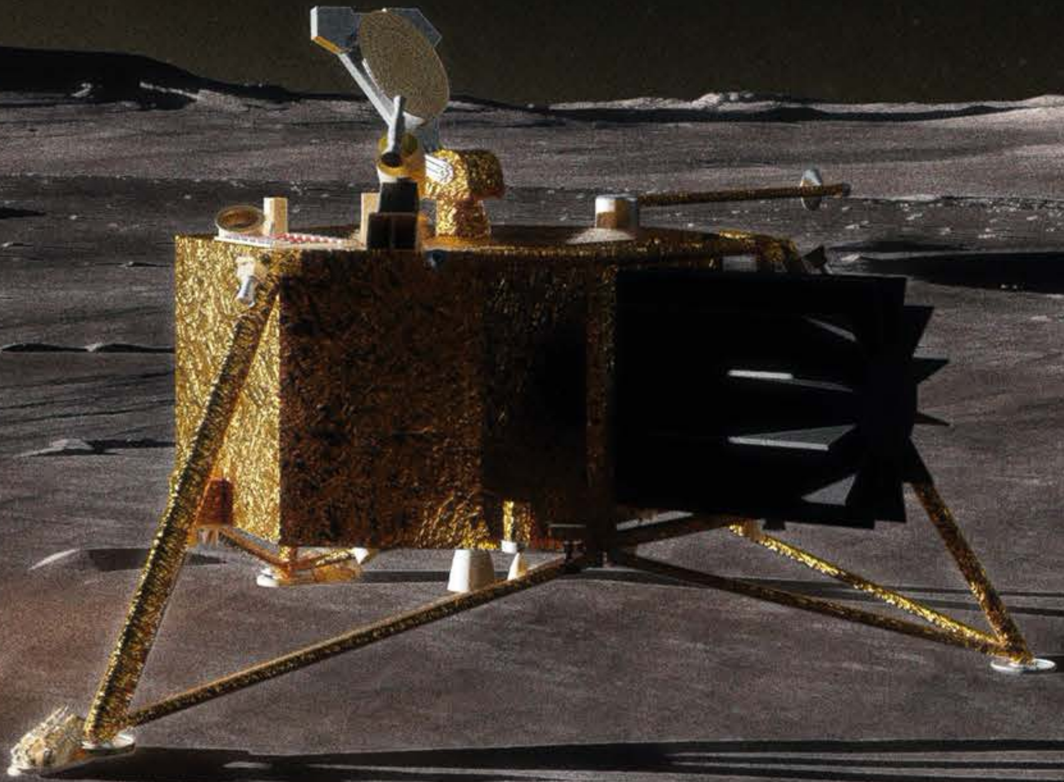
PLANETARY MISSION CONCEPT STUDY FOR THE 2023–2032 DECADAL SURVEY

Mercury Lander

Transformative science from the surface of the innermost planet

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY



Carolyn Ernst, Principal Investigator

Decadal Survey on Planetary Science and Astrobiology
Steering Group
27 May 2021

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Mercury Lander

Transformative science from the surface of the innermost planet

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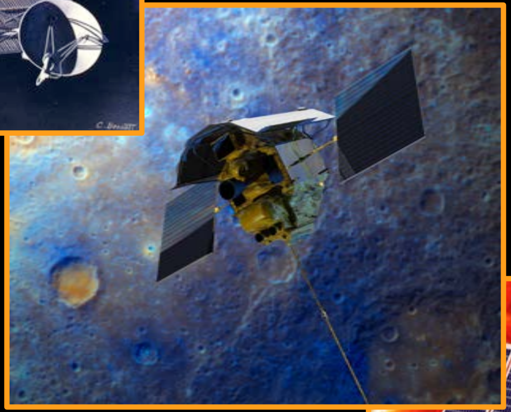
Spacecraft Reconnaissance of Mercury



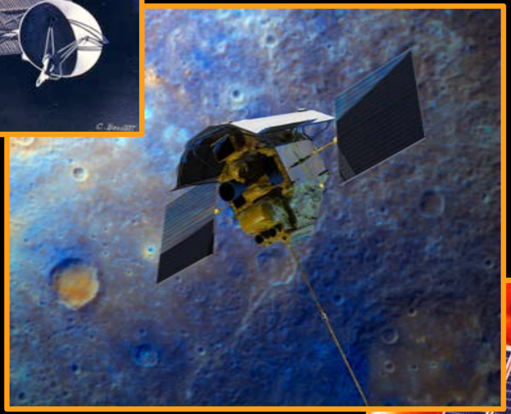
flyby ✓

orbit ✓

land ___

- **Mariner 10 (NASA)**
  - Launched 1973
  - 3 flybys of Mercury in 1974/1975
- **MESSENGER (NASA)**
  - Launched 2004
  - 3 flybys of Mercury in 2008/2009
  - Orbital reconnaissance 2011–2015
- **BepiColombo (ESA/JAXA)**
  - Launched 2018
  - Several flybys of Mercury from 2021–2025
  - Orbital reconnaissance 2025–2028

Spacecraft Reconnaissance of Mercury



flyby ✓

orbit ✓

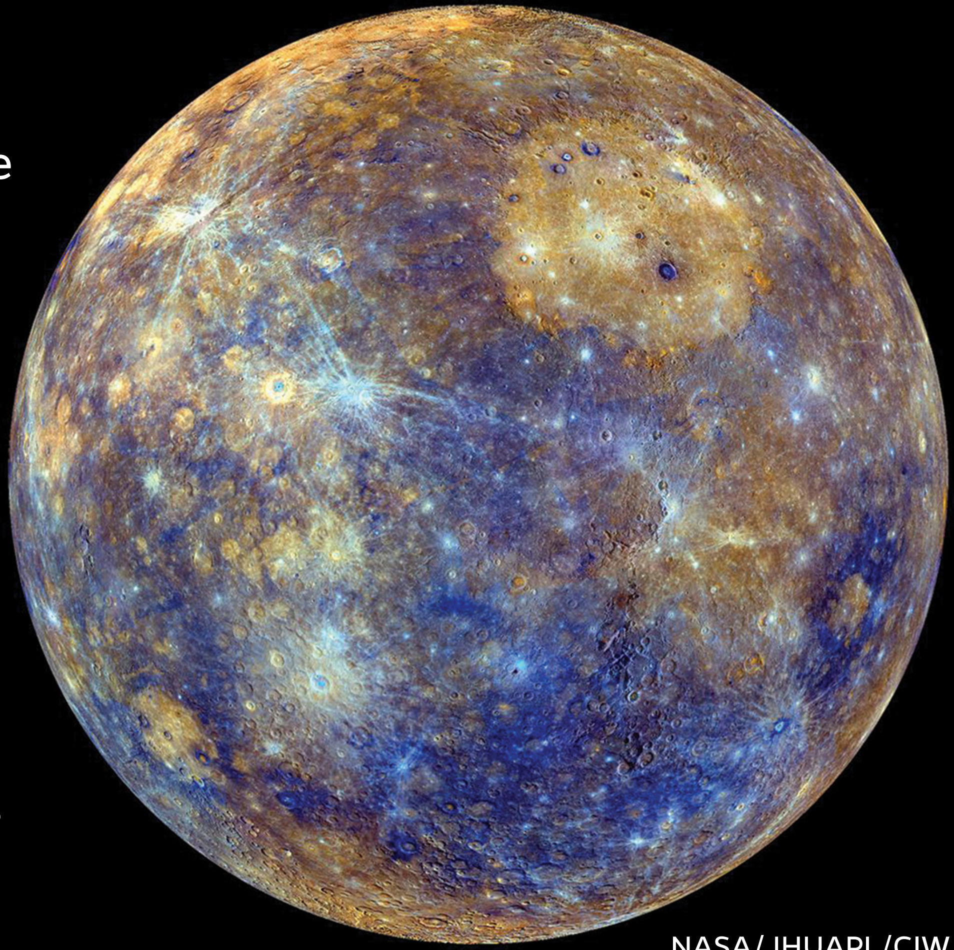
land ___

- **Previous Decadal Study**
  - Limited lander concept study completed in 2010
  - Concluded too challenging and expensive for New Frontiers in the last decade

- **Significant advances in the last decade make it important to perform a new study for a new decade**
  - MESSENGER orbital observations
  - Technology and capability advances
  - Changes to NF costing

Why Land on Mercury?

- MESSENGER revealed Mercury's highly chemically reduced and unexpectedly volatile-rich composition
    - Unique among the terrestrial planets
    - Unlike any predictions of previously proposed hypotheses of the planet's origin
- *In situ* measurements from the surface are needed to:
    - Understand Mercury's unique mineralogy and geochemistry;
    - Constrain the massive core's structure;
    - Measure its active and ancient magnetic fields at the surface;
    - Investigate the processes that alter its surface and produce its exosphere;
    - Provide ground-truth for remote datasets.
- As an end-member of terrestrial planet formation, Mercury holds unique clues about the original distribution of elements in the earliest stages of the solar system and how planets (and exoplanets) form and evolve in close proximity to their host stars.



NASA/JHUAPL/CIW

Science Goals

- **Goal 1 (geochemistry):** Investigate the highly chemically reduced, unexpectedly volatile-rich mineralogy and chemistry of Mercury's surface, to understand the earliest evolution of this end-member of rocky planet formation.
- **Goal 2 (geophysics):** Investigate Mercury's interior structure and magnetic field, to unravel the planet's differentiation and evolutionary history and to understand the magnetic field at the surface.
- **Goal 3 (space environment):** Investigate the active processes that produce Mercury's exosphere and alter its regolith, to understand planetary processes on rocky airless bodies, including the Moon.
- **Goal 4 (geology):** Characterize the landing site, to understand the processes that have shaped its evolution, to place the *in situ* measurements in context, and to enable ground truth for global interpretations of Mercury.

Study Philosophies

- There is no shortage of transformative science that can be done by the first landed mission to the innermost planet. Consequently, two overarching philosophies were adopted for this concept study:
  - **Investigate a comprehensive, scientifically robust payload spanning the wide-ranging science measurements that could be made in situ on Mercury's surface.**
    - Coverage of all four goals in fairly equal detail
    - Inclusion of a large number of instruments to provide a more valuable resource for the science community when planning a landed mission to Mercury in the future
  - **Prioritize landing safely on Mercury.**
    - Focus resources on this fundamental challenge, without which landed science is not possible
    - Considered only payload implementations that leveraged previous development efforts; the first landed measurements on the surface of Mercury are so fundamental that they can be made by current existing instrumentation
- The only absolute requirement to achieve ground-breaking science from a Mercury Lander is to perform *in situ* measurements on the surface of Mercury.

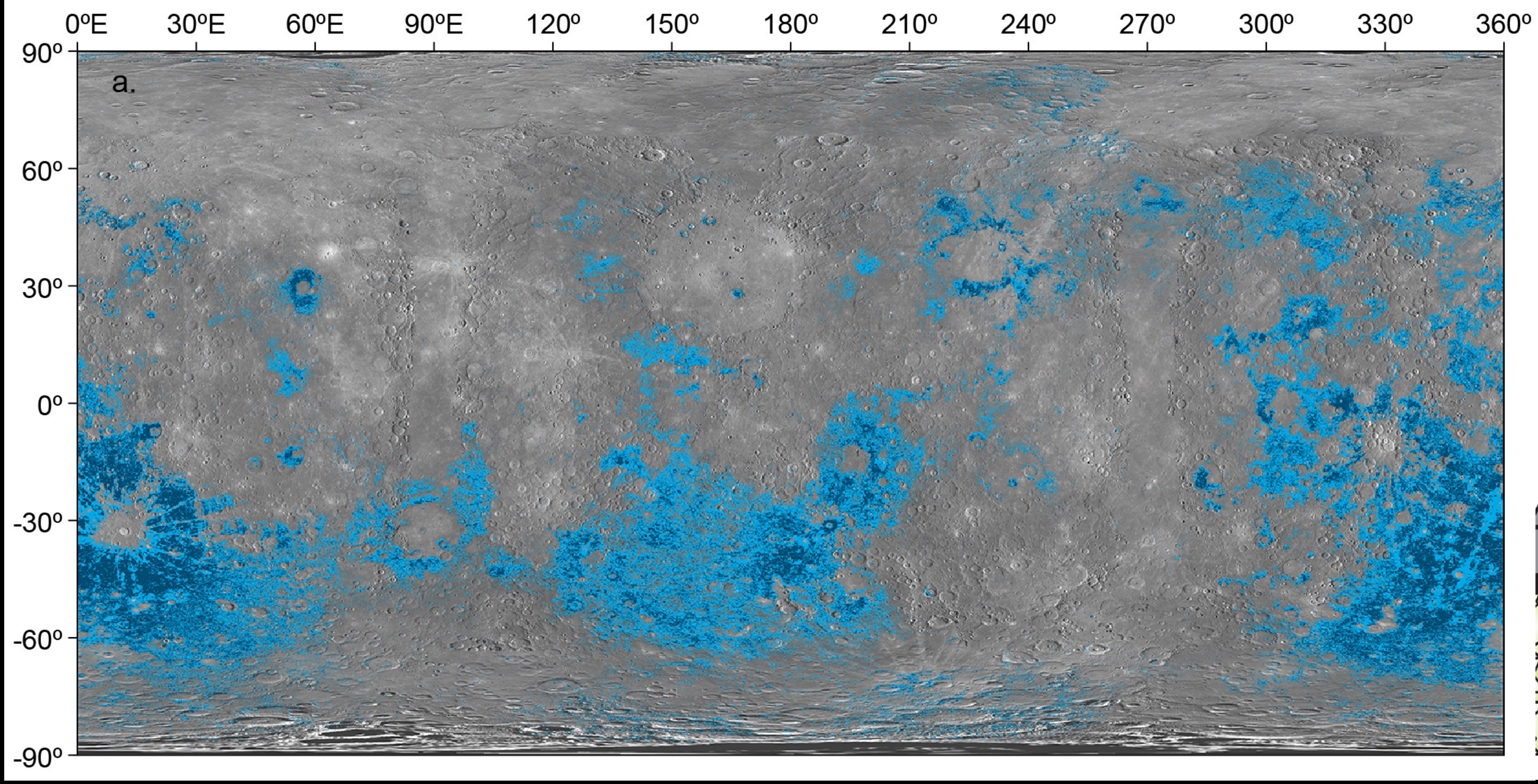
Study Flexibility

- There are compelling scientific cases to be made for a wide range of landing locations.
  - The overarching science goals remain the same regardless of the ultimate landing site choice (specifics of Goal 1 would necessarily be adapted for a polar deposit lander).
  - The measurements made by the first landed mission to Mercury will be foundational and transformative, answering high-priority outstanding science questions for Mercury from any location.

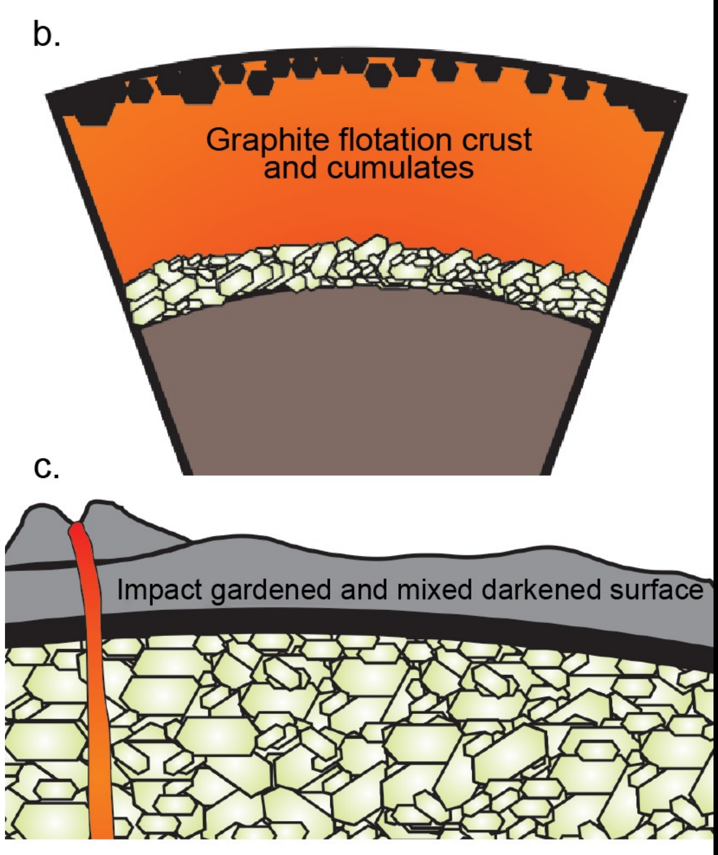
- The science payload chosen for this study is just one possible configuration that could accomplish the high-priority science goals
  - Alternate payload implementations could be designed to return equally compelling science measurements.
  - A future Mercury Lander mission should take advantage of technology advancements.
  - It may be advantageous to reduce the payload or to consider foreign contributions.

Goal 1 (geochemistry)

Investigate the highly chemically reduced, unexpectedly volatile-rich mineralogy and chemistry of Mercury's surface, to understand the earliest evolution of this end-member of rocky planet formation.



Klima et al. (2018)



Vander Kaaden and McCubbin (2019)

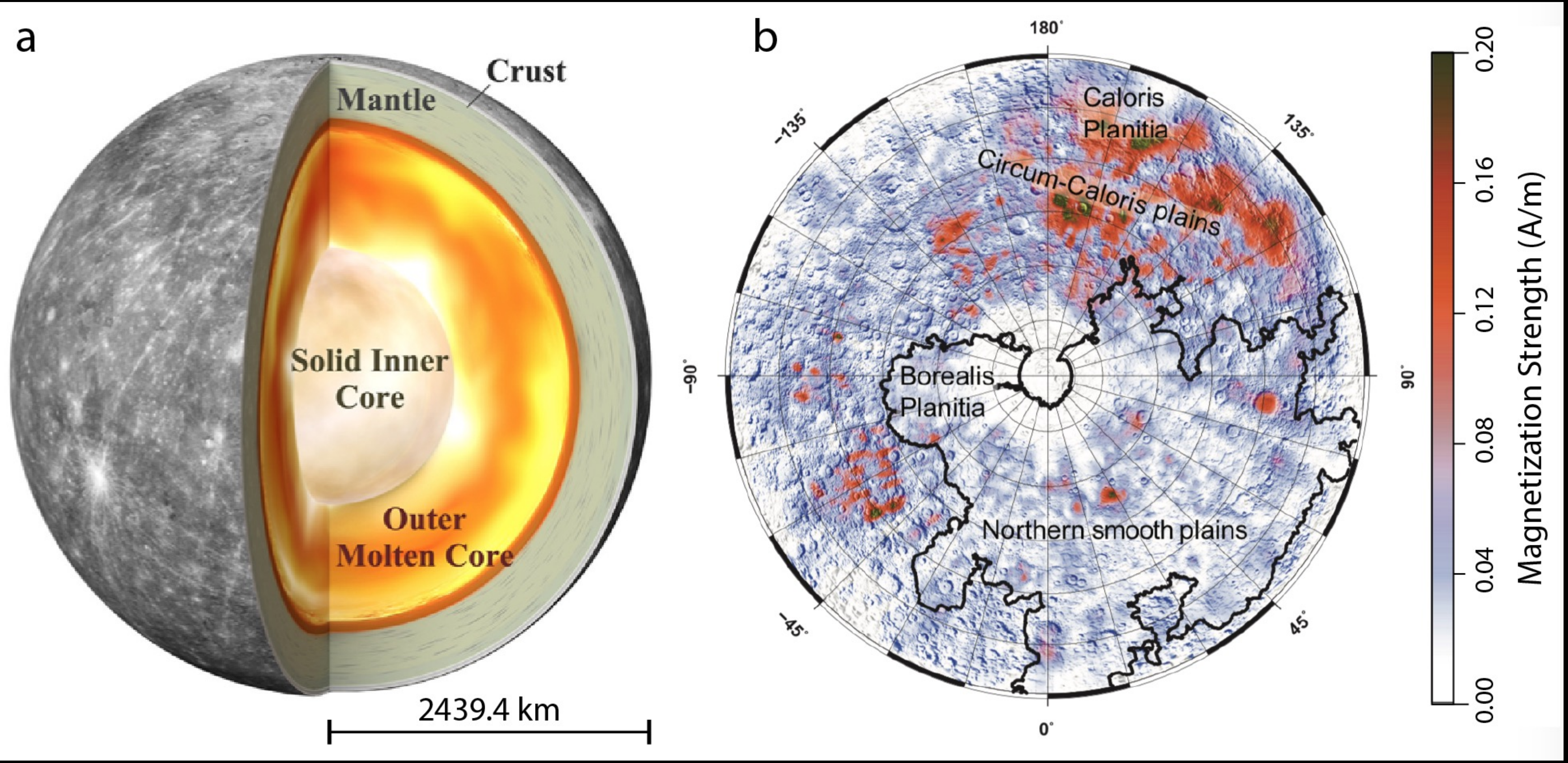
Goal 1 (geochemistry)

Investigate the highly chemically reduced, unexpectedly volatile-rich mineralogy and chemistry of Mercury's surface, to understand the earliest evolution of this end-member of rocky planet formation.

Science Objectives	Measurement	Instrument (analogs) [TRL # of analogs]	Functional Requirement
1.1 Determine the major- and minor-elemental composition of the LRM, including its C content and volatile-element abundances (e.g., Na, K, S)	Absolute abundances of: C, O, Na, Mg, Si, S, Cl, K, Ca, Fe, Th, U, Cr, Mn, if present at concentrations of >1 wt%	**GRS:** Gamma-Ray Spectrometer (MESSENGER [TRL 9], Psyche [TRL 7], MMX [TRL 7], Dragonfly [TRL 7])	Continuous operation to avoid instrument degradation; unobstructed FOV of the surface; surface operations ≥72 hrs
1.2 Determine the mineralogy of the components of the LRM, including any silicate, sulfide, or carbide phases that are present	Identification of silicates, sulfides, carbides, metallic phases, if present at concentrations of >1 wt%	**XRD/XRF:** X-Ray Diffractometer/X-Ray Fluorescence Spectrometer (MSL CheMin [TRL 9], CheMin-V [TRL 6])	Surface sample must be delivered into the XRD/XRF instrument
1.3 Investigate the chemical and mineralogical heterogeneity of the landing site	Measurements of Objective 1.2 from two locations at the landing site and from ≥two distinct surface disturbance events		Ability to collect samples from multiple locations and to produce distinct surface disturbance events

Goal 2 (geophysics)

Investigate Mercury's interior structure and magnetic field, to unravel the planet's differentiation and evolutionary history and understand the magnetic field at the surface.



Genova et al. (2019)

Hauck and Johnson (2019)

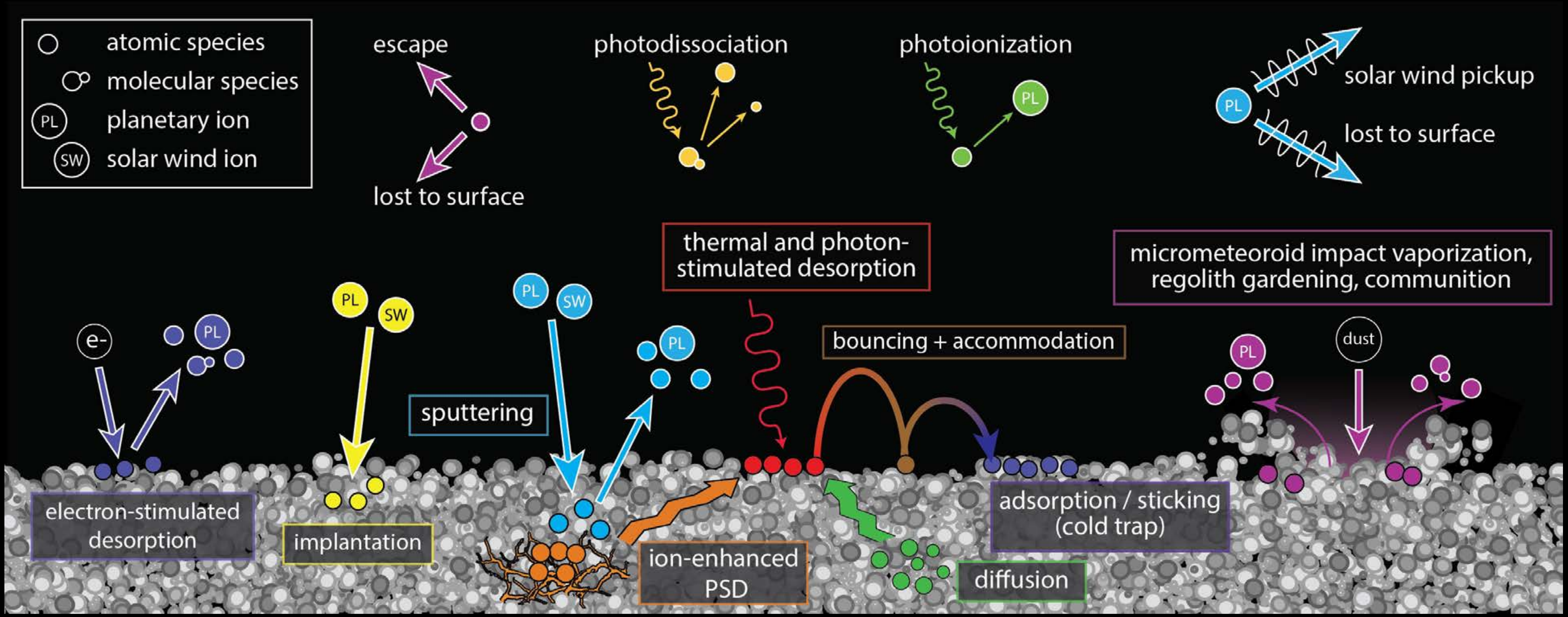
Goal 2 (geophysics)

Investigate Mercury's interior structure and magnetic field, to unravel the planet's differentiation and evolutionary history and understand the magnetic field at the surface.

Science Objectives	Measurement	Instrument (analogs) [TRL # of analogs]	Functional Requirement
2.1 Investigate the distribution of mass in Mercury's interior, determine the size and state of the core to characterize the solid and liquid portions, and search for seismic activity	Longitude libration amplitudes; obliquity	**RS:** Radio science (InSight RISE [TRL 9])	Ka-band communication to enable the most-sensitive science measurements
	Gravitational acceleration change due to solid-body tides; short-period seismic observations	**MAC:** Mercury accelerometer/short-period seismometer (InSight SEIS-SP [TRL 9])	Positioned near surface; high data rate from continuous operations needed to detect potential seismic events
2.2 Measure the magnetic field at the surface to investigate the coupling between the dynamo and external field, the time variation of the field, the strength of the crustal field, and the electrical conductivity structure of the crust and mantle	Measurements of magnetic field at the surface as a function of time, with a precision of 1 nT and at cadence of 20 vector sample/sec	**MAG:** Magnetometer (MESSENGER MAG [TRL 9])	Positioned to minimize contributions from spacecraft-generated fields
2.3 Investigate the mineralogy of the surface to identify potential magnetic carrier minerals	Covered by Objective 1.2 mineralogical measurements above		

Goal 3 (space environment)

Investigate the active processes that produce Mercury's exosphere and alter its regolith, to understand planetary processes on rocky airless bodies, including the Moon.



Goal 3 (space environment)

Investigate the active processes that produce Mercury's exosphere and alter its regolith, to understand planetary processes on rocky airless bodies, including the Moon.

Science Objectives	Measurement	Instrument (analogs) [TRL # of analogs]	Functional Requirement
3.1 Determine the composition and density of the near-surface neutral exosphere and compare with the surface compositional measurements, to investigate processes releasing materials from the surface	Densities of atomic and molecular species 1–100 amu, $M/\Delta M$ ~100, sensitivity ~1 count/sec at density 10 cm^{-3}	**NMS**: Neutral mass spectrometer (BepiColombo STROFIO [TRL 9])	Unobstructed FOV of space environment, angled 45º toward surface
3.2 Determine and characterize the incoming and outgoing fluxes of charged particles at Mercury's surface	Identification of low-energy charged particles, 1 eV/e to 20 keV/e, $M/\Delta M$ 4–40 over M/q 1–50, angular resolution <20º	**IMS:** Ion mass spectrometer (MESSENGER FIPS [TRL 9])	Unobstructed FOV of space environment, angled 45º away from surface
	Identification of high-energy charged particles, 20 keV to 1 MeV, angular resolution <20º	**EPS:** Energetic particle spectrometer (New Horizons PEPSSI [TRL 9])	Unobstructed FOV of space environment, angled 45º away from surface

Goal 3 (space environment)

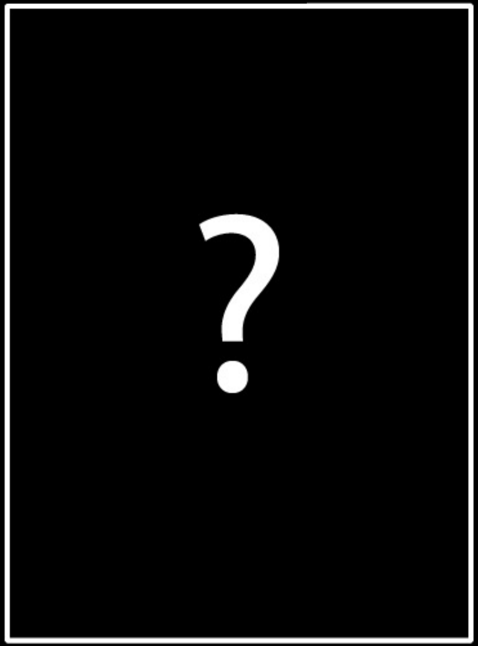
Investigate the active processes that produce Mercury’s exosphere and alter its regolith, to understand planetary processes on rocky airless bodies, including the Moon.

Science Objectives	Measurement	Instrument (analogs) [TRL # of analogs]	Functional Requirement
3.3 Determine and characterize the influx of micrometeoroids (dust) at Mercury's surface	Measurements of dust flux with sensitivity to measure 10^{-15} kg m^{-2} s^{-1}	**DD:** Dust detector (New Horizons SDC [TRL 9])	Unobstructed FOV of space environment, looking toward zenith
3.4 Investigate the nature of Mercury's regolith, including particle sizes and heterogeneity	Images of regolith in ≥3 visible colors, pixel scales ≤500 µm @ 1-m distance	**FootCam:** 2 cameras, to image PlanetVac (Malin Space Science Systems, ECAM [TRL 9])	Mounted to resolve 1-mm grains; LED illumination @ 450, 550, 650, 750 nm
3.5 Investigate the characteristics of space weathering on Mercury	Measurements for Objective 1.2 and 3.4 repeated for ≥two distinct surface disturbances of the same location		Ability to collect multiple samples from the same location and to produce distinct surface disturbance events

Goal 4 (geology)

Characterize the landing site, to understand the processes that have shaped its evolution, to place the *in situ* measurements in context, and to enable ground truth for global interpretations of Mercury.

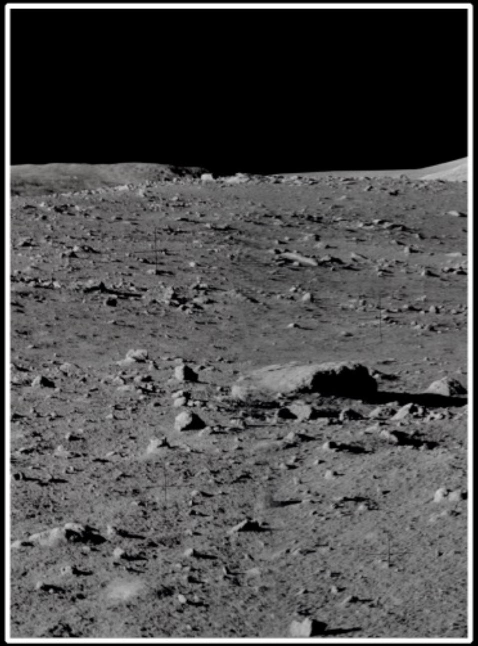
Mercury



Venus

Earth

Moon



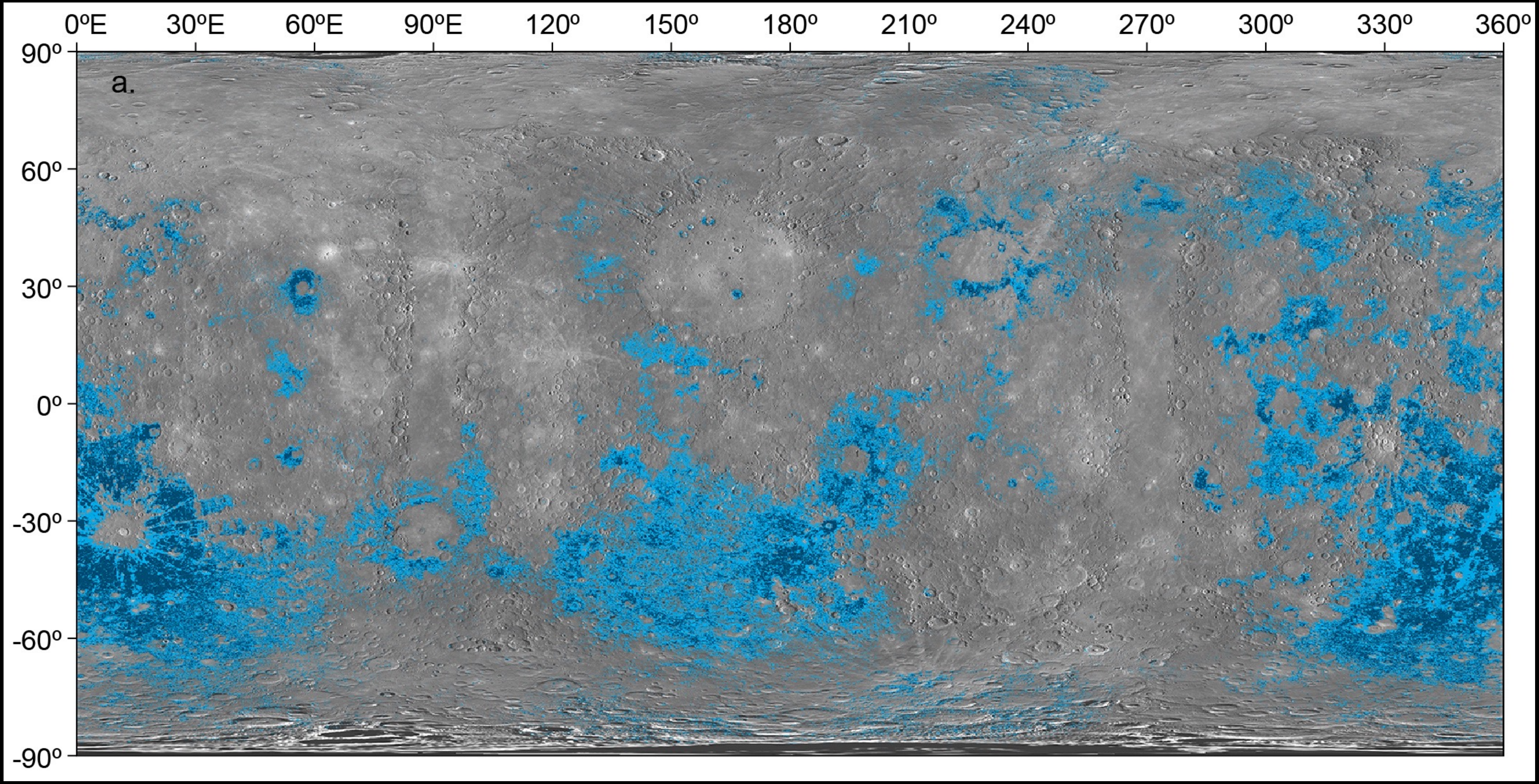
Mars

Goal 4 (geology)

Characterize the landing site, to understand the processes that have shaped its evolution, to place the *in situ* measurements in context, and to enable ground truth for global interpretations of Mercury.

Science Objectives	Measurement	Instrument (analogs) [TRL # of analogs]	Functional Requirement
4.1 Connect observations from images acquired by orbiting spacecraft to those from the Lander and determine the geological context of the landing site	Images of landing site acquired during descent, pixel scales 1 cm to 1 m	**DescentCam:** Descent Imagers (Malin Space Science Systems, ECAM [TRL 9])	Periodic imaging of the surface during descent; two cameras oriented 90° from one another to enable surface imaging despite changing orientation during descent
4.2 Characterize the geological setting of the landing site, including heterogeneity and landforms, and search for changes over the mission by surface, horizon, and exosphere imaging	Images of the landing site, pixel scale ≤5 cm within 50 m; ≥180° az, 0°– -45° elev	**StaffCam:** Panoramic Imager (MER PanCam [TRL 9], MSL Mastcam [TRL 9])	Unobstructed access to ≥ 180º of the landing site; articulation to achieve angular coverage
4.3 Characterize the bulk-element composition of the local landing site and place it into context with the equivalent orbital measurements	Covered by Objective 1.1 elemental measurements		

Where to Land?



Klima et al. (2018)

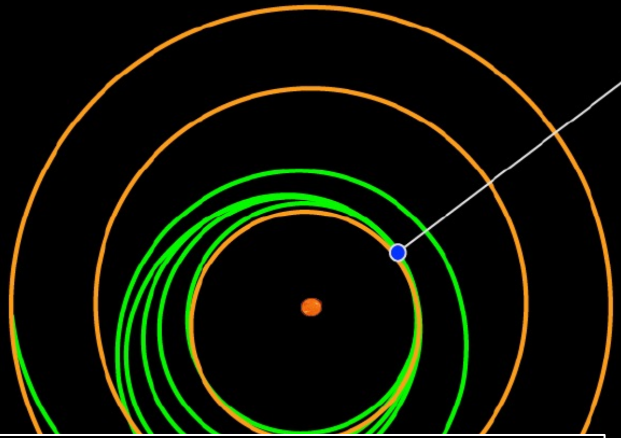
Mission Timeline

Launch: March 2035 on an expendable Falcon Heavy

Landing: April 12, 2045

Cruise Phase

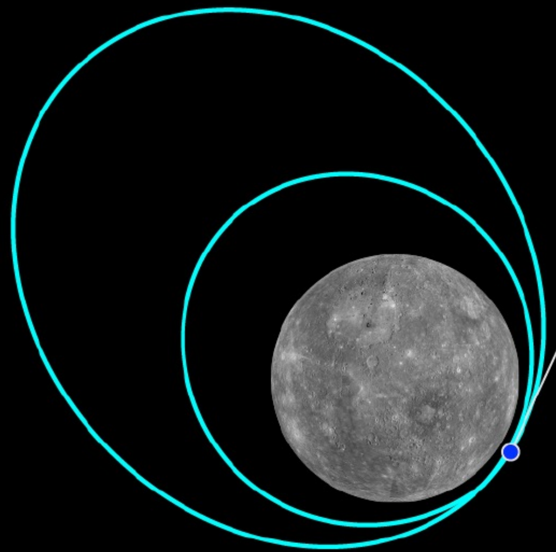
10 Year solar electric propulsion cruise



- Earth flyby – March 2036
  (back-up launch opportunity)
- Venus flyby 1: June 2036
- Venus flyby 2: March 2038
- Mercury flyby 1: May 2038
- Mercury flyby 2: Feb 2039
- Mercury flyby 3: Jan 2040
- Mercury flyby 4: Jan 2041
- Mercury flyby 5: June 2042

Orbital Phase

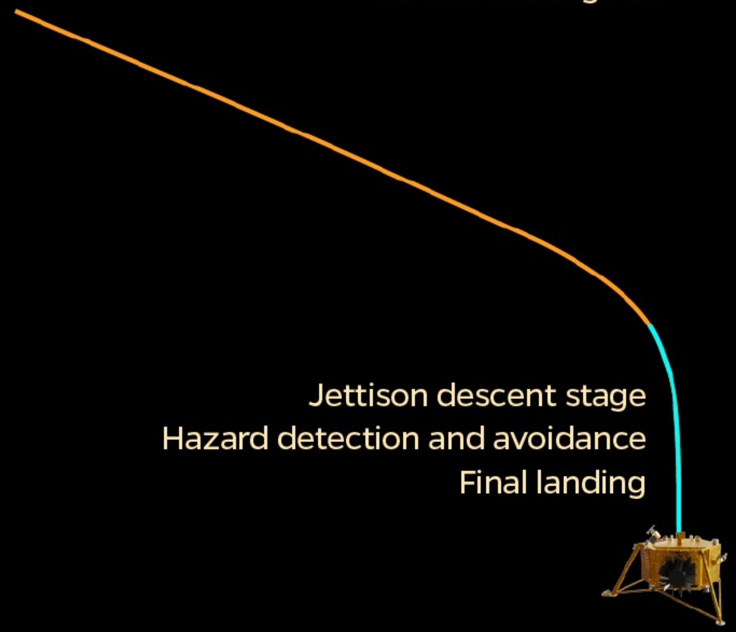
Jettison cruise stage
Mercury orbit insertion
2.5 Months in 100 x 6000 km orbit



- MOI: Jan 2045
- Apoherm lowering: March 30, 2045
  (2 Weeks in 100 x 2000 km orbit)

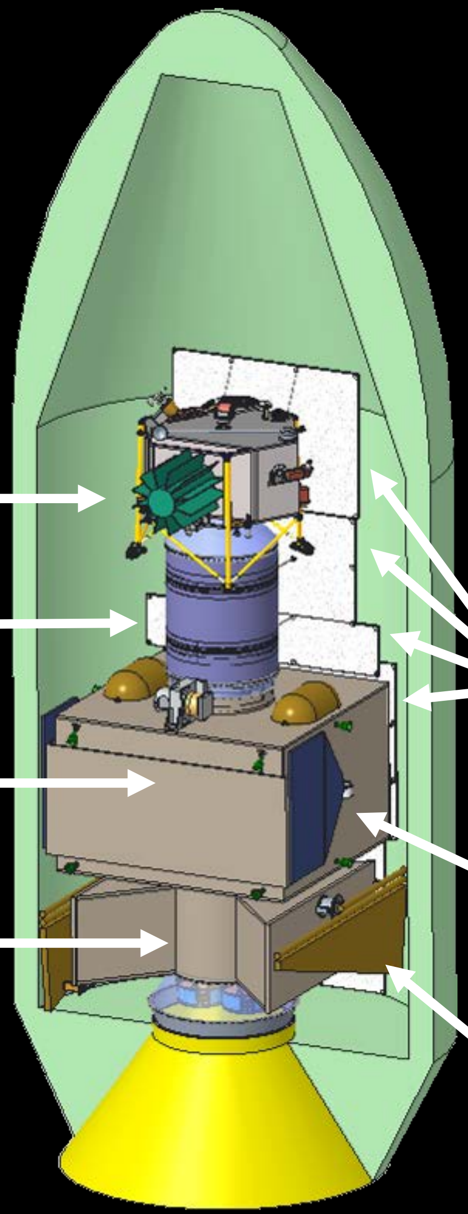
Descent Phase

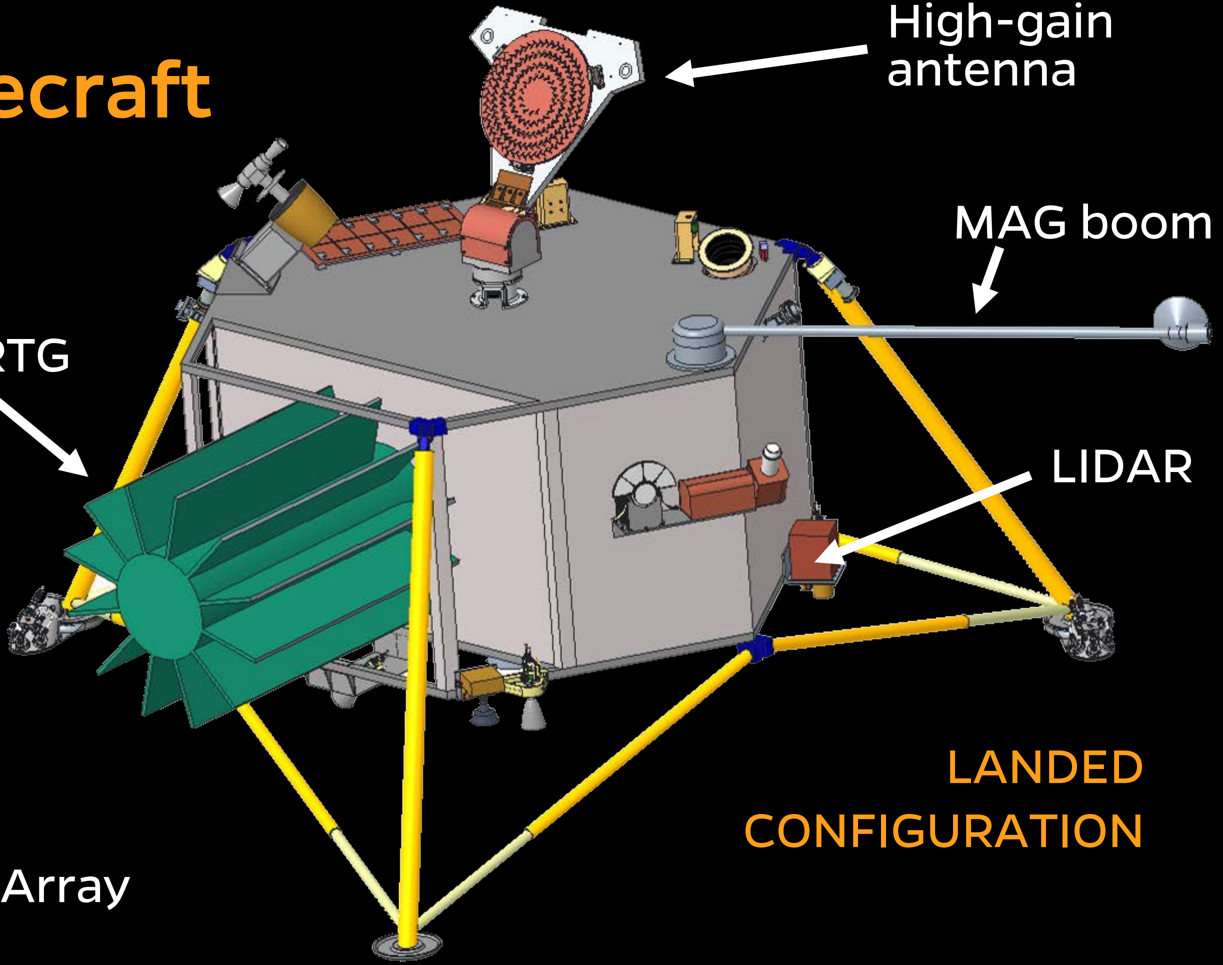
Jettison orbital stage
Initiate braking burn



- Landing: April 12, 2045

Spacecraft

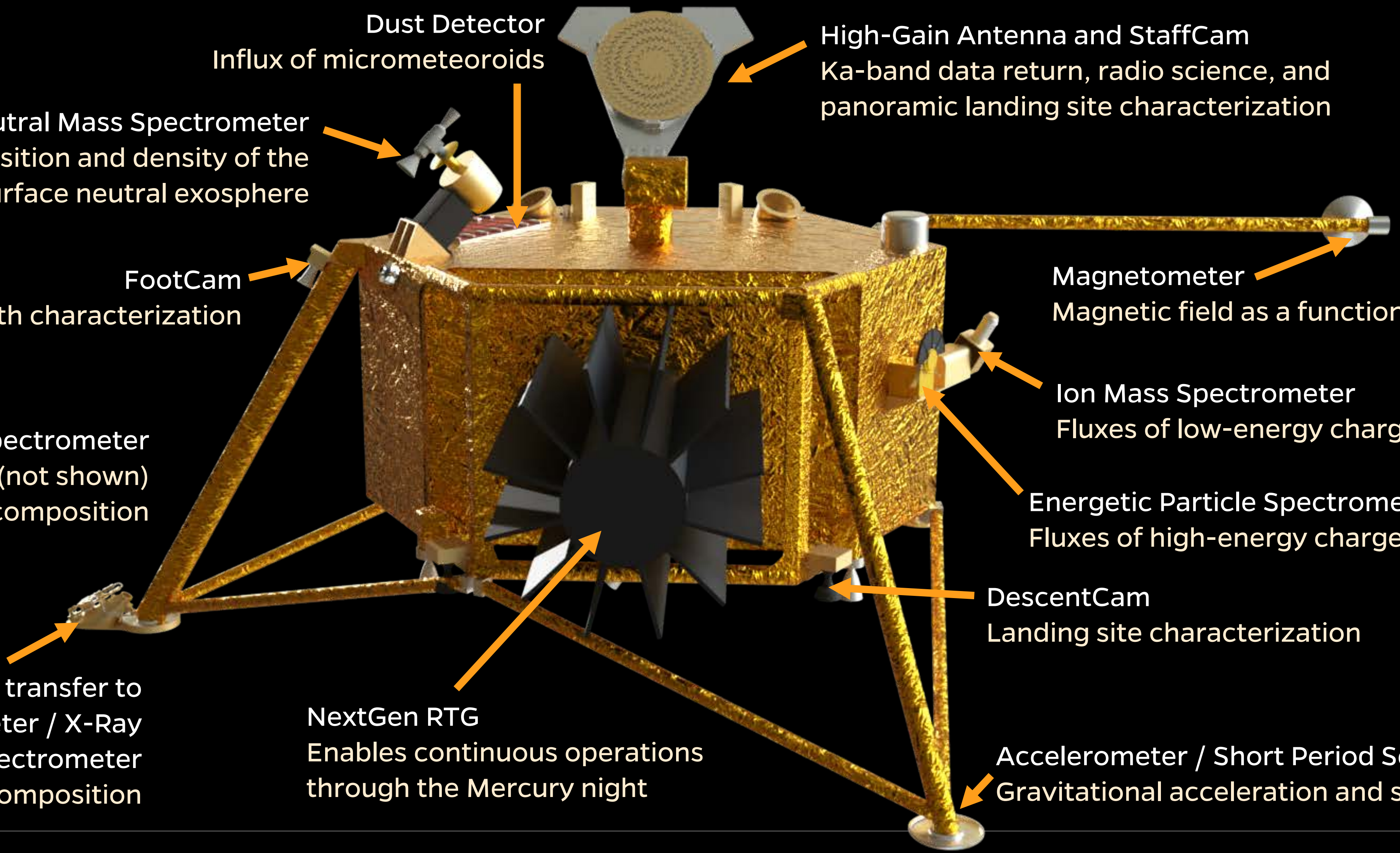




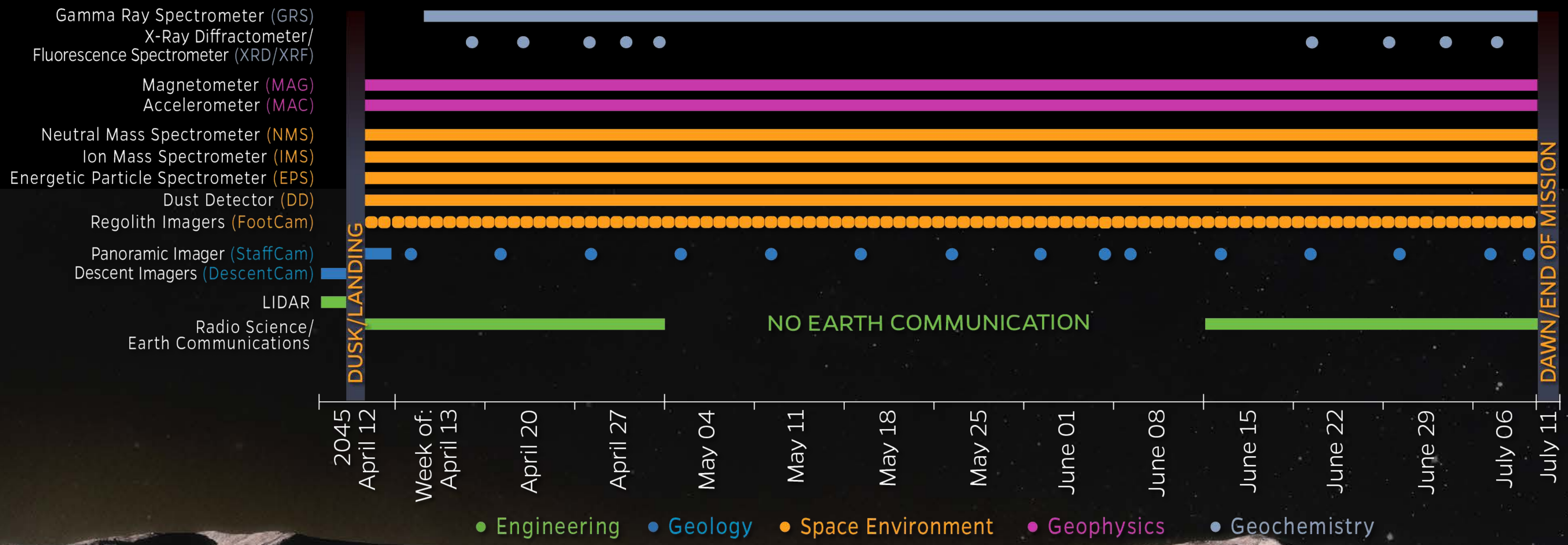
Four-stage flight system:

- Cruise Stage
- Orbital Stage
- Descent Stage
- Lander

Lander and Payload



One Full Mercury Year of Surface Operations

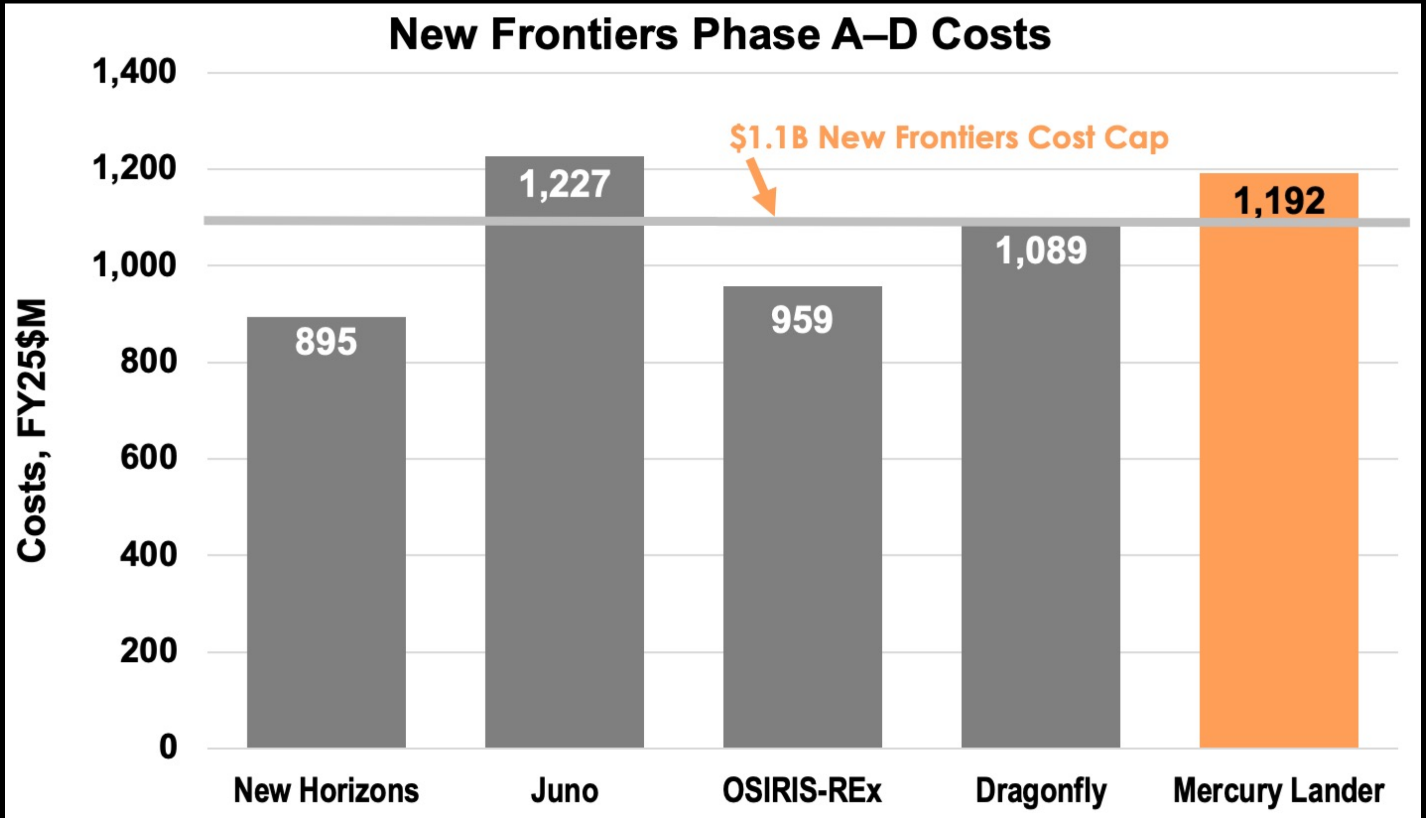


	NMS	IMS	EPS	DD	GRS	XRD/XRF#	MAG	MAC	StaffCam	FootCam	DescentCam	TOTAL
Surface Ops Description	Cont*	Cont*	Cont*	Cont*	Cont	Specific Collection Times	Cont*	Cont*	Specific Collection Times	Daily	Descent Only	
Total Data Volume Downlinked (MB)	228	1138	228	228	484	93	1422	4619**	773	1138	469	10,820

* Continuous except for during XRD/XRF analyses
# Includes XRD/XRF and PlanetVac data
** Only difference between data acquired and data downlinked; MAC acquires 7111 MB of data.

Baseline Plan:
10.8 GB total data

Cost



- Phase A–D mission cost estimate (50% unencumbered reserves, excluding the launch vehicle) with the 11-instrument payload is $1.2 B (FY25$).
- Compares favorably with past NF missions, and cost cap prescribed in the NF4 AO (~$1.1B FY25$).
- Payload descopes and foreign contributions are options for lowering the total cost.

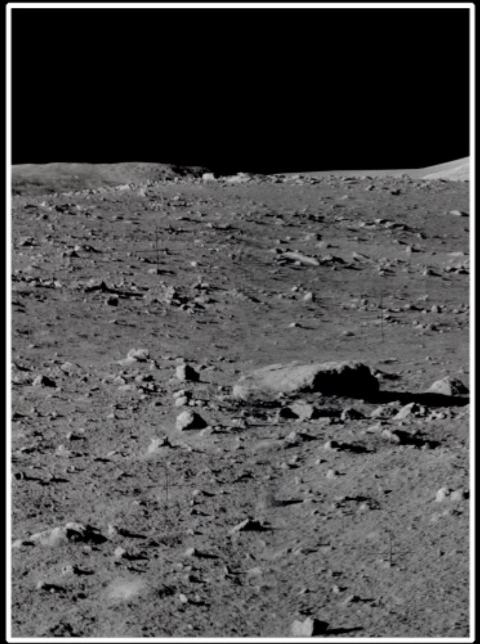
Ground-breaking science that can only be addressed by *in situ* surface measurements on the innermost planet…

Mercury

Venus

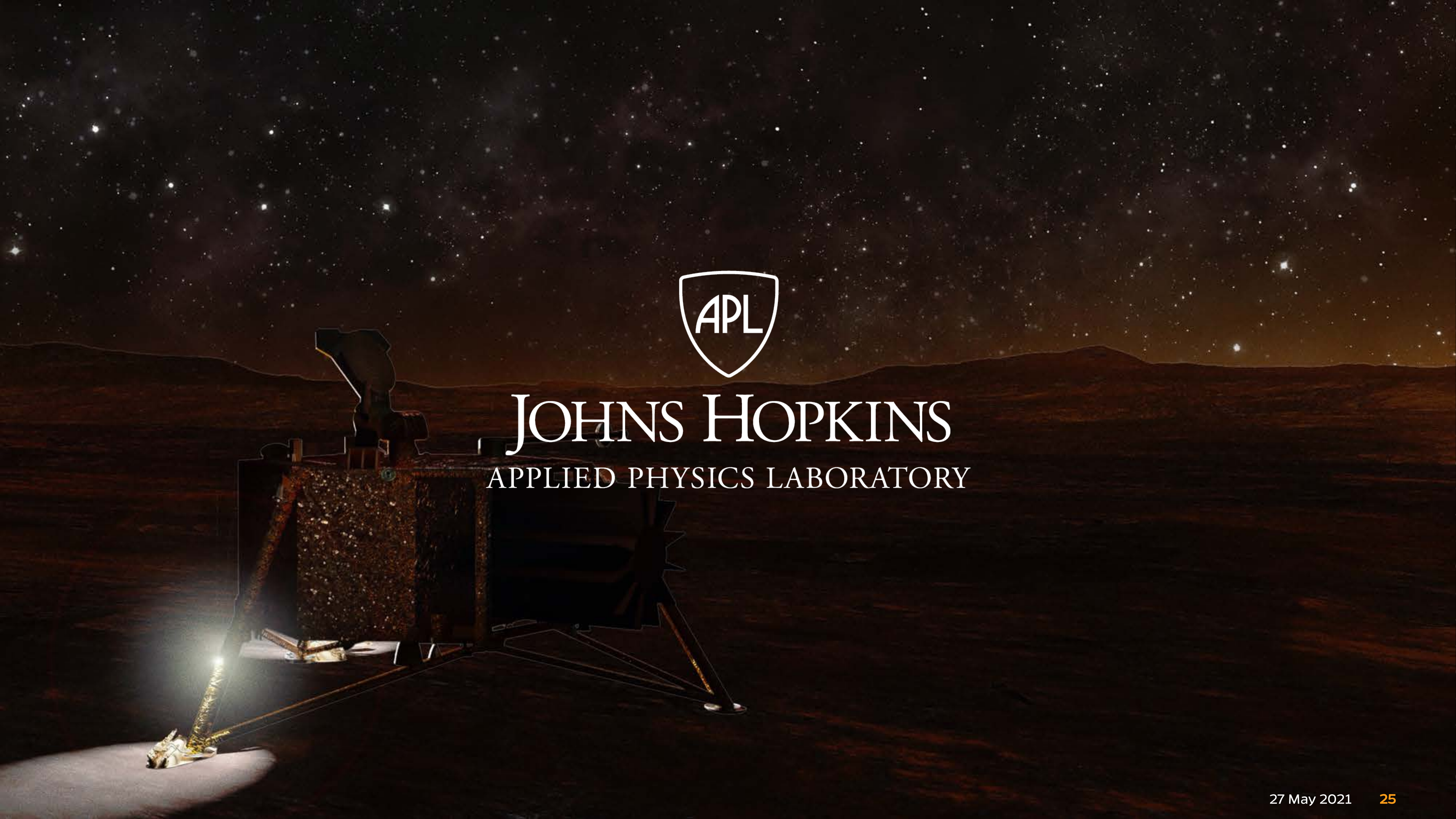
Earth

Moon



Mars

…is feasible and compelling for a New Frontiers-class mission in the next decade!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Key Trades

	Trade Space, Result	Rationale
Cruise Propulsion	Chemical vs **SEP**	Propellant savings
	Aerojet XR5 vs Qinetiq T6 vs **NEXT-C**	Thrust requirements, propellant savings
MOI / Orbit Propulsion	**Chemical** vs SEP	Long duration for SEP implementation, impacts to solar array thermal management and cell degradation
Braking Burn Propulsion	Bipropellant vs **SRM**	Mass savings, load path efficiency
Lander Propulsion	Monopropellant vs **Bipropellant**	Mass savings
Landing Area Risk Reduction	Targeted imaging orbits vs **opportunistic imaging**	Thermal constraints in lower orbits
Vehicle Stages	3 vs **4**	Propellant savings through jettison of stages prior to large burns

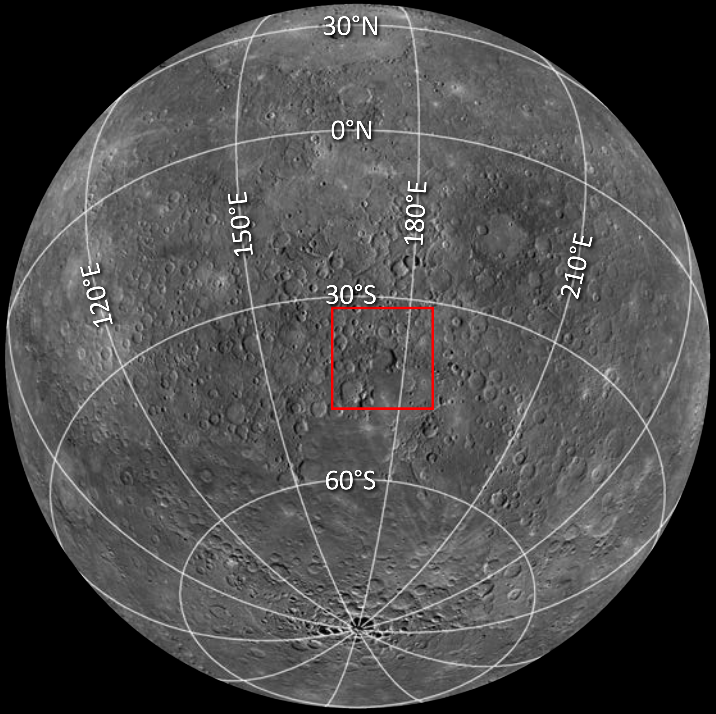
Trajectory Trade

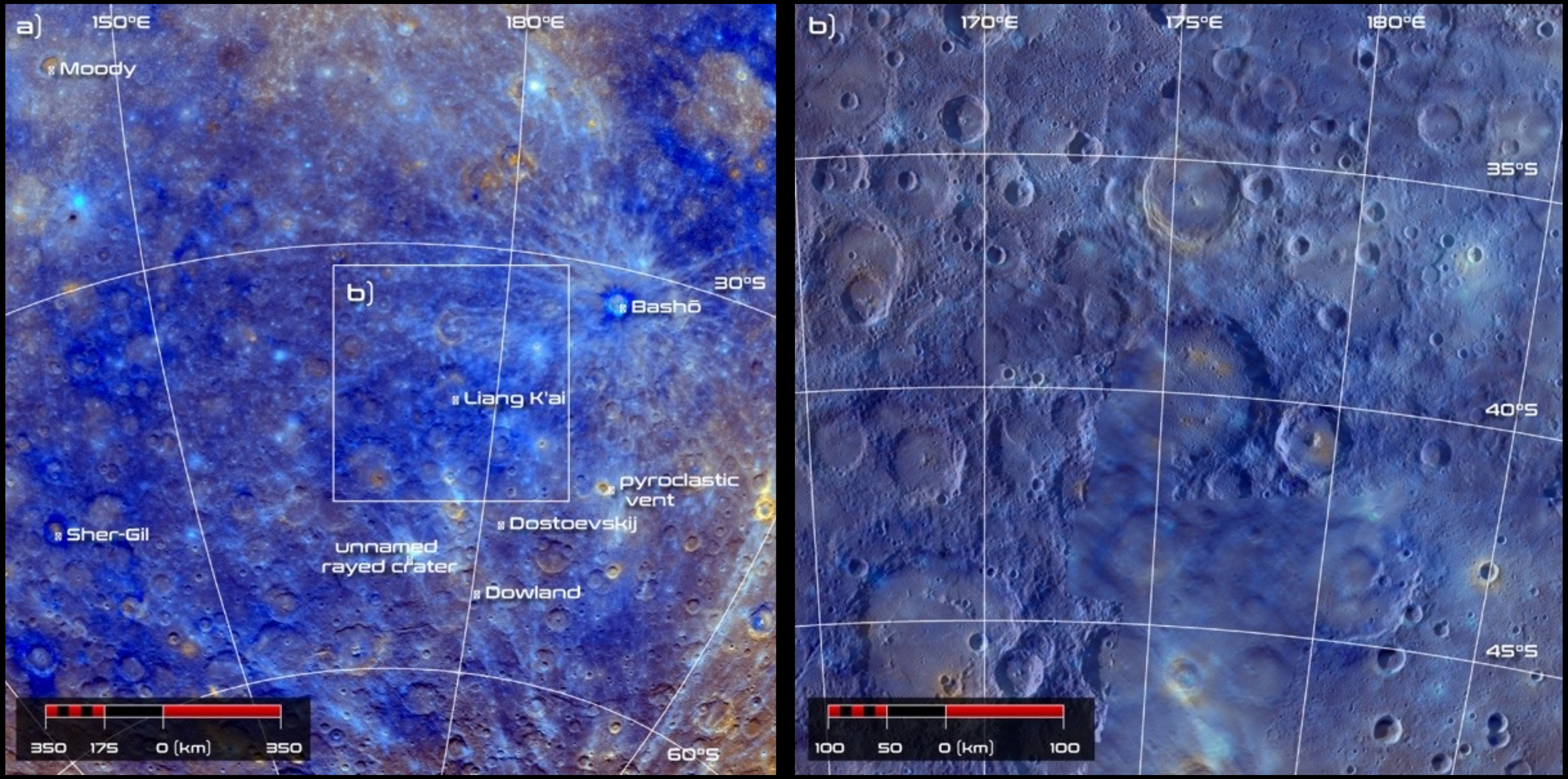
Scenarios Explored

- Fully Ballistic
  - Arrive with C3 > 0, chemical orbit lowering
  - Significant propellant requirements
- Ballistic Interplanetary, Solar Electric Propulsion (SEP) Spiral
  - Arrive with C3 > 0
  - SEP system cannot reduce orbital energy fast enough for capture
- Fully SEP
  - C3 = 0, spiral down using SEP
  - Low thrust values result in significant spiral flight times
  - Complicated spiral trajectory
- → SEP Interplanetary, Chemical Orbit Lowering
  - Arrive with C3 = 0 to reduce orbit insertion costs
  - Lowering with chemical thrusters eliminates long flight times @ Mercury
  - **Launch Vehicle:** fully expendable Falcon Heavy

Landing Site

Study landing site is situated at ~40°S, ~170°E, within a regional exposure of low reflectance material (LRM), in the terrain type termed "intercrater plains". This area is one of the oldest on Mercury.





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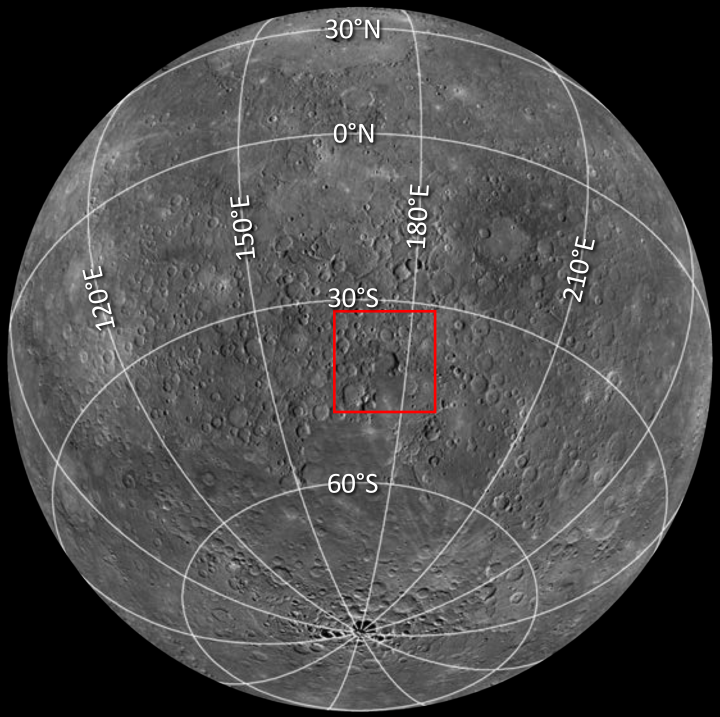
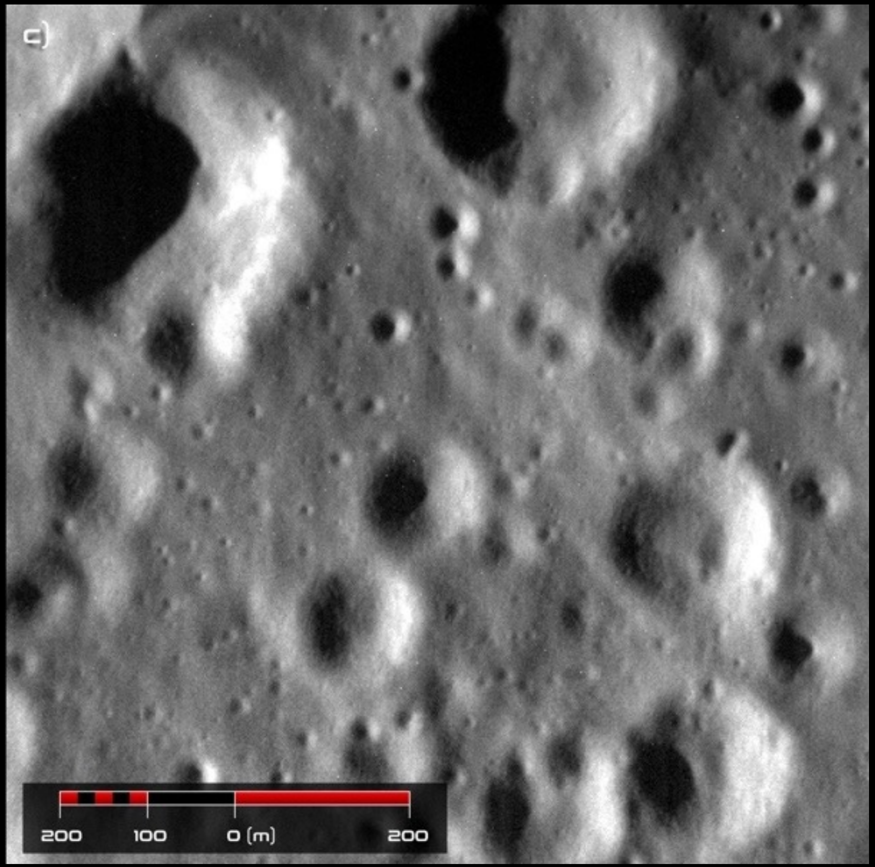
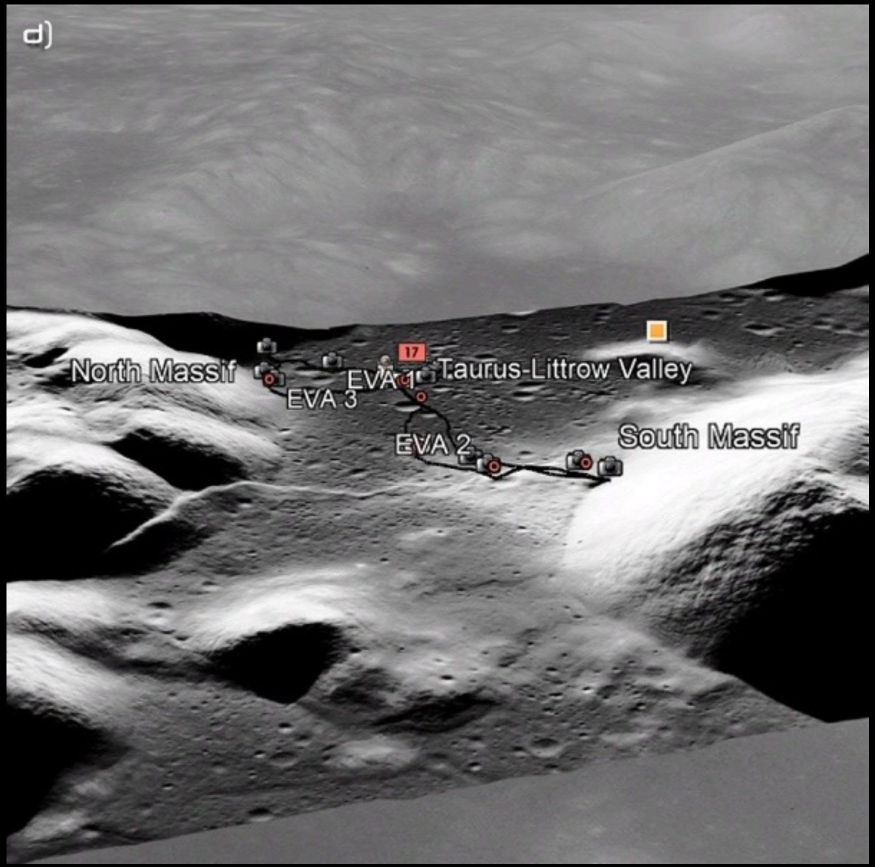
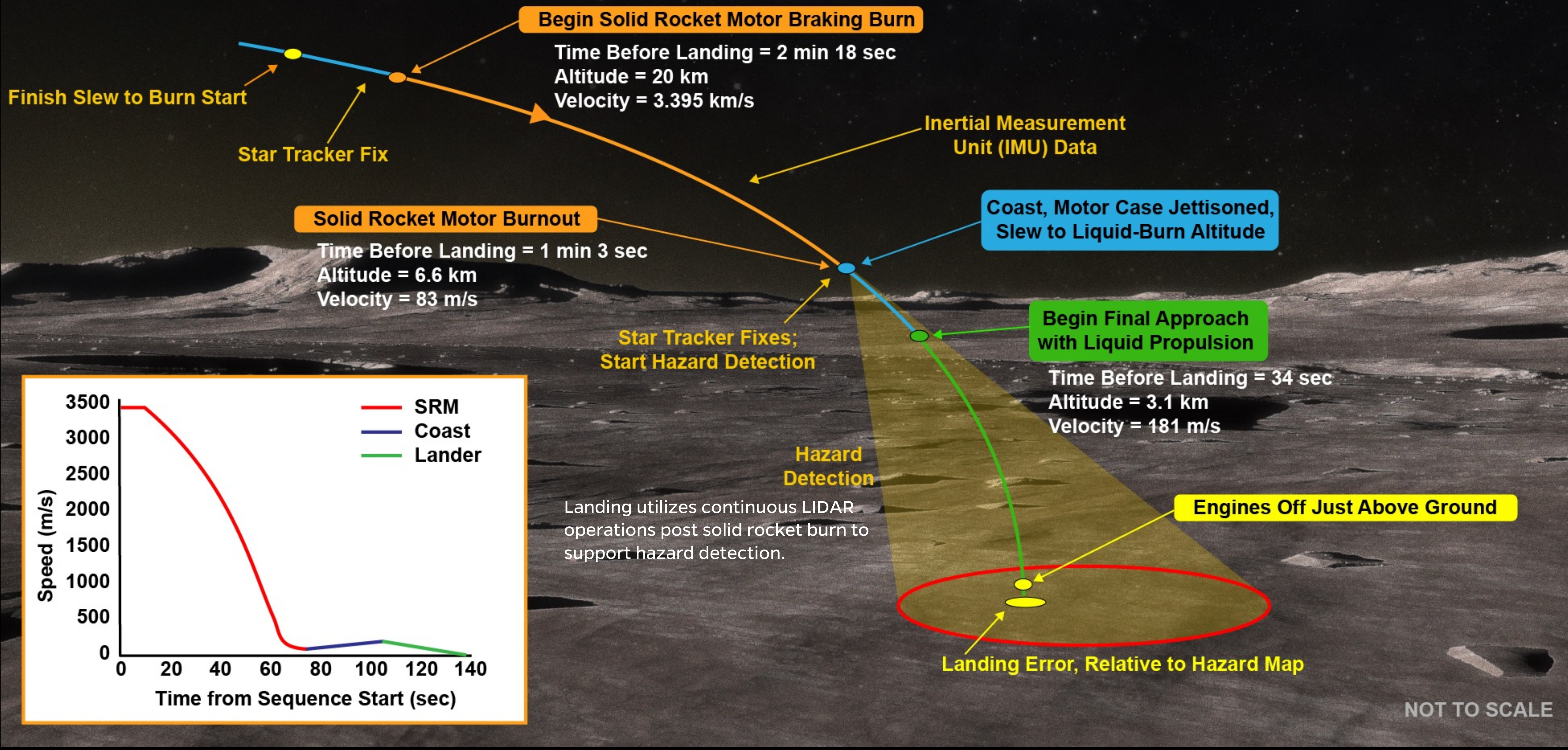




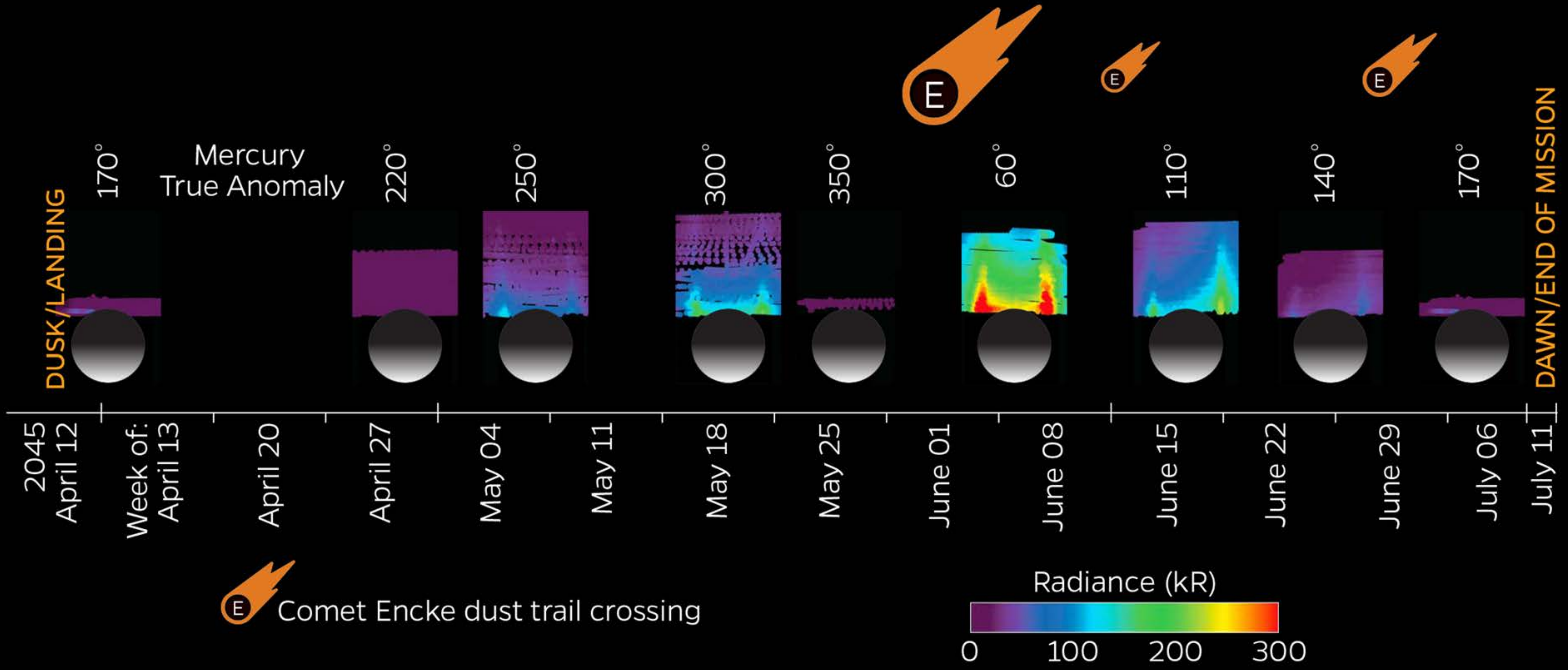


Descent and Landing Sequence



Landing utilizes continuous LIDAR operations post solid rocket burn to support hazard detection.

One Full Mercury Year of Surface Operations



One Full Mercury Year of Surface Operations

Baseline Plan:
10.8 GB total data

Direct to Earth downlink, one 34-meter Ka band, 24 hrs/day when geometry allows, meets all science goals for the full payload

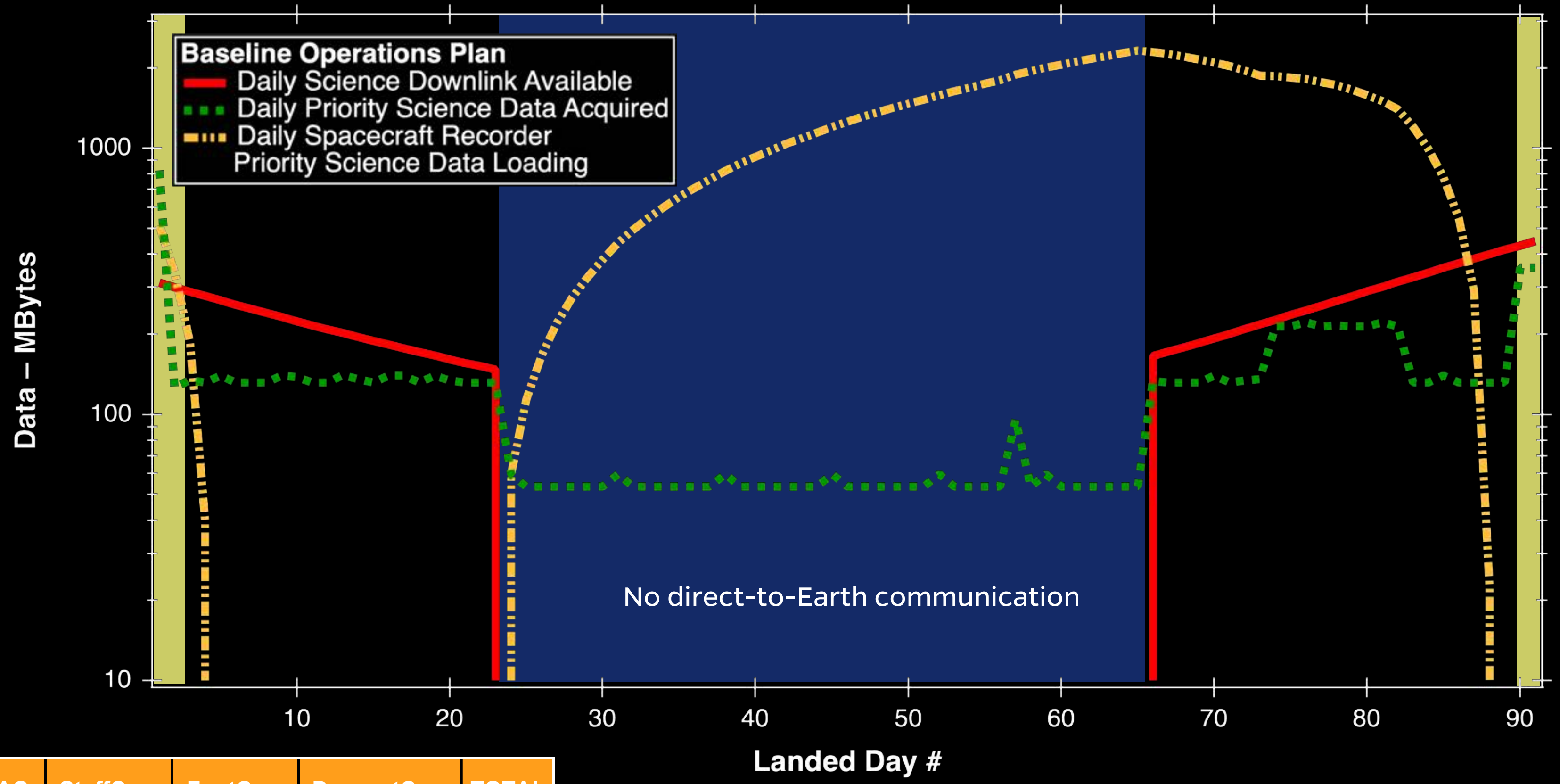


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Exhibit 2. Science Traceability Matrix.

SCIENCE GOALS	SCIENCE OBJECTIVES	MEASUREMENT REQUIREMENTS	INSTRUMENT (ANALOGS [TRL])	FUNCTIONAL REQUIREMENT
Goal 1: Investigate the highly chemically reduced, unexpectedly volatile-rich mineralogy and chemistry of Mercury's surface, to understand the earliest evolution of this end-member of rocky planet formation.	**1.1** Determine the major- and minor-elemental composition of the LRM, including its C content and volatile-element abundances (e.g., Na, K, S)	Absolute abundances of: C, O, Na, Mg, Si, S, Cl, K, Ca, Fe, Th, U, Cr, Mn, if present at concentrations of >1 wt%	**GRS: Gamma-Ray Spectrometer** (MESSENGER [TRL 9], Psyche [TRL 7], MMX [TRL 7], Dragonfly [TRL 7])	Continuous operation to avoid instrument degradation; unobstructed FOV of the surface; surface operations ≥72 hrs
	1.2 Determine the mineralogy of the components of the LRM, including any silicate, sulfide, or carbide phases that are present	Identification of silicates, sulfides, carbides, metallic phases, if present at concentrations of >1 wt%	**XRD/XRF**: **X-Ray Diffractometer/X-Ray Fluorescence Spectrometer** (MSL CheMin [TRL 9], CheMin-V [TRL 6])	Surface sample must be delivered into the XRD/XRF instrument
	1.3 Investigate the chemical and mineralogical heterogeneity of the landing site	Measurements of Objective 1.2 from two locations at the landing site and from ≥two distinct surface disturbance events		Ability to collect samples from multiple locations and to produce distinct surface disturbance events
Goal 2: Investigate Mercury's interior structure and magnetic field, to unravel the planet's differentiation and evolutionary history and to understand the magnetic field at the surface.	**2.1** Investigate the distribution of mass in Mercury's interior, determine the size and state of the core to characterize the solid and liquid portions, and search for seismic activity	Longitude libration amplitudes; obliquity	**RS: Radio Science** (InSight RISE [TRL 9])	Ka-band communication to enable the most-sensitive science measurements
		Gravitational acceleration change due to solid-body tides; short-period seismic observations	**MAC: Mercury Accelerometer/Short-Period Seismometer** (InSight SEIS-SP [TRL 9])	Positioned near surface; high data rate from continuous operations needed to detect potential seismic events
	2.2 Measure the magnetic field at the surface to investigate the coupling between the dynamo and external field, the time variation of the field, the strength of the crustal field, and the electrical conductivity structure of the crust and mantle	Measurements of magnetic field at the surface as a function of time, with a precision of 1 nT and at cadence of 20 vector samples per second	**MAG: Magnetometer** (MESSENGER MAG [TRL 9])	Positioned to minimize contributions from spacecraft-generated fields
	2.3 Investigate the mineralogy of the surface to identify potential magnetic carrier minerals	Covered by Objective 1.2 mineralogical measurements above		
Goal 3: Investigate the active processes that produce Mercury's exosphere and alter its regolith, to understand planetary processes on rocky airless bodies, including the Moon.	**3.1** Determine the composition and density of the near-surface neutral exosphere and compare with the surface compositional measurements, to investigate processes releasing materials from the surface	Densities of atomic and molecular species 1–100 amu, M/ΔM ~100, sensitivity ~1 count/sec at density of 10 cm^{-3}	**NMS: Neutral Mass Spectrometer** (BepiColombo STROFIO [TRL 9])	Unobstructed FOV of space environment, angled 45° toward surface
	3.2 Determine and characterize the incoming and outgoing fluxes of charged particles at Mercury's surface	Identification of low-energy charged particles, 1 eV/e to 20 keV/e, M/ΔM 4–40 over M/q 1–50, angular resolution <20°	**IMS: Ion Mass Spectrometer** (MESSENGER FIPS [TRL 9])	Unobstructed FOV of space environment, angled 45° away from surface
		Identification of high-energy charged particles, 20 keV to 1 MeV, angular resolution <20°	**EPS: Energetic Particle Spectrometer** (New Horizons PEPSSI [TRL 9])	Unobstructed FOV of space environment, angled 45° away from surface
	3.3 Determine and characterize the influx of micrometeoroids (dust) at Mercury's surface	Measurements of dust flux with sensitivity to measure 10^{-15} kg m^{-2} s^{-1}	**DD: Dust Detector** (New Horizons SDC [TRL 9])	Unobstructed FOV of space environment, looking toward zenith
	3.4 Investigate the nature of Mercury's regolith, including particle sizes and heterogeneity	Images of regolith in ≥3 visible colors, pixel scales ≤500 µm @ 1-m distance	**FootCam: Regolith Imagers** (Malin Space Science Systems, ECAM [TRL 9])	Mounted to resolve 1-mm grains; LED illumination @ 450, 550, 650, 750 nm
	3.5 Investigate the characteristics of space weathering on Mercury	Measurements for Objective 1.2 and 3.4 repeated for ≥two distinct surface disturbances of the same location		Ability to collect multiple samples from the same location and to produce distinct surface disturbance events
Goal 4: Characterize the landing site, to understand the processes that have shaped its evolution, to place the in situ measurements in context, and to enable ground truth for global interpretations of Mercury.	**4.1** Connect observations from images acquired by orbiting spacecraft to those from the Lander and determine the geological context of the landing site	Images of landing site acquired during descent, pixel scales 1 cm to 1 m	**DescentCam: Descent Imagers** (Malin Space Science Systems, ECAM [TRL 9])	Periodic imaging of the surface during descent; two cameras oriented 90° from one another to enable surface imaging despite changing orientation during descent
	4.2 Characterize the geological setting of the landing site, including heterogeneity and landforms, and search for changes over the mission by surface, horizon, and exosphere imaging	Images of the landing site, pixel scale ≤5 cm within 50 m; ≥180° az, 0°– -45° elev	**StaffCam: Panoramic Imager** (MER Pancam [TRL 9], MSL Mastcam [TRL 9])	Unobstructed access to ≥ 180° of the landing site; articulation to achieve angular coverage
	4.3 Characterize the bulk-element composition of the local landing site and place it into context with the equivalent orbital measurements	Covered by Objective 1.1 elemental measurements above		

Exhibit 36. Estimated Phase A–F Mercury Lander mission costs by Level 3 WBS element (FY25$K).

	DESCRIPTION	PHASE A–D	PHASE E–F	PRIMARY ESTIMATE TOTAL	PRIMARY ESTIMATE METHODOLOGY	VALIDATION ESTIMATE	REMARKS
1,2,3	PMSEMA	$102,865	N/A	$102,865	See 5.3	N/A	E–F contained in WBS 7
4	Science	$14,927	$69,463	$84,390	See 5.3	N/A	
5	Payload	$101,547	-	$101,547	N/A	$116,075	
	Payload Management	$7,559	-	$7,559	Wrap Factor	$8,797	8.2% of hardware based on analysis of VAP, NH, MESSENGER and PSP payload suite data.
	GRS	$23,366	-	$23,366	ROM BUE, NICM	$25,653	Primary estimate assumes that GRS will be able to leverage work performed for MMX-MEGANE, Dragonfly-DraGNS, and work done under a MatISSE grant
	XRD/XRF	$25,151	-	$25,151	MSL-CheMin, NICM	$29,806	CheMin actuals adjusted for mass difference
	Magnetometer	$4,247	-	$4,247	MESSENGER-MAG, NICM	$5,247	
	Accelerometer/SP Seismometer	$2,616	-	$2,616	InSight SEIS, NICM	$2,957	Draws heritage from Insight-SEIS-SP but is of much lower complexity
	Neutral Mass Spectrometer	$16,879	-	$16,879	BepiColombo-STROFIO, NICM	$21,212	
	Ion Mass Spectrometer	$5,959	-	$5,959	MESSENGER-FIPS, NICM	$5,231	
	Energetic Particle Detector	$7,999	-	$7,999	NH-PEPSSI, NICM	$9,171	
	Dust Detector	$5,132	-	$5,132	NH-SDC, NICM	$4,422	
	StaffCam	$266	-	$266	Vendor Quote, NICM	$306	1 camera. Malin Space Science Systems (MSSS) vendor quote for commercial-off-the-shelf (COTS) ECAM system cameras (N50)
	FootCam	$201	-	$201	Vendor Quote, NICM	$731	2 cameras. MSSS vendor quote for COTS ECAM system cameras (C50). Vendor quote for C50s is lower than N50s. SEER-Space does not differentiate between monochrome and color.
	DescentCam	$370	-	$370	Vendor Quote, NICM	$429	2 cameras. MSSS vendor quote for COTS ECAM system cameras (N50)
	DVR8	$1,802	-	$1,802	Vendor Quote, NICM	$2,113	Shared by all 5 MSSS ECAM Cameras
6	Spacecraft	$472,500	-	$472,500	N/A	$593,014	
	Cruise Stage	$120,353	-	$120,353	Vendor Quotes, SEER-H, BUE	$147,180	
	Orbital Stage	$124,528	-	$124,528		$155,977	$3.1M Orbital Camera
	Descent Stage	$41,384	-	$41,384		$56,315	
	Lander	$186,234	-	$186,234		$233,542	$17.6M PlanetVac, RTGs included as a pass-thru cost to cross-check estimate. $16.3M LIDAR
7	Mission Operations	$14,920	$175,580	$190,501	See 5.3	N/A	$19.0M DSN charges
8	Launch Vehicle & Services	$246,000	-	$246,000	See 5.3	N/A	EFH + $26.0M RTG
9	Ground Data Systems	$14,918	$11,661	$26,578	See 5.3	N/A	
10	System Integration & Test	$72,904	-	$72,904	See 5.3	N/A	
Subtotal w/ LV		$1,040,582	$256,704	$1,297,286			
Subtotal w/o LV		$794,582	$256,704	$1,051,286			
Unencumbered Reserves		$397,291	$59,426	$456,717	A–D: 50%, E–F: 25%		Prescribed by Decadal Ground Rules
Total w/ LV		$1,437,873	$316,130	$1,754,003			
Total w/o LV		**$1,191,873**	**$316,130**	**$1,508,003**			**Comparison point to NF4 Phase A–D cost cap ($1.1B FY25$)**