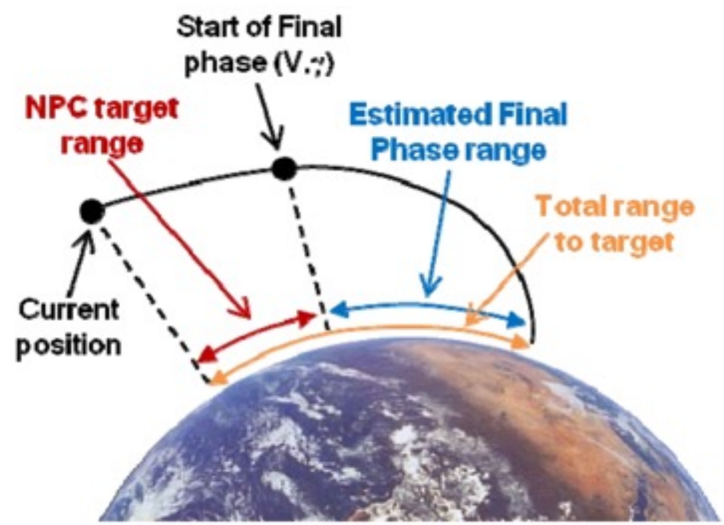
Effect of Range Trigger – Ellipse Size Decrease



Numerical Predictor-Correctors



Credit: NASA



Credit: IEEE 2010.5447010

- **Numerically predict conditions based on current conditions, then correct the controls to get desired target**
- **Used for EFT-1 to target landing site (guidance scheme was PredGuid)**

NAVIGATION

Dead-Reckoning

Ship Dead-Reckoning Tools

Apollo IMU

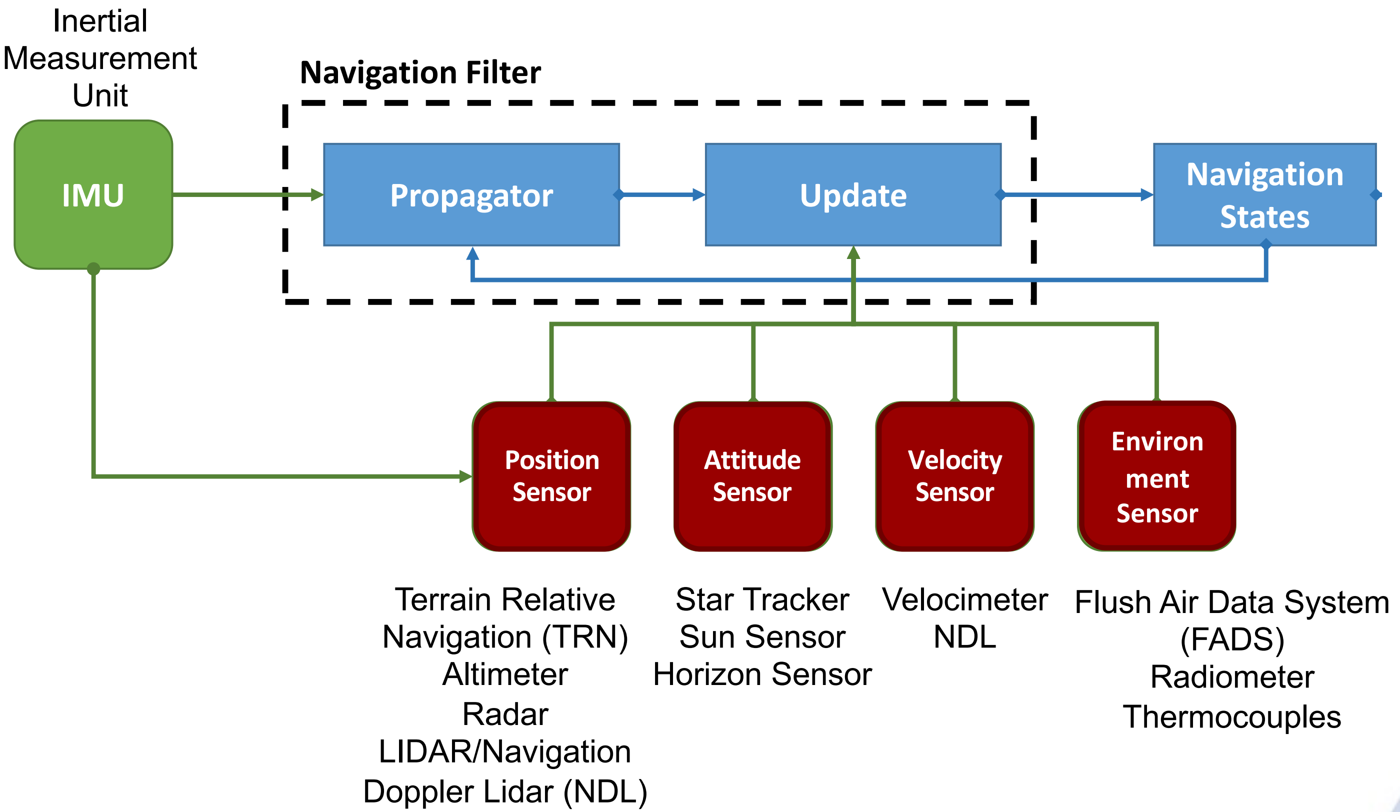
Credit: NASA AAS 16-092

MSL MIMU

- **Integrating Inertial Measurement Unit data to calculate position, velocity, and attitude**
- **Very typical and used on most missions with navigation systems. G's from accelerometer used for even non-active navigation systems**
- **Susceptible to drift**

More Advanced Navigation

Credit: Adapted from AIAA 2022-0609

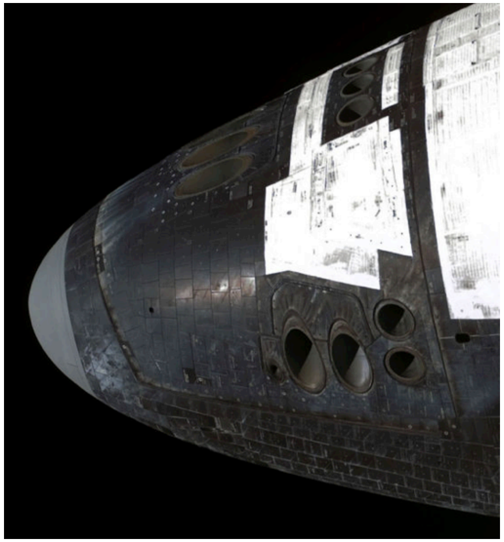


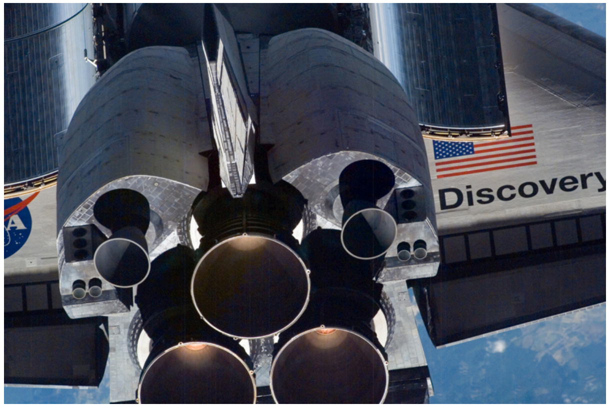
- **Integrate data from various types in a navigation filter**
- **Consists of batch or Kalman filters**
- **Past and present NASA projects: ALHAT, COBALT, SPLICE, etc.**

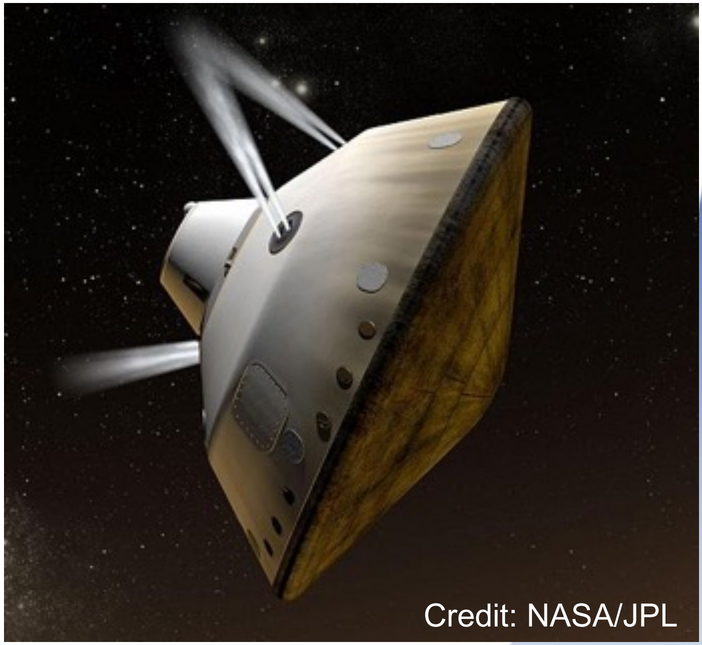
CONTROL

Reaction Control Systems

Credit: NASA AAS 16-092



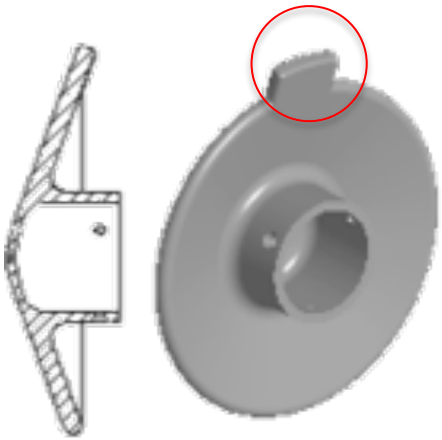




Credit: NASA/JPL

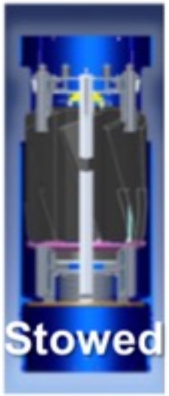
- Used for Apollo, Space Shuttle, and Mars missions
- Small ΔV applied at a moment arm moves the vehicle in pitch, yaw, or roll planes. Usually, has been used for rolling (really banking) vehicles during active guidance

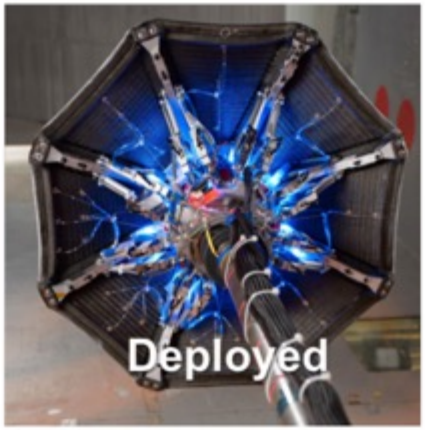
Aerodynamics Surfaces



Credit: AIAA 2013-2809

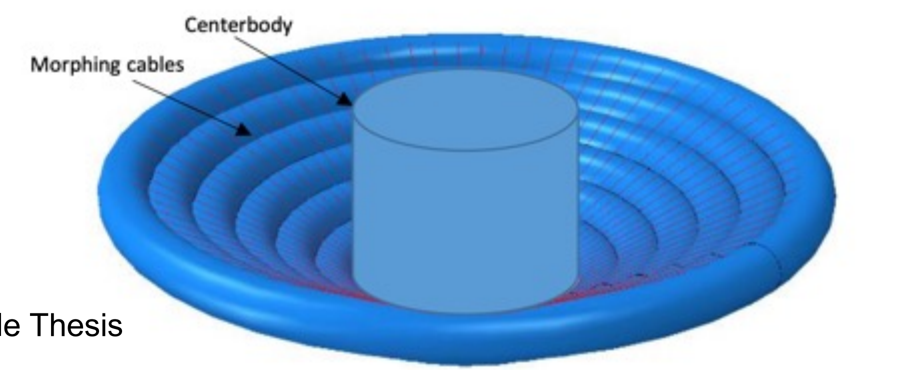
ADEPT – Mechanical Deployable





Credit: Pterodactyl Study

HIAD – Morphing Inflatable



Credit: A. Slagle Thesis

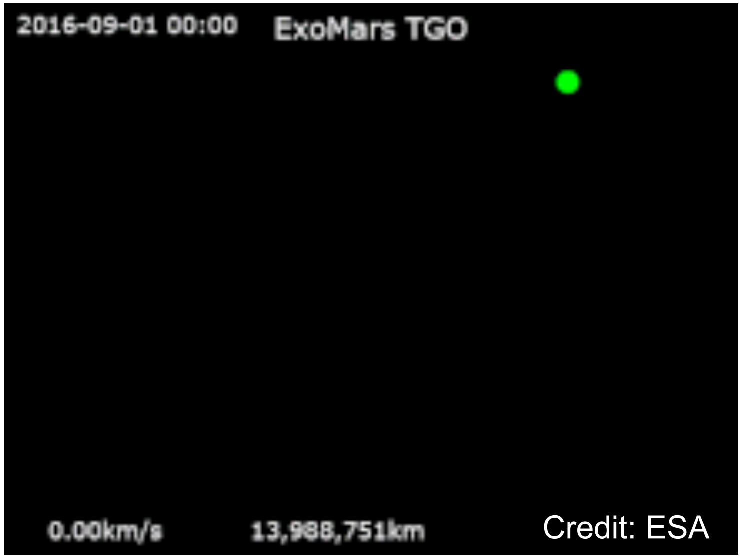
- **Space Shuttle has elevons and flaps, but not used during hypersonic entry**
- **Flaps or trim tabs can extend beyond outer mold line to provide pitching or yawing control**
- **Vehicles could morph shapes to change ballistic coefficient**

OTHER AEROASSIST APPLICATIONS

AEROBRAKING

Many, many dips into the atmosphere

- First demonstrated by the Magellan mission in Venus at the end-of-life extension
- Conducted on Mars Odyssey, Mars Reconnaissance Orbiter, ExoMars TGO, and some others
- No entry vehicle aeroshell or heatshield

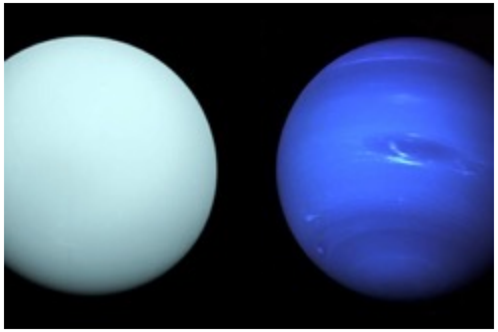


AEROCAPTURE

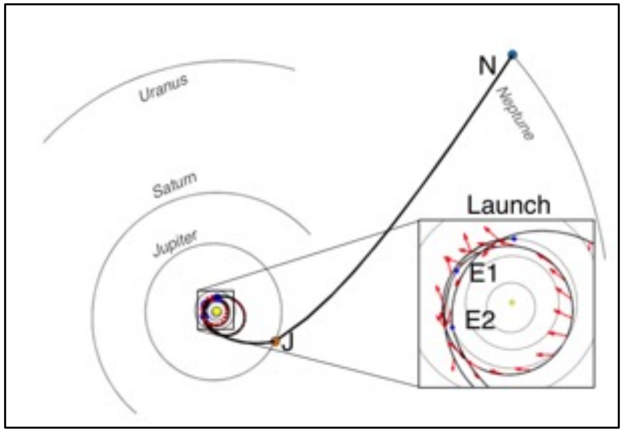
Motivation

➢ Mission to the Ice Giants (Uranus and Neptune)

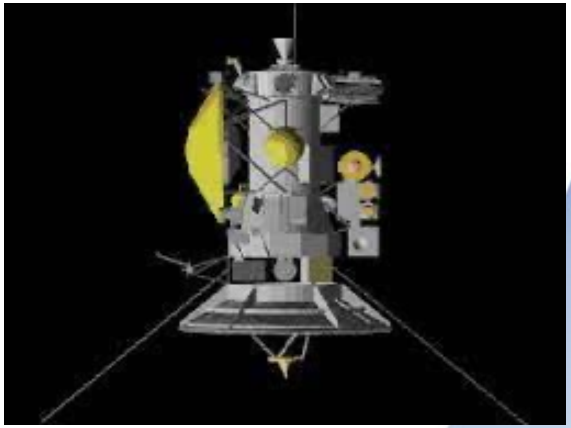
- Direct mission to the planet (16 years) or with Jupiter Fly-by (14-15 years)
- Orbital insertion maneuver: 1000+ m/s; propellant mass fraction is 55-70%



Credit: NASA



Credit: JAXA

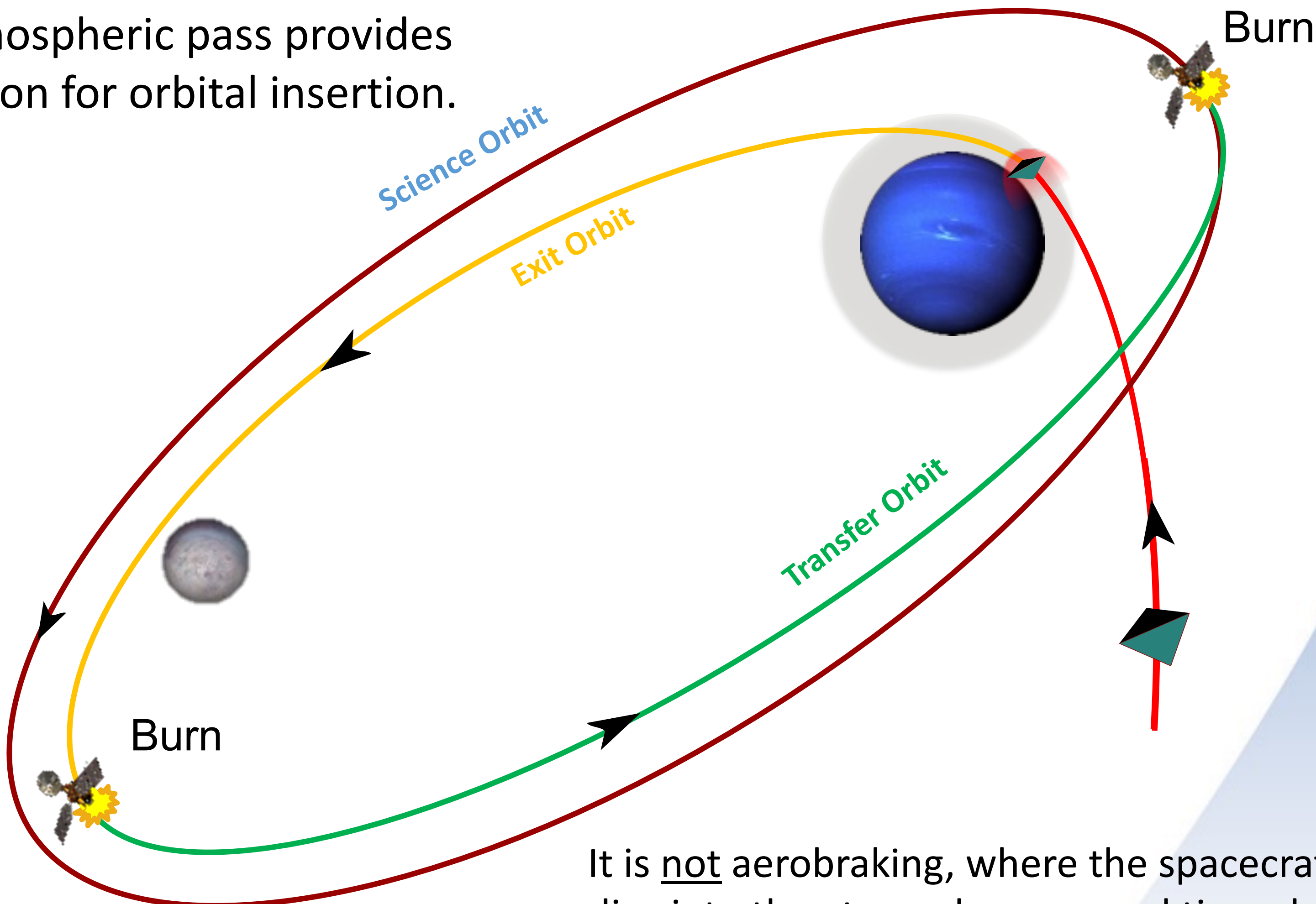


Credit: APL

- What if you could use the atmosphere of the planetary body to do most of the orbital insertion ΔV?
- What if the on-orbit mass could be increased by 40%?
- What if the interplanetary cruise duration could be cut by 2-5 years?

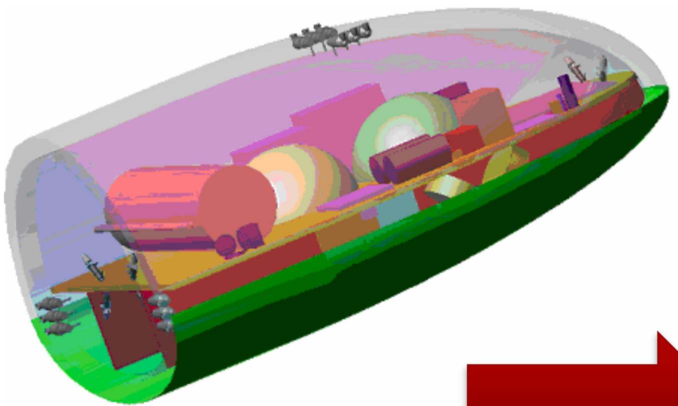
What is Aerocapture?

Orbital maneuver where the drag from a single atmospheric pass provides deceleration for orbital insertion.



It is not aerobraking, where the spacecraft dips into the atmosphere several times before the target orbit is reached.

Updates to Entry Vehicle Configurations, Guidance Schemes, and Control Methods



Credit: AIAA 2004-4953

Mid L/D shapes
L/D > 0.5
Higher control authority needed

AEROGRAVITY ASSIST

Gravity Assist + Aerodynamics

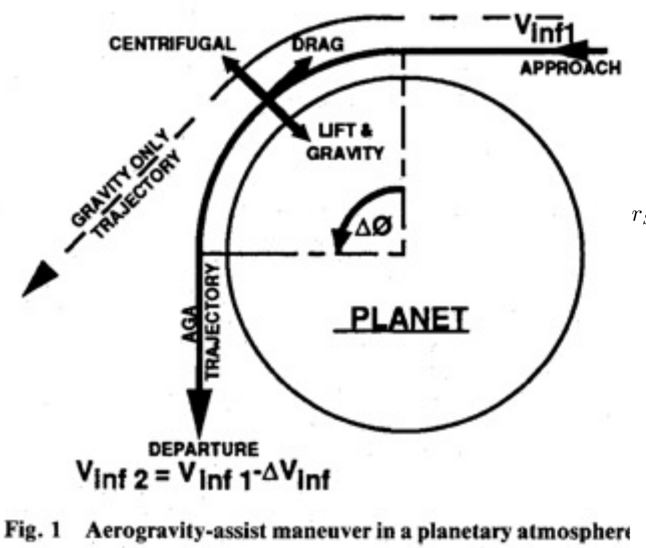
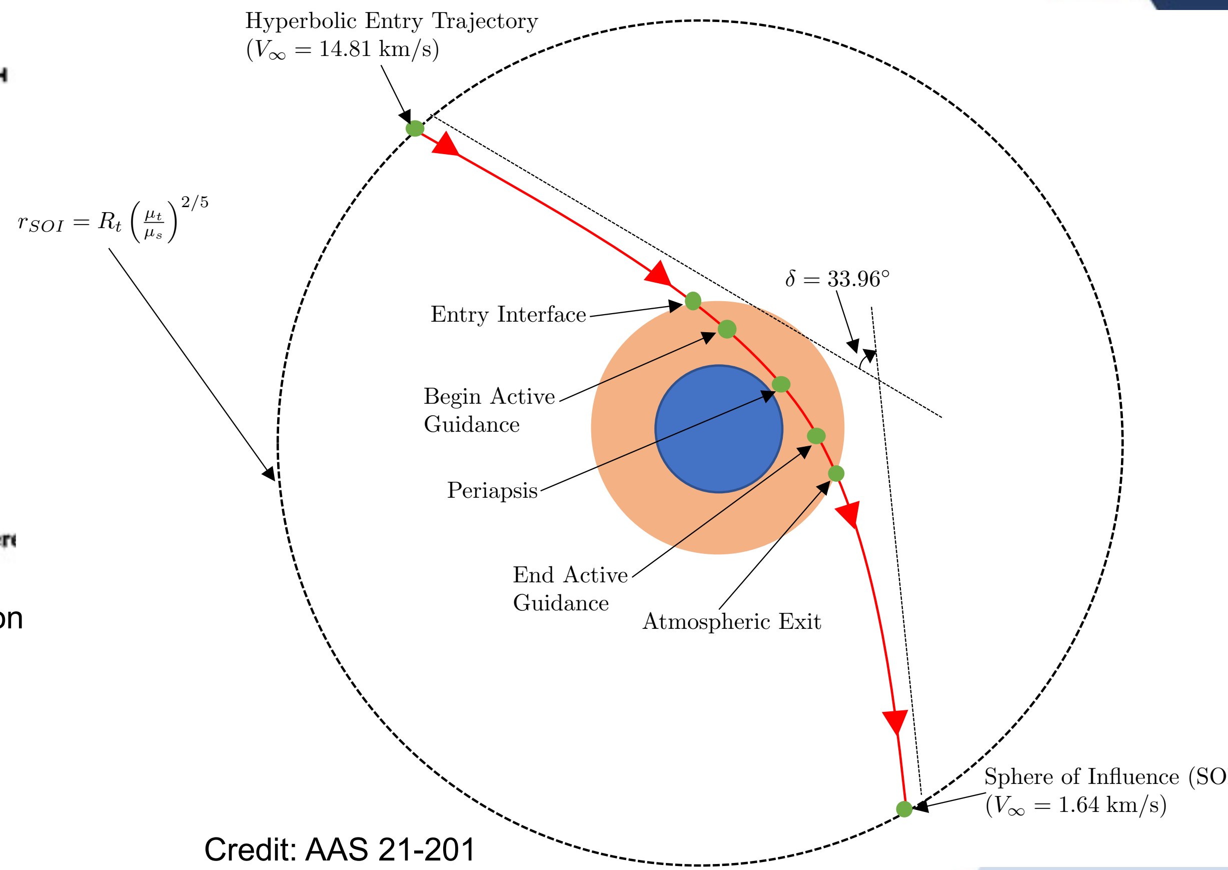


Fig. 1 Aerogravity-assist maneuver in a planetary atmosphere

Credit: J. Arnold Summer 2021 Presentation



Credit: AAS 21-201

- Allows for large orbital maneuverability without fuel usage
- Potential application for Enceladus orbiter/lander using Titan as a fly-by body

Summary

- Control authority can make heavily affect EDL trajectories in range traveled, peak deceleration, and heat flux/load
- Guidance schemes that have been mostly implemented have been analytical and reference-following, but numerical predictor—corrector options are coming
- Navigation systems have been IMU based, but more precise landing requires integrating a plethora of sensor data that observe position, velocity, attitude, and environmental conditions
- Control systems include reaction control systems (RCS), aerodynamic surfaces (like flaps), morphing shapes etc.
- GNC systems also affect flight for other aeroassist missions, such as aerobraking, aerocapture, and aerogravity-assist