AEROCAPTURE TECHNOLOGIES FOR OUTER SOLAR SYSTEM EXPLORATION

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1. NASA'S OCT. 2015 MULTI-CENTER AEROCAPTURE STUDY

NASA's Planetary Science Division requested a study to determine which technology developments would most benefit NASA's readiness to implement aerocapture at various destinations in the solar system. JPL hosted the study on Oct. 7-8, 2015, with aerocapture experts from multiple NASA centers and JPL (see below). The entire study was conducted in plenary sessions, so all disciplines represented were involved in all aspects of the study. Destinations considered were Venus, Mars, Uranus, Neptune, and Titan. The sessions also addressed aerocapture's current state of readiness.

2. MAJOR STUDY CONCLUSIONS

1. An aerocapture demonstration is **not needed** prior to flight implementation
2. Within the time frame considered, aerocapture at destinations considered is feasible with no or modest technical developments
3. Use of aerocapture at Uranus or Neptune could reduce the time of flight, increase the science payload, and/or reduce overall mass.
4. Trade studies and Design Reference Mission developments are needed to determine necessary pre-project developments
5. There are several activities NASA could pursue to mitigate risk in aerocapture implementations; details are below and in Table 1

TABLE 1. Risk mitigation activites for aerocapture implementations. Phases are color-coded to match those used in Fig. 1 to the right. Schedule indicators are: Green, pre-project feasibility & trade studies; Khaki, specific risk reduction prior to project start; and Violet, development work as part of the project.

Mission Phase, Characteristics, & Risks	Risk Mitigation Activities	Feasibility & Trade Studies	Risk Reduction prior to Project Start	Project Development Effort
CRUISE				
Heat rejection	Investigate the complexity, reliability, & lifetime of heat rejection systems	Green		
APPROACH				
• Navigation errors • Need OPNAV(s)? • Late maneuvers? • Equipment failures	Determine whether OPNAV or a late autonomous maneuver is needed	Green		
	Quantify flight path angle errors	Green		
Deployments, stowage, & ejections				
• Mechanism failures • Environmental issues • Warming up electronics	Develop redeployables, including solar panels, if needed	Green		Violet
Attitude determination & control	Aerocapture introduces no additional risk			Violet
Atmosphere & gravity field knowledge & uncertainty				
• Temperature, density, & pressure profiles • Composition	Increase atmosphere & rings modeling efforts	Green		
	Advocate opportunistic stellar occultations	Green	Khaki	Violet
	Take spacecraft-based measurements on approach			Violet
	Send an advance scout probe			Violet
	Improve knowledge with Earth- & space-based observations			Violet
• Gravity field	Aerocapture introduces no additional risk			Violet
ATMOSPHERIC FLIGHT				
Survival				
• Heating • Pressure • Shear • Turbulence (including "pot holes" and buoyancy waves) • Acceleration	Establish a peak acceleration requirement	Green		
	Determine CFD aerothermal model quality		Khaki	
	Understand uncertainty on radiative heating component		Khaki	
	Work on high-velocity physics development		Khaki	
	Expand/build aerothermal & hypersonic turbulent flow test facilities		Khaki	
	Develop heat shields: flexible TPS, carbon phenolic, woven TPS, deployable carbon fabric		Khaki	
	Investigate long-term storage & protection of heat shields			Violet
	Analyze & test roughness effects			Violet
	Identify cold & micrometeoroid survival means			Violet
Flight control—knowledge & algorithms				
Vehicle aerodynamics database	Improve/expand hypersonic wind tunnel capability		Khaki	
• Knowledge (attitude & initial deceleration) • In-flight guidance algorithms	Aerocapture introduces no additional risk			Violet
Flight control—actuators				
Actuators	Determine whether anything beyond heritage hypersonic control is needed	Green		
Flaps or other shape change	Analyze & wind-tunnel test		Khaki	
CG change	Analyze & wind-tunnel test or low-cost flight test		Khaki	
Deployable drag modulation through release or adjustment	Research, analyze, & wind-tunnel test for different drag conditions		Khaki	
• Thrusters • Mass modulation	Aerocapture introduces no additional risk			Violet
POST-EXIT				
• Attitude control • Critical reconfigurations & maneuvers (escape avoidance cleanup, periapsis raise) • Non-critical reconfigurations & maneuvers (additional cleanup)	Aerocapture introduces no additional risk			Violet
Aerocapture communications (any flight phase)				
• Occultation issues • Relay asset? • Direct-to-Earth semaphores/low data rates/Doppler • Engineering performance & instrumentation data	Aerocapture introduces potential mission constraints but no additional risk	Green		Violet

Recommended Risk Mitigation Activities

- Update and improve Uranus and Neptune atmosphere and ring models; identify astronomical opportunities for new data
- Quantify the complexity, reliability, and lifetime of heat rejection systems
- Determine whether techniques beyond heritage hypersonic guidance and control are needed (destination-dependent)
- Develop redeployable solar arrays, if needed
- Determine whether late autonomous maneuvers would be needed (destination-dependent)
- Identify mission constraints from flight data capture requirements
- Quantify achievable entry flight path angle errors from practical approach navigation accuracies and planetary ephemeris uncertainties

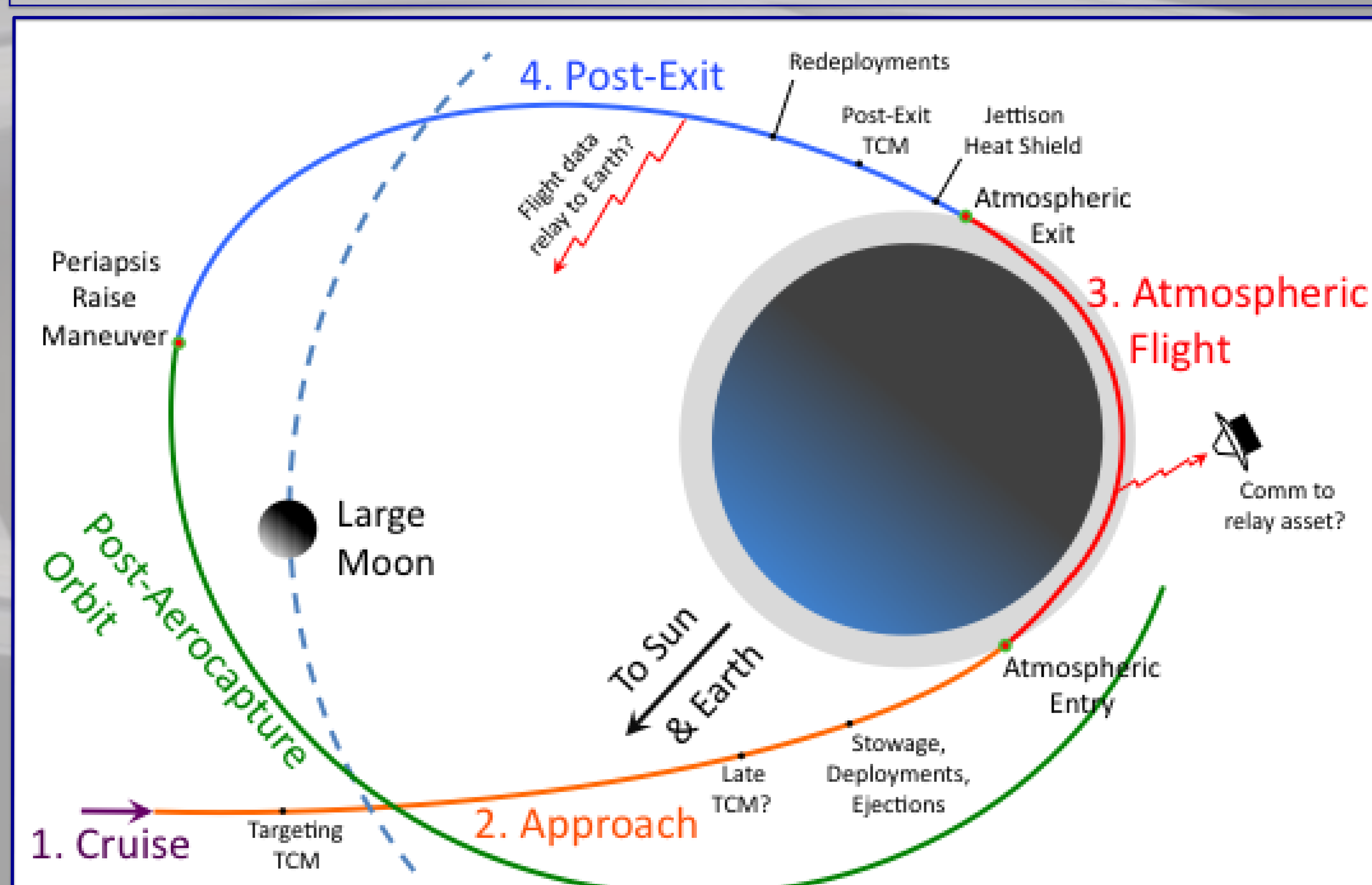

FIGURE 1. Aerocapture maneuver phases and events; see text to the right

	Knowledge Required	Actions Required	Driving Technologies
Cruise	(nothing unique to aerocpature)	RPS waste heat rejection (if RPS is used inside aeroshell)	(nothing unique to aerocapture)
Approach	Destination gravity field, & atmospheric structure & its uncertainties	TCMs; deployments, stowage, & ejections; attitude determ'n & control; late TCM?	Restowable solar array (if used); autonomous navigation & maneuver execution for late TCM
Atmospheric Flight	Destination gravity field; atmosphere, its uncertainties, & gas dynamics; aeroshell hypersonic aero-dynamics	Autonomous navig'n [knowledge & algo-rithms]] & flight path control [actuators] to exit; rejection of RPS waste heat	Aeroshells & TPS; autonomous navigation code; flight control actuators; inertial sensors
Post-Exit	Destination gravity field; satellite ephemerides	Attitude determ'n & control; autonomous exit state verific'n & TCM; reconfiguration	Spacecraft extraction frm aeroshell, redeploy; autonomous navigation & maneuver execution

TABLE 2. Knowledge, activities, and technologies important to the successful conduct of an aerocapture maneuver. Colors correspond to the phase color code in Fig. 1 above.

3. AEROCAPTURE – WHAT IS IT?

Aerocapture is orbit insertion from an unbound (hyperbolic) approach using aerodynamic drag in the destination's atmosphere to dissipate excess kinetic energy. The aerocapture concept is not new but is yet to be used on a space flight mission.

Figure 1 to the left illustrates the four primary phases of an aerocapture maneuver and key events during each phase. Phases are color-coded to match Table 2, which for each phase gives the knowledge required to plan and execute the phase, the actions required of the vehicle to execute the phase, and unique or critical technologies associated with the phase.

After a standard interplanetary Cruise, the vehicle is navigated along the hyperbolic Approach trajectory to a precision atmospheric entry within the "entry corridor". Upon entry it begins autonomous Atmospheric Flight, dissipating kinetic energy through drag as it uses onboard sensors, navigation software, and flight control hardware to control the flight path to an exit at the desired speed and direction. In the Post-Exit phase, the heat-soaked aeroshell is ejected and a propulsive post-exit trajectory correction cancels any velocity residuals. The post-exit orbit's periapsis is within the planet's atmosphere, so a final Periapsis Raise Maneuver establishes a stable science orbit.

4. WHY USE AEROCAPTURE?

For orbit insertions requiring a large ΔV, aerocapture offers greater science payload mass (for a given approach mass) than chemical propulsive orbit insertions. The mass of propellant and tankage needed to provide the required ΔV for a propulsive insertion is quasi-exponential with ΔV. But the mass of hardware needed for an aerocapture maneuver is quasi-*linear* with ΔV, so for a given large-ΔV insertion, the aerocapture system required can be less massive than the propulsion system required. This allows greater science payload mass, shorter trip times, or reduced total mass at launch.

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