National Aeronautics and Space Administration

Entry, Descent and Landing for Future Human Space Flight

Briefing to the National Research Council Technical Panel

March 27, 2013

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Outline

- **Introduction: EDL applicability beyond LEO**
  - Mars
  - Earth Return
- **Lander Challenges**
- **Mars EDL Challenges**
  - History of Mars landings
  - Human Architecture Team (HAT) Activities
  - Roadmapping Efforts and Results
- **EDL Supporting Capabilities**
- **Summary Comments**

EDL Challenges for Humans Beyond LEO

- **Entry, Descent and Landing requires development to flight readiness, *to varying degrees*, for multiple human mission scenarios:**
  - Earth Return from a NEO/NEA (12-13 km/s)
  - Mars surface missions – aerocapture, entry, descent and landing
  - Earth Return from Mars (up to 13.5 km/s)
- **Challenges for Earth return are in aerothermal environment prediction, lightweight, reliable thermal protection systems (TPS), and landing systems**
- ***Challenges for Mars are in all aspects of EDL systems***

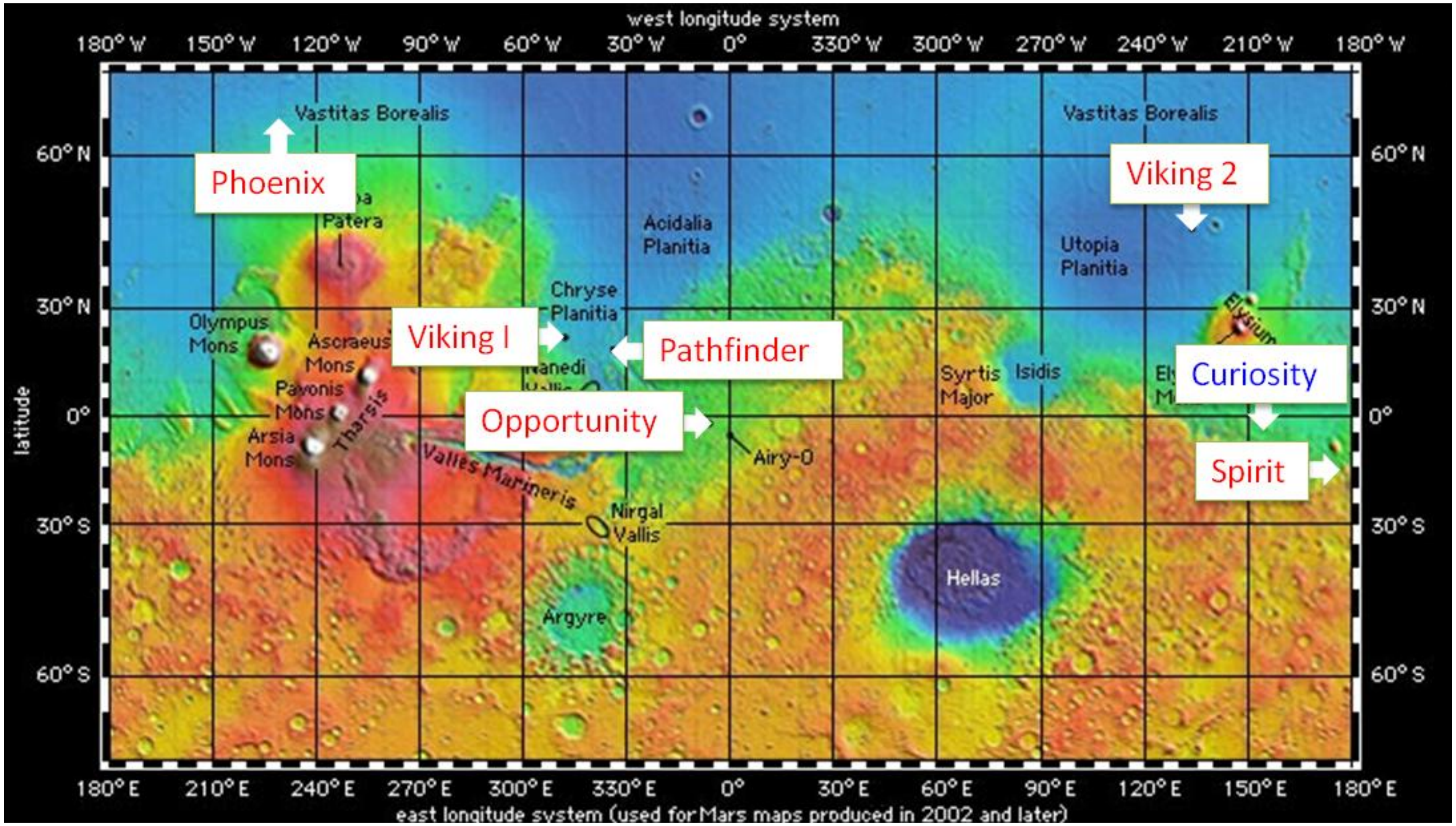
Lander Capabilities

- **Autonomous landing for assets**
- **Hazard avoidance and site redesignation**
- **Ability to land within a given proximity of a predeployed asset**
- **High-thrust, multi-restart, deep throttling engines (100 kN)**
- **Feed-forward propellants and engine designs are desired**
  - LOX/CH4 engines can be used at Mars, potentially with ISRU
- **Lightweight, high-strength materials certification enables lighter designs**
- **Inflatable pressure vessels (habitats or other) could reduce launch volume and improve system performance**

Why is Mars EDL So Challenging?

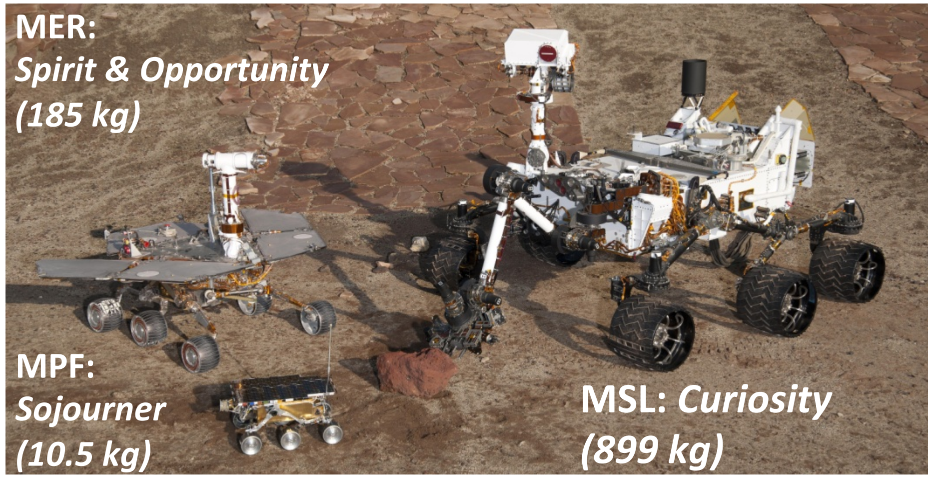
Mars has too much atmosphere to ignore, and too little to be very useful

- Heating and aerodynamic loads are significant enough to require a heatshield
- In an atmosphere with density 1/100th that of Earth's atmosphere, slowing heavy, fast-moving payloads over a vertical distance of 125 km is difficult

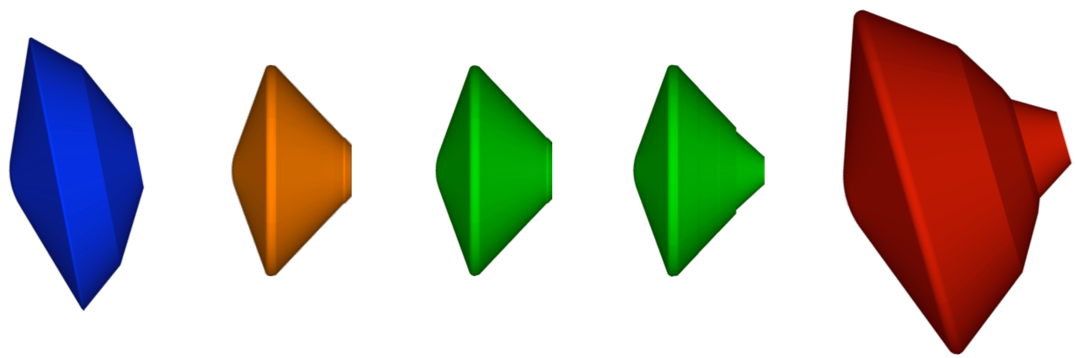


Mars Entry, Descent & Landing (EDL) History

- We've come a long way, but have that much further to go…
- Our 1970's Viking era technology is "broken" beyond MSL-sized spacecraft

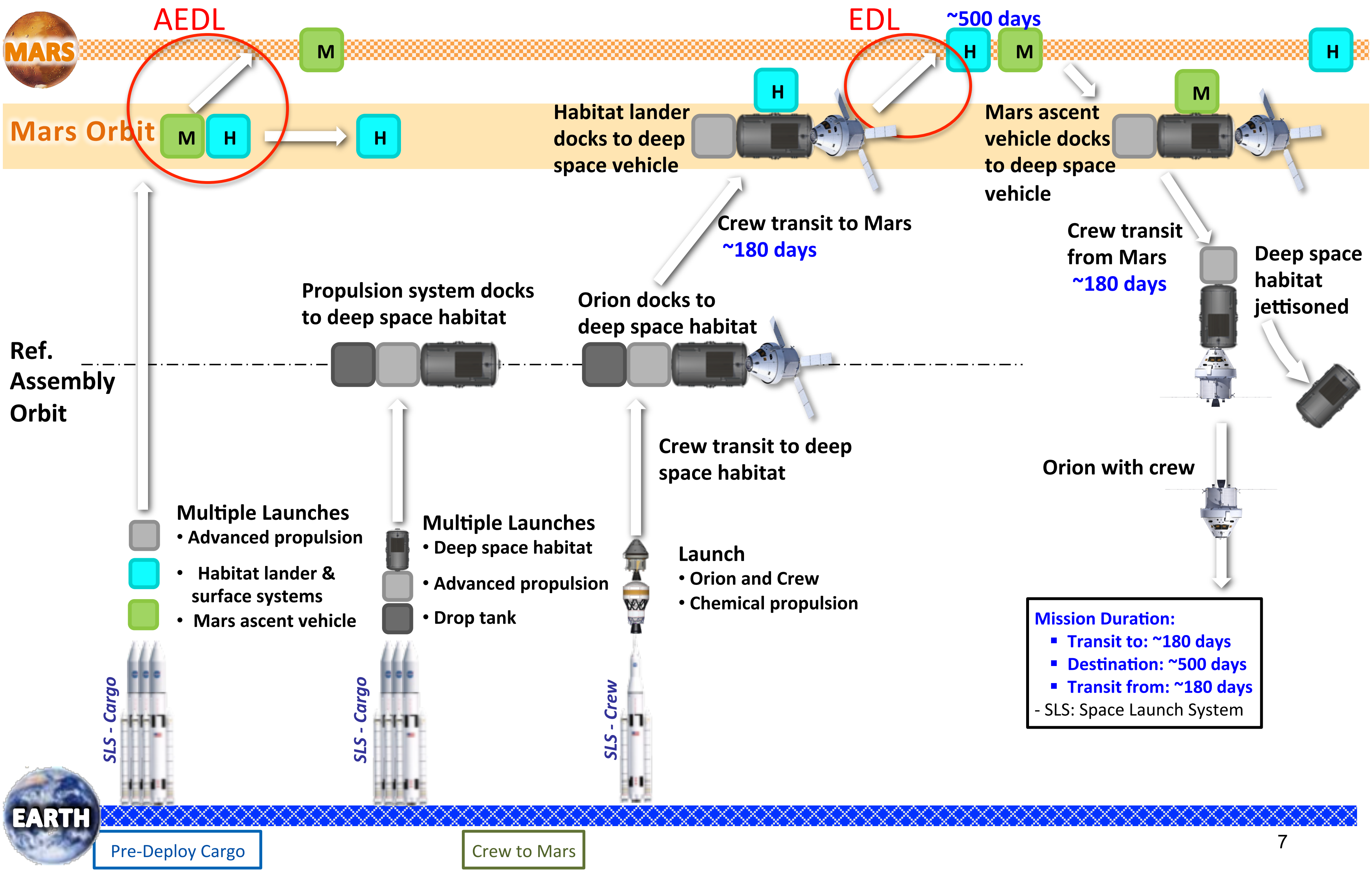


First hypersonic guidance
First 4.5-m aeroshell
First PICA heatshield
First 21.5-m chute
First good instrumentation



	Viking 1/2	Pathfinder	MER A/B	Phoenix	MSL	
Diameter, m	3.505	2.65	2.65	2.65	4.5	9+ (varies)
Entry Mass, kg	930	585	840	602	3151	80,000-100,000
Landed Mass (kg)	603	360	539	364	1541	Up to 60,000
Landing Altitude (km)	-3.5	-1.5	-1.3	-3.5	-4.4	<=2
Peak Heat Rate, W/cm^2	24	106	48	56	~120	~120-350

Example Crewed Mars Surface Mission
(NASA Mars Design Reference Architecture 5.0 Derived)



Mars EDL Capability Needs Increase

Parameter	Mars Robotic Class Mission	Mars Exploration Class Mission
Payload Mass on Mars	1 to 5 metric tons	20 to 50 metric tons
Entry Initial Condition	Direct Entry or Mars Orbit, up to 7.6 km/s	Mars Orbit or Aerocapture from up to 9+ km/s
Landed Elevation	0 km MOLA	Unconstrained (up to 2+ km MOLA?)
Landing footprint	< 5 km accuracy (MSL footprint was 9x16 km, landed within 2.5 km of center)	< 100 m accuracy (depends on surface ops scenario, predeployed assets)
Launch Vehicle	Atlas, Various	SLS
On Orbit Assembly?	None	Rendezvous & Docking
Atmosphere	Avoid dust storm season	Unconstrained
Design Point of Departure	Mars Sample Return	DRA 5.0

EDL – Systems Analysis Background

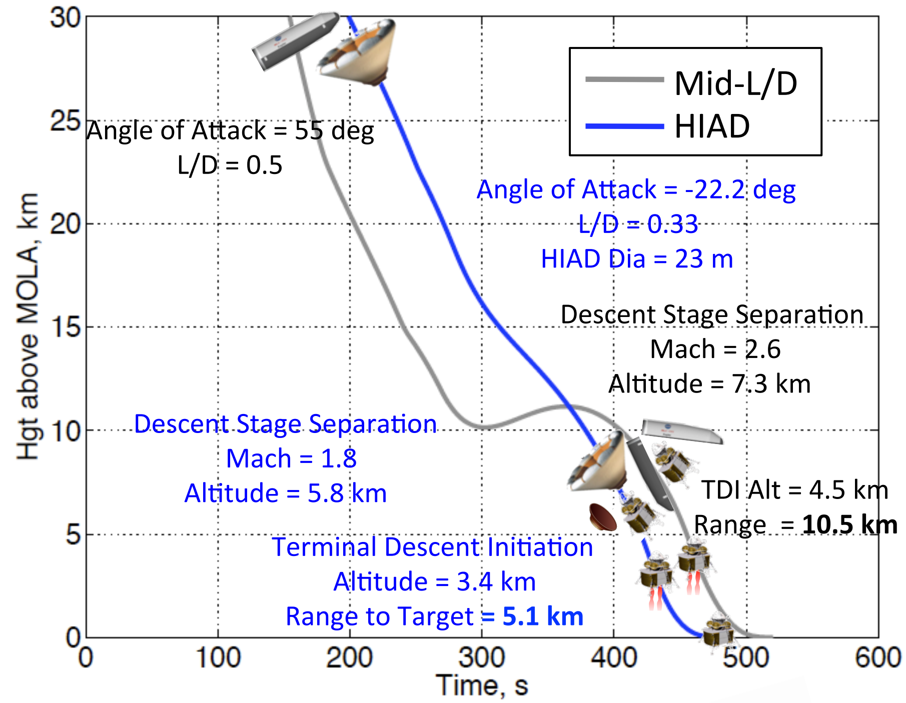
- **In 2009-10, the Entry, Descent and Landing Systems Analysis (EDL-SA) study was performed by a team of multiple NASA centers to examine the EDL portion of the Human Mars architecture presented in Design Reference Architecture 5.0 (DRA5), specifically to:**
  - Identify candidate technologies for performing the Mars EDL portion of DRA5
  - Determine the relative performance of the technologies through simulation
  - Perform expert Figure-of-Merit (FOM) assessment of the candidate technologies/ architectures—a mixture of quantitative and qualitative assessment
- **Deceleration technologies considered:**
  - Hypersonic Inflatable Aerodynamic Decelerators (HIADs)
  - Mid-L/D rigid aeroshells (aka Ellipsleds)
  - Supersonic Inflatable Aerodynamic Decelerators (SIADs)
  - Supersonic Retropropulsion (SRP) – actually a continuum of system performance
- **Conclusions:**
  - Inflatable decelerators potentially reduce Mars arrival mass by 20% over rigid, mid-L/D aeroshells
  - Those architectures with fewer technologies fared better in FOM assessment
  - Multiple technologies should continue to be considered

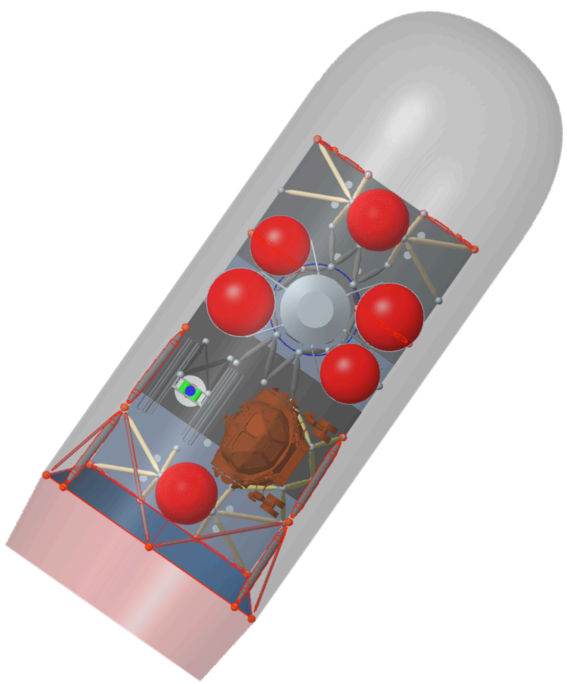
EDL-SA Architectures Considered

	#1	#2	#3	#4	#5	#6	#7	#8	#9
Arrival Mass (mt)	110	84	265	109	134	141	107	81	99

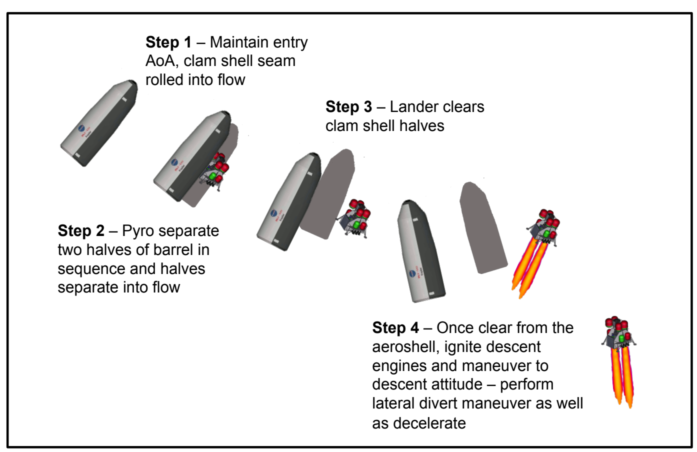
HAT Activities Following EDL-SA

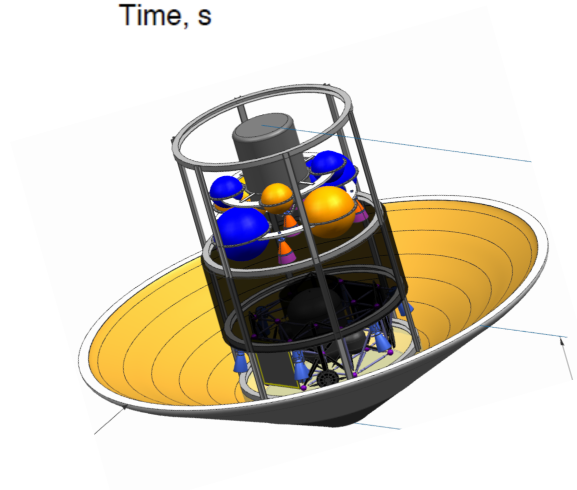
- **Higher-fidelity simulation follows from payload definition and packaging to inform <u>risk posture</u> and define specific challenges in the areas of:**
  - stability
  - controllability
  - transition feasibility
  - divert capability



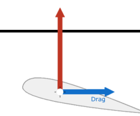
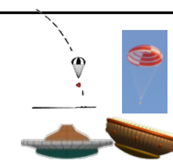
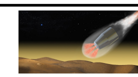
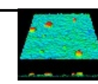
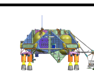


Side Exit Clam Shell





Key Technologies for Entry, Descent & Landing-MPPG

		Near-Term Robotic (1-2mT)	Sub-scale Precursor (5-10mT)	Human Full-Scale (20-40mT)	
Approach Phase					
Approach Navigation	Precision Star Tracker, Late Update, Optical Nav, Precision IMU	●	●	●	
Entry Phase					
Atmospheric Guidance	Lift Modulation, Drag Modulation	●	●	●	
Hypersonic Decelerators	Deployables: Inflatable, Mechanical	○	○ ↕	○ ↕	
	Rigid: Slender body Aeroshell		○	○	
Descent Phase					
Supersonic Decelerators	Smart Deploy Logic	●	○		
	30m Supersonic Parachute	●	○		
	SIAD	●	○ ↕	○ ↕	
Supersonic Retro-propulsion	High-thrust liquid	○	○	○	
Landing Phase					
Terrain Relative Navigation	Pinpoint Landing, Hazard Avoidance	●	○	○	
Subsonic Propulsion	Solids, Liquids	●	●	●	
Energy Absorption	Airbags, Crushables	●	○		
High-g Systems	Rough Lander	○			

○ *Potentially Applicable*

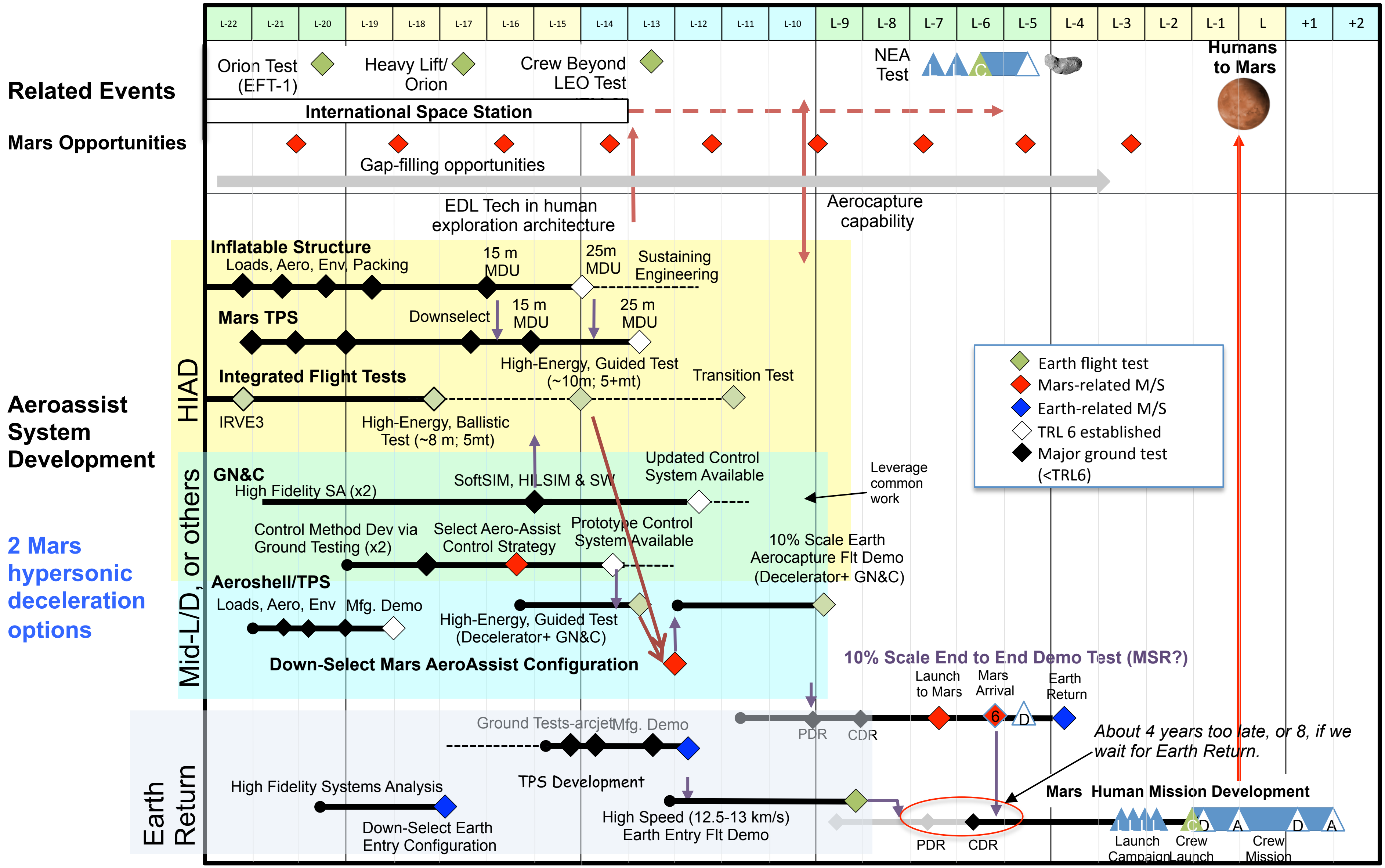
● *Fully Applicable*

Investment Priorities

EDL Developments Require Early Start

- **EDL requires extensive lead times, and Mars landing opportunities are limited.**
  - It took 8 launch opportunities to get from Sojourner to Curiosity.
  - It took until 2012 to obtain unambiguous engineering data from a Mars heatshield.
- **Numerous roadmapping activities all agree that development of Mars EDL for humans will take 20+ years**
  - 2005 Human Planetary Landing Systems Roadmap
  - TA09 Agency EDL roadmap (2010-2012)
  - Mars Program Planning Group roadmapping activity (June 2012)
- **EDL systems require ground test, Earth flight test, and Mars flight test**
  - Mars EDL cannot be validated end-to-end at Earth
  - Years to accomplish complex flight tests

Aerocapture EDL Development – Notional Schedule (2012)



Leveraging Near-Term Missions

- **Current and planned robotic Mars missions can be leveraged to address the SKGs related to EDL.**
  - Atmospheric measurements can reduce atmospheric model uncertainties, which drive mission risk, entry system mass, landing site altitude, and may force non-optimal technology choices.
  - Understanding surface and subsurface soil characteristics can help predict landing plume ejecta properties and drive designs.
  - Electrical properties of the soil and near-surface atmosphere may affect vehicle and operations designs.
- **Atmospheric model validation and data assimilation can take multiple years following data acquisition, and must be factored into phasing**
- **Entry vehicle engineering data is critical to improving the models and methods *used across all missions*.**
  - Mars Science Laboratory Entry, Descent and Landing Instrumentation (MEDLI)
  - Flight Test – 1 flight instrumentation

Infrastructure for EDL

EDL spans a broad range of core capabilities:

- Aerodynamics
- Aerothermodynamics
- Guidance, Navigation & Control
- Propulsion
- Structures
- Landing Systems
- EDL Flight Simulators
- Inflatable/Deployable Decelerators
- TPS
- Atmospheric Element Mission Design
- Operational Support
- Instrumentation
- Atmospheric Characteristics
- Surface Effects
- Systems Engineering

EDL technology development, qualification, and certification in flight systems will require heavy use of numerous test facilities and laboratories around the country:

- Wind Tunnels
- Arc-jets
- Shock Tubes
- Ballistic Ranges
- Balloon and Sounding Rocket Programs
- Drop Test Services
- Computing

Summary Comments

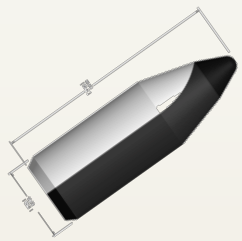
- **EDL for Mars is a significant challenge requiring multiple Earth-based tests and end-to-end Mars testing at subscale then full scale; repeated roadmapping activities show development will take 20+ years.**
- **High-speed Earth return capabilities are cross-cutting for several destinations**
  - Robust, low-cost, high-reliability thermal protection system materials
  - A solid understanding of the flight environment to allow informed decisions
- **Systems analysis is essential for maturing system concepts, making investment decisions, and establishing requirements for technology development.**
- **Flight engineering data from flight tests and robotic missions is vital for improving models, assessing system performance, establishing a risk posture, and improving future designs.**
- **EDL will require extensive use of unique Earth-based facilities and skill sets throughout capability development.**

Additional Information

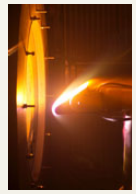
Mission Enabling EDL Technologies

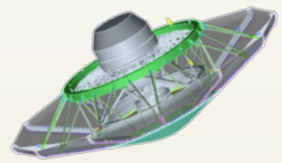
Hypersonic

Rigid Mid L/D Aeroshells

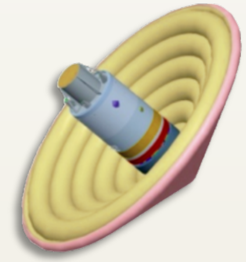


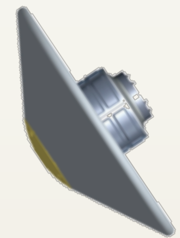
TPS & Deployable Aeroshells





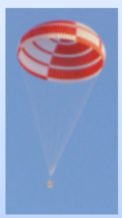
Inflatable Aeroshells

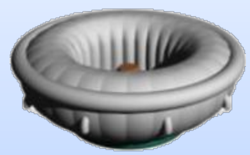




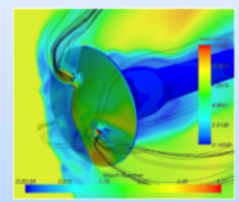
Supersonic

Low Density Supersonic Decelerators

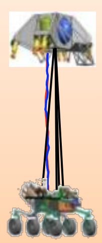




Supersonic Retro-propulsion

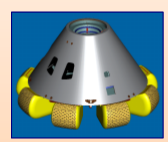


Subsonic / Terminal Descent



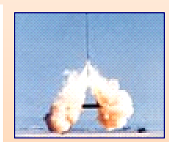
Landing System Technologies and Concepts

Air Bags (Vented and Anti-bottoming Bags)

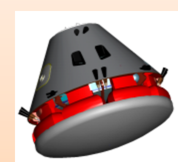


Deployed Crushable Energy Absorbers

Landing Gear and Legs

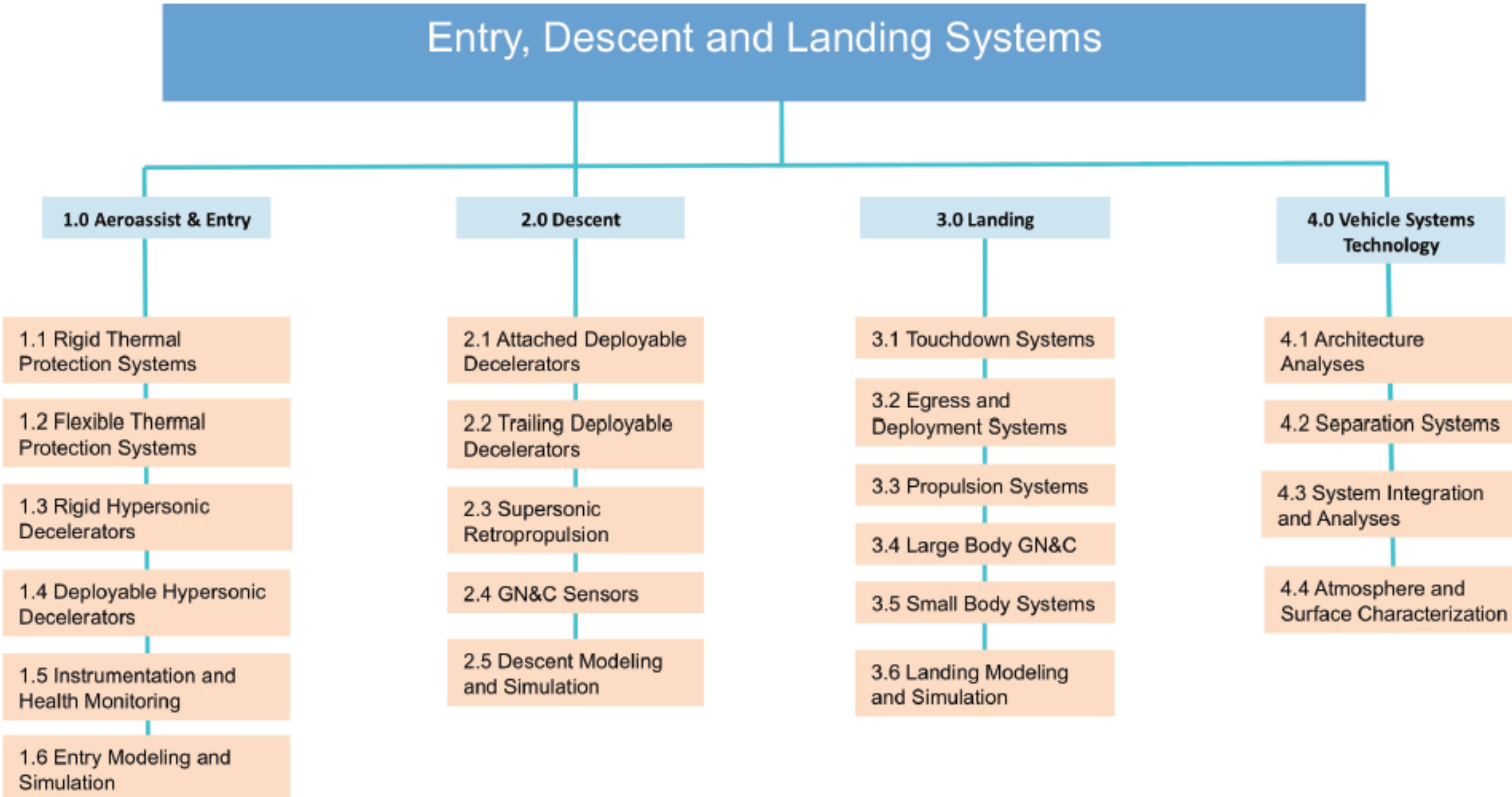


Propulsive Systems (Retro Rockets)



Hybrid Concepts

Agency EDL Roadmap (TA09)



Lander Propulsion Capability Needs

Capability or Technology	SOA	Required for Lunar & Mars
Primary ΔV Engines Pump-fed, LOX/CH4 deep throttling Pressure-fed Pressure-fed, throttling	 None 25kN @ TRL 5 18kN, 20% @TRL4	 100kN & 200 kN, 15% - 100% continuous throttle, TRL 3 18kN – 90kN, TRL 4/5 TBD, TRL 3/4
Ancillary Engines (RCS)	Hypergol, TRL 9	LOX/LCH4 , 400 - 440N (TBR), TRL 5/6
Zero-g liquid acquisition	Hypergol, TRL 9	Cryogenic liquid acquisition for RCS, TRL 4/5
Long-term cryogenic storage	<6 hours, passive	Zero-boil off LOX/LCH4, indefinite duration in loiter and surface (Mars 1600+ days)
Propulsion system components	n/a	Long duration, low leakage, low heat leak cryogenic valves & components
Lightweight, high performance tanks	COPV for ambient helium. AL FSW tanks	COPV for intermediate (300-500 psia) cryogenic propellants; Metallic or Composite tanks for low (40-60 psia) and intermediate (300-500 psia) pressure cryogenic propellants; COPV for cryogenic helium (3000-5000 psia)

Liquid Oxygen / Liquid Methane Cryogenic Propulsion System: Chemical Propulsion (TA2.1)

- **Description:**
  - An In-Space Stage, powered by a demonstrated workhorse engine, intended for boosting crew and cargo from LEO to destinations well beyond LEO.
  - The oxygen and methane propellant combination has the potential for good engine performance, which can result in lower vehicle mass and greater payload-carrying capability.
- **Performance characteristics:**
  - Improved handling & non-toxicity benefit of the LCH4/oxygen combination (hrs rather than days ground ops)
  - Approximately 10% specific impulse performance improvement relative to Hypergolic systems.
- **Applicable to these Capabilities/Elements; Destinations/ Con-Ops**
  - Driving: Lander; potentially Lunar surface, Mars surface
  - Beneficiary: CPS*; Min. capability NEA; NEA with Propellant Resupply

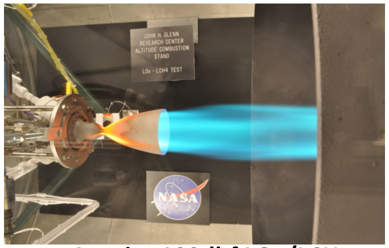
    **CH4 vs. LH study recommends LH for CP*S: Ref. MSFC Advanced Concepts, "In-Space Stage Propellant Assessment - Comparison of LOX/LH2 VS. LOX/CH4," dated 9 June, 2010.
- **Current TRL Level: Pressure Fed = 5, Pump Fed = 4**

Aerojet LOx/LCH4 5,500-lbf pressure fed workhorse engine in test at NASA White Sands Test Facility

Acronym list: • LOX Liquid Oxygen • LCH4 Liquid Methane

Liquid Oxygen / Liquid Methane Reaction Control Engines: Chemical Propulsion (TA2.1)

- **Description:**
  - The oxygen and methane (LCH4) propellant combination has the potential for greater engine performance, which can result in lower vehicle mass and greater payload-carrying capability.
  - An existing Demonstrated performance of a TRL 6 engine include:
    - Specific impulse of 317-sec; Impulse bit of 4 lbf-sec; 50,000 cycles with a cryogenic valve;
    - Ignition & operation over a range of propellant inlet conditions (liquid/liquid to gas/gas)
- **Performance characteristics:**
  - Improved handling & non-toxicity benefit of the LCH4/oxygen combination (hrs rather than days ground ops).
  - Approximately 10% specific impulse performance improvement relative to Hypergolic systems.
- **Applicable to these Capabilities/Elements; Destinations/Con-Ops**
  - Driving: Lander (assumes the use of CH4 for Lander propellant); potentially Lunar surface, Mars surface
  - Beneficiary: SEV; Min. capability NEA; NEA with Propellant Resupply
- **Current TRL Level: 6**



Aerojet 100-lbf LOx/LCH_4 reaction control engine in test at NASA GRC ACS

Acronym list: • LOX Liquid Oxygen • LCH4 Liquid Methane • ISP Specific Impulse • RCE Reaction Control Engine

Non-Toxic Reaction Control Engines: Chemical Propulsion (TA2.1)

- **Description:**
  - Propulsion system technologies for non-toxic or "green" propellants for use in reaction control systems.
  - Non-toxic technologies for RCS (reaction control system) engines over the thrust range of 25-1000 lbf. Propellant options include hypergolic ionic liquids and nitrous oxides monopropellants, both of which can be easily stored in space and on the ground.
- **Performance characteristics:**
  - Improved handling and non-toxicity benefit of hours rather than days ground ops.
  - Non-toxic bipropellant or monopropellants that have higher specific impulse (greater than hypergolic) and/or high specific impulse density (greater than hypergolic) with better safety and reduced handling risks
- **Applicable to these Capabilities/Elements; Destinations/Con-Ops**
  - Driving: None Identified
  - Beneficiary: CPS, SEV, SEP; Min. capability NEA, NEA with Propellant Resupply, Mars
- **Current TRL Level: 3-4**

Integrated Schedule Anatomy – Mars Example

- In this schedule-driven example, flight systems must arrive at KSC to support a launch date (which may be set by planetary physics)
- Flight system development for large human systems is 5-8 years
- New technologies incorporated into spacecraft design at PDR if TRL 6 or >
- Data gaps may need to be resolved in order to begin flight system design (e.g., choice of an asteroid target, planetary surface characteristics), or can be incorporated later in the design process (e.g., narrowing a landing site)
- Early incorporation of new technologies and data sets reduces mission risk
- The timeline varies for each destination, for different flight system developments, for different technology programs, and for the acquisition of different data sets