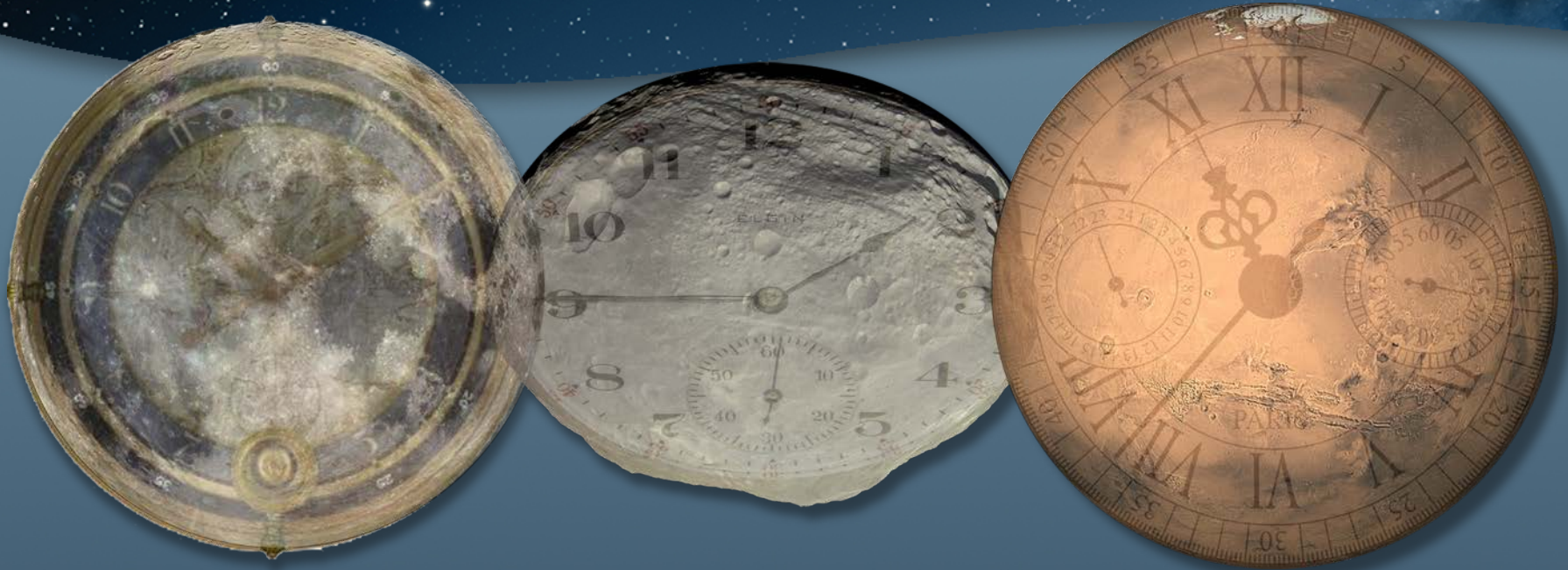




Geochronology for the Next Decade

A Planetary Mission Concept Study for the 2023 Decadal Survey

PI: Barbara Cohen, NASA GSFC (barbara.a.cohen@nasa.gov)

With the Science Definition Team and the GSFC Engineering Team

<https://science.nasa.gov/files/science-pink/s3fs-public/atoms/files/Geochronology%20Report.pdf>

Study motivation and goals



- **Geochronology:** determination of absolute ages for geologic events
- **Motivation:** Major advances in planetary science can be driven by absolute geochronology in the next decade, calibrating body-specific chronologies and creating a framework for understanding Solar System formation
 - Traceable to 2014 NASA Science Goals, p.61; Planetary Science Decadal Survey: p.151, p.143; LEAG, MEPAG, and SBAG goals documents
- **Why Now?** In the last two decades, NASA has invested in the development of in situ dating techniques; K-Ar and Rb-Sr instruments will be TRL 6 by the time of the next Decadal Survey
- **Study Goals:**
 - Assess how in situ geochronology could be accomplished in the inner solar system (Moon, Mars, and asteroids) – multiple CML 3-4 studies
 - Give the next Decadal Survey panel a viable alternative -- or addition to -- sample return missions to accomplish longstanding geochronology goals within a New Frontiers envelope

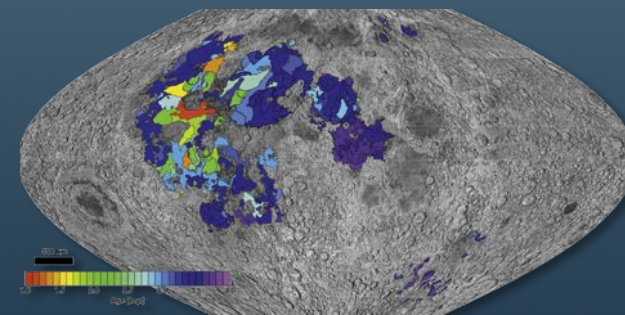
Rheasilvia basin, Vesta



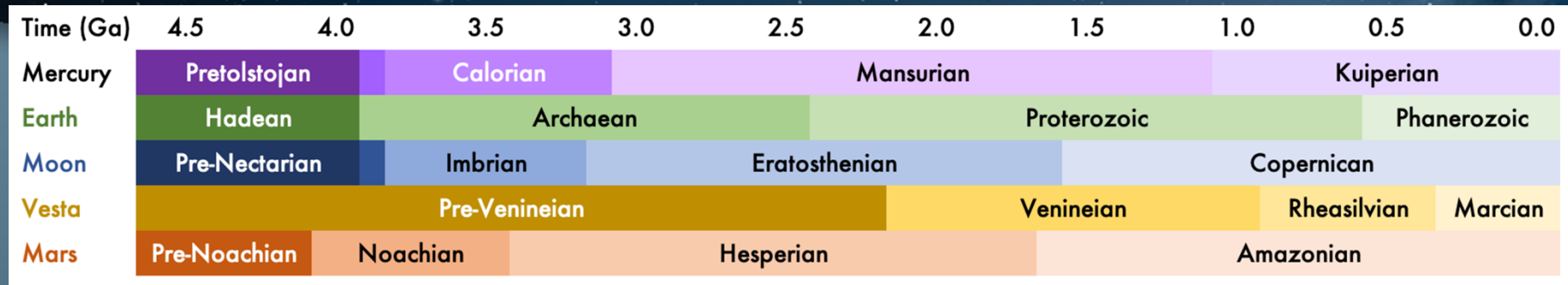
Ancient Martian Crust, Syrtis Major



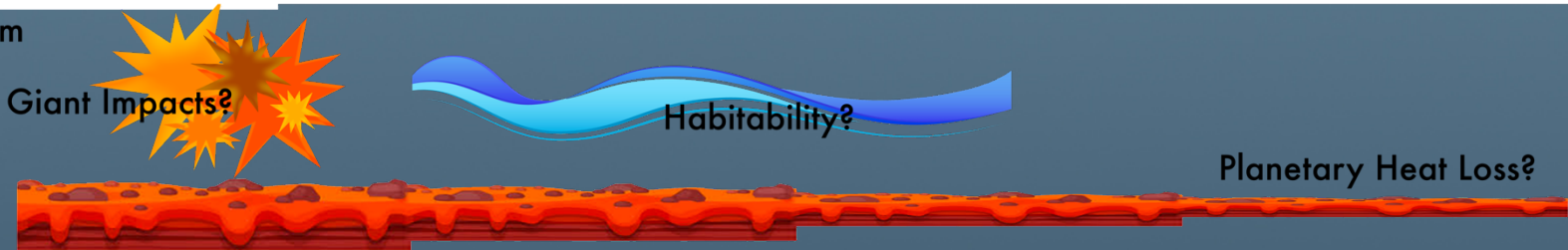
Lunar volcanic units



Geochronology in the next decade



Solar System



- **Science Goal:** More rigorously constrain the age of major events on the Moon that inform solar system chronology
 - Determine the age of a major basin on the Moon to compare with the history recorded in Apollo samples and constrain the time period of heavy bombardment in the inner solar system
 - Determine the age of a young lunar basalt to fill in the “middle ages” of the lunar chronology curve and understand the longevity of the planetary heat engines
- An age is an interpretation, requiring accurate and precise measurement of the isotopes *and* adequate knowledge to interpret that measurement.

Geochronology

Science

Payload

Mission

Cost

Recommendations

Science Traceability Matrix



Science Objectives	Measurement Goals	Measurement Requirements	Mission Support
Determine the chronology of basin-forming impacts and constrain the time period of heavy bombardment in the inner solar system Constrain the 1 Ga uncertainty in solar system chronology from 1-3 Ga, informing models of planetary evolution Establish the history of habitability across the Solar System	Measure the age of the desired lithology with precision ± 200 Myr	Use Rb-Sr radiometric chronology to directly measure the age of samples derived from the target lithology	Collect, triage, and analyze 10 0.5-2 cm sized samples at each site * <i>see additional information on sampling statistics</i> Conduct sample analysis at 2 different sites on each body ** <i>see additional information on sites</i> Remotely sense the workspace around the landing legs to provide sample context and of landing site at low and high sun angles to create spatially contiguous maps
		Use K-Ar radiometric chronology to directly measure the age of samples derived from the target lithology	
	Contextualize the desired lithology using petrology, mineralogy, and/or elemental chemistry	Measure the major- and trace-element geochemistry of the samples to establish parentage and evolution of lithologies	
		Identify the mineralogy by mapping abundances of olivines, pyroxenes, oxides, plagioclases; Identify aqueous alteration minerals including phyllosilicates, sulfates, carbonates, and other hydrated salts	
		Image the samples at the microscale to determine grain size, petrology, etc.	
		Determine the composition of the surface unit to place the lithologies into a regional and global context	
	Relate the measured lithology age to crater counting of the lithology's terrain	Determine the geology of the landed site and map discrete lithologic units to relate them to maps and crater counts determined from remote sensing	

Science Traceability Matrix

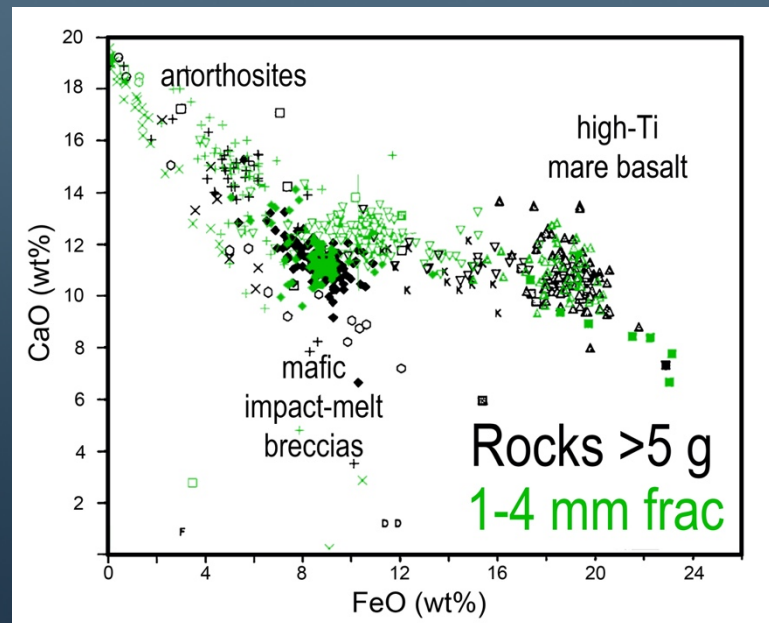


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Sampling statistics



- Robotic sampling, either vertically or laterally, is an excellent way to ensure sampling the substrate of any given site as well as the site's overall lithologic diversity
- Carefully choose sites where the geologic setting enables robust expectation of collecting the lithology of interest, like the mare surfaces of A11
- Comparing small rocks separated from rake samples at the Apollo 17 site to samples carefully chosen by astronauts on the mission shows the same range of composition and frequency
- *This is a fundamentally different situation from dating basin ejecta!*



Adapted from data in Jolliff et al. (1996)

Sampling statistics



How many rocks do we need?

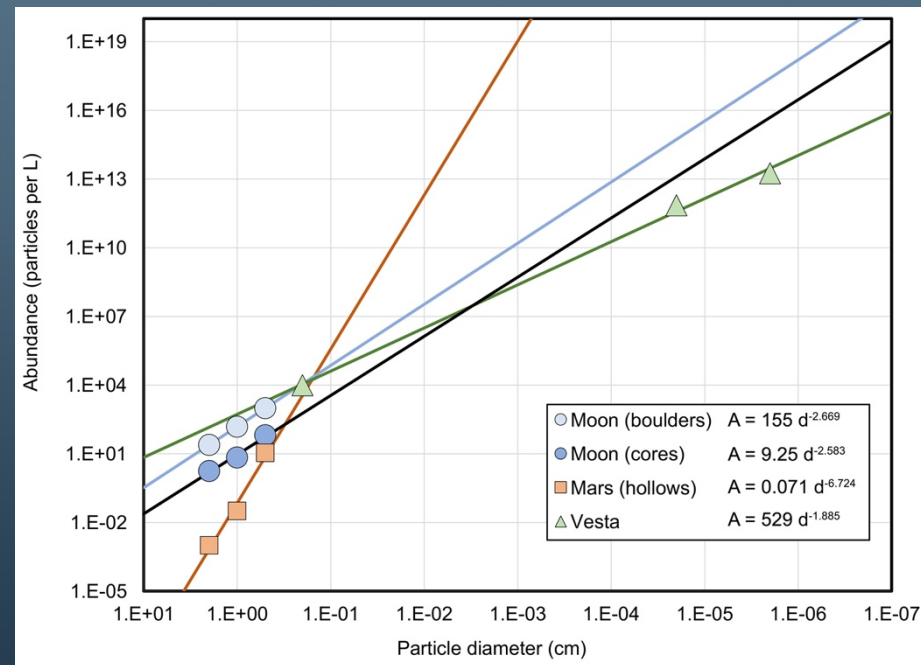
- Confidence requires 3 samples of the lithology to agree in age
- Allow for some rocks and experiments being uncooperative = 10 samples analyzed per lithology of interest
- Allow for some rocks at each site being not what we want = **30 samples acquired per lithology**

Instruments require rocks measuring 0.5-2 cm in diameter to obtain sufficient analyses.

How many rocks of correct size (0.5 – 2 cm in diameter) are in the regolith?

This volume must be excavated and sieved and samples delivered to the instruments. Few L is readily accommodated by dual PlanetVac inlets or a scoop & sieve.

Body	Volume for 30 samples (L)
Moon (boulders)	0.03
Moon (cores)	0.62
Mars (bedrock)	small
Mars (hollows)	2.68
Vesta (Kapoeta)	similar to Moon



Science Traceability Matrix

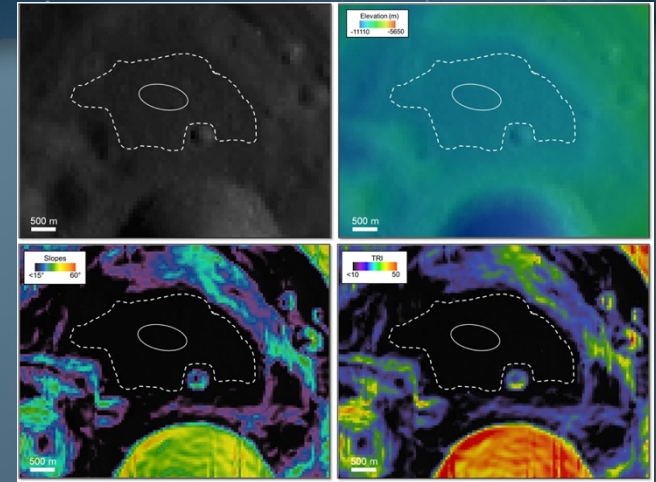


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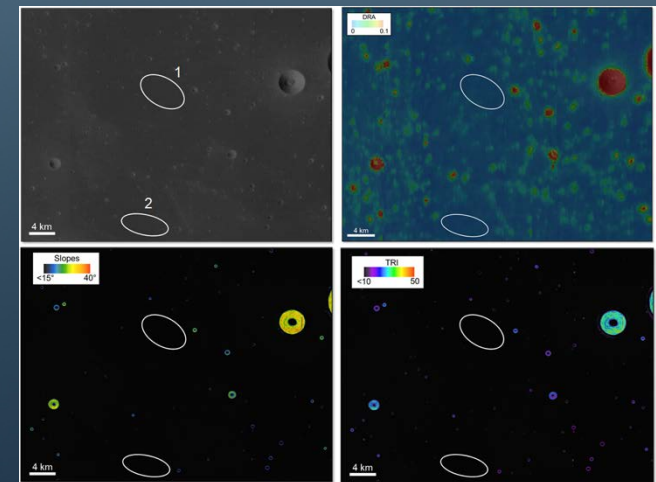
Lunar candidate sites



- Establish the chronology of basin-forming impacts by measuring the radiometric age of samples directly sourced from the impact melt sheet of a pre-Imbrian lunar basin.
 - Crisium and Nectaris are stratigraphically older than Imbrium
 - Confirming whether they are Imbrian-aged (3.9 Ga) or significantly older (≥ 4.1 Ga) will help resolve whether LHB occurred or not
 - Rosse and Peirce craters have excavated spectrally unambiguous noritic material interpreted to be impact melt sheet material
 - Lat/Lon: 18.296°N, 54.44°E
- Establish the age of a very young lunar basalt to correlate crater count with crystallization age
 - P60 basalt is ~ 1 Ga in the west and to 2.7 Ga in the east (Stadermann et al., 2018)
 - Site has been recently characterized for landed mission proposals (MARE, ISOCHRON, Chang'E-5)
 - Lat/Lon: 20°N, 50°W



Potential 1km x 0.5km landing areas inside Peirce crater (top) and P60 basalt (bottom). Upper left: WAC mosaic. Upper Right: Diviner rock abundance (DRA). Lower left: Slopes < 15 deg in black. Lower right: Terrain Ruggedness Index < 10 in black.

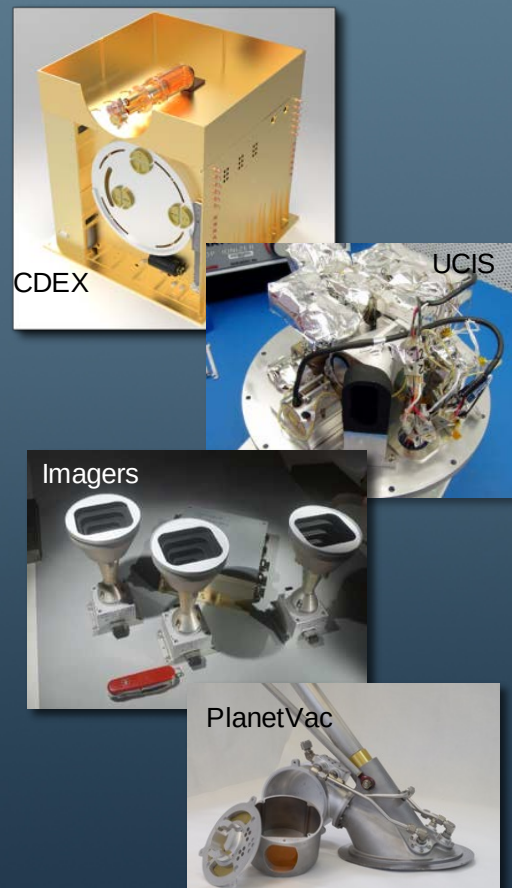


Payload concept

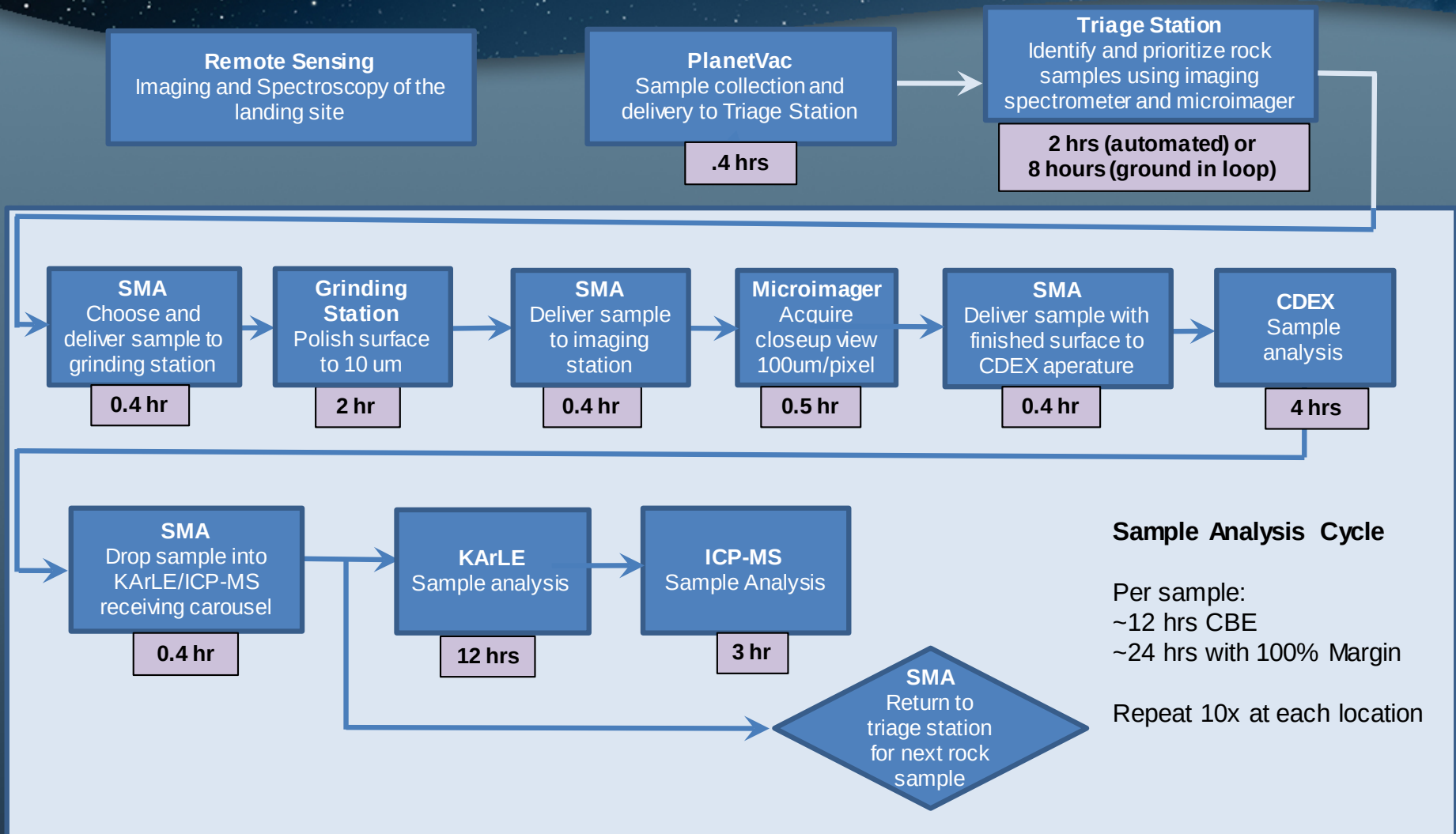


- Measurement requirements for all goals and objectives are met by carrying a single payload
- Study payload comprises representative instruments - generalizable to any suite of instruments that can accomplish the Measurement Requirements
- TRL in 2023 (start of next Decadal) - no additional costs or technology will be required

Measurement Requirement	Measurement	Payload Element	Element Lead	TRL in 2023
Geochronology	Rb-Sr geochronology	CDEX	Scott Anderson / SWRI	6 (MatISSE)
	K-Ar geochronology	KArLE	Barbara Cohen / GSFC	6 (DALI)
Sample & site context	Trace-element geochemistry	ICPMS	Rick Arevalo / UMD	4 (PICASSO) – 6 (DALI or MatISSE)
	Mineralogy	UCIS-Moon	Bethany Ehlmann / JPL	6 (DALI)
	Visible/color imaging and micro-imaging	Panoramic and microimagers	Aileen Yingst / MSSS	9 (MSL / CLPS)
Sample Handling	Acquire, prepare, and introduce samples to analysis instruments	PlanetVac	Stephen Indyk / Honeybee Robotics	9 (CLPS / MMX)



Surface operations concept



Payload mass, power, data

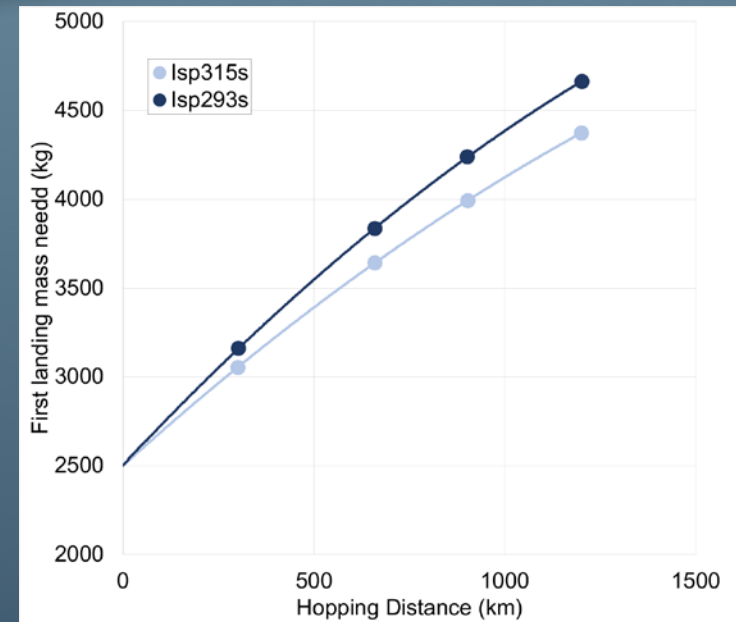


Payload Element	Mass (kg) (incl 30%)	Peak Power (W) (incl 30%)	Data Generation (Mbit) (postcompression)
CDEX			
CDEX instrument	71.5	182	22400
Grinding station	7.4	26	N/A
Postgrind Imager	0.8	9	1500
Sample Manipulation Arm	13	26	1600
KArLE			
KArLE Instrument	29.8	130	21220
ICPMS	12.4	133	38
UCIS (Including DPU)	6.5	39	11268
Panoramic Imagers (total for 2)	1.5	19	1454
Microimager	1.4	10	180
Imaging DEA	1.4	0	N/A
Sample acquisition and triage			
PlanetVac	20.8	42	30
Triage station	3.8	8	N/A
Electronics box	3.0	30	
Totals	173		59690

Lunar hopper concept



- We conducted a full Mission Design Lab (MDL) at GSFC March 9-13
- Focused on a lunar case – full payload and mobility to widely-separated sites (100's of km) – large lander/hopper
- F9 Heavy 5.2-meter fairing gives us 15500 kg wet mass lander
 - 11641 kg of propellant
 - 1359 kg of everything else, including payload, structure to hold all that propellant, and power (battery+MMRTG) to heat liquid prop through a lunar night
- Thermal need to keep hop fuel warm drove need for RTG; in turn, cooling was an issue at lunar noon and low latitudes of interest
- Cost would place mission out of New Frontiers class
- It takes a lot of fuel to hop
 - The Moon is a marginal case for hopping. We didn't get a design to close
 - Hopping isn't going to work on Mars
 - Hopping works on Vesta – lower gravity = less fuel, less severe day/night cycle = less heating

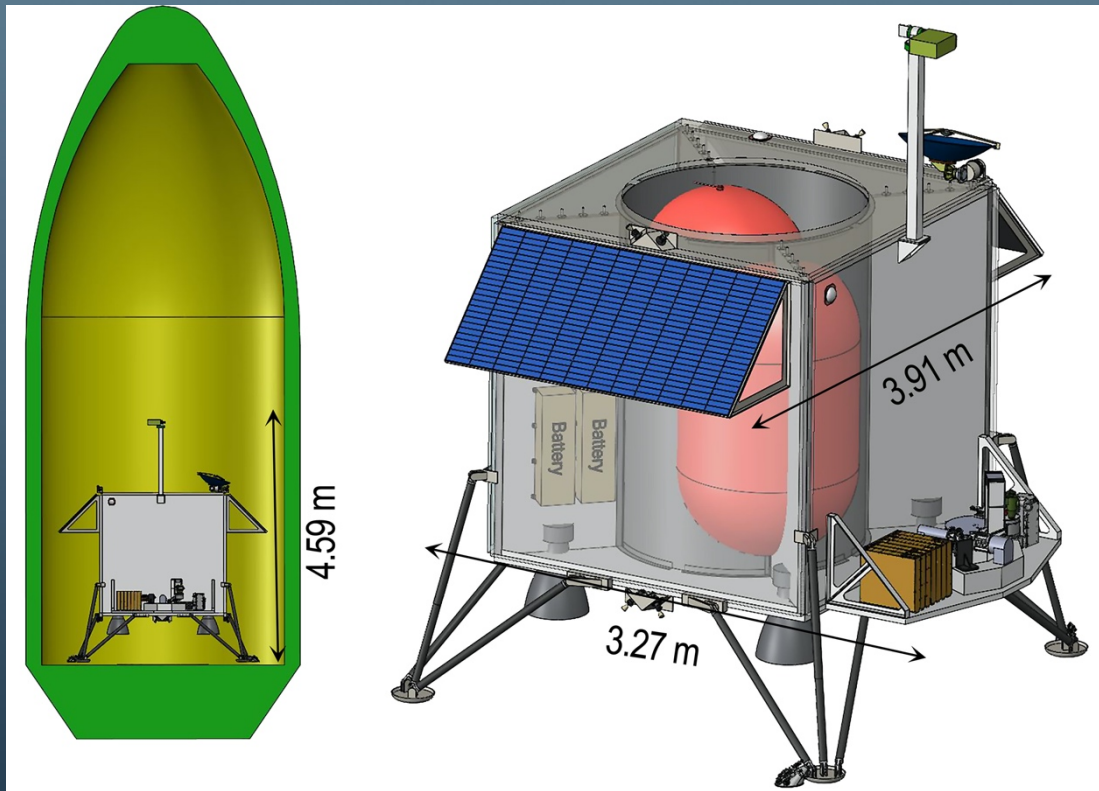


- Feasible hop distance for full payload = 100's of meters
- Hop distance could increase for smaller payloads (e.g. single geochronology instrument)

Lunar lander concept



- Downsized the lunar hopper concept without the extra propellant, structure, and power needed to hop
- Single lunar lander design closes with full payload and concept of operations



- Class B mission - Selective Redundancy/fault tolerance
- Falcon 9 Heavy launch vehicle
- Direct insertion to land using 4 Aerojet R-40B engines with Terrain-Relative Navigation (TRN)
- Redundant Processor for Landing and all other CPU control functions
- 2 body-mounted TjGaAs solar panels and 1100Ahr battery
- X-band comm
- Lifetime 1 year / 12 nights

Summary of architecture options



- NF-class single-site landers at the Moon can carry full payloads for ~1 year of operations. Sites may exist where multiple objectives could be met by analyzing more rocks up to the mission lifetime.

Target	Science Goal	Sample Science	Multiple Sites	Cost Class
Moon	Determine the chronology of basin-forming impacts	Full	Single lander	New Frontiers
	Constrain uncertainty in lunar chronology from 1-3 Ga	Full	Single lander	New Frontiers
	Do both	Reduced	Hopper 100's of km	Flagship
Mars	Validate crater-counting ages on Mars	Full	Single lander	New Frontiers
	Bound the epoch of habitability	Full	Single lander	New Frontiers
	Do both	Reduced	Rover 10's of km	Flagship
Vesta	Establish the Vestan chronology	Full	Hopper 100's of km	New Frontiers

Evaluation

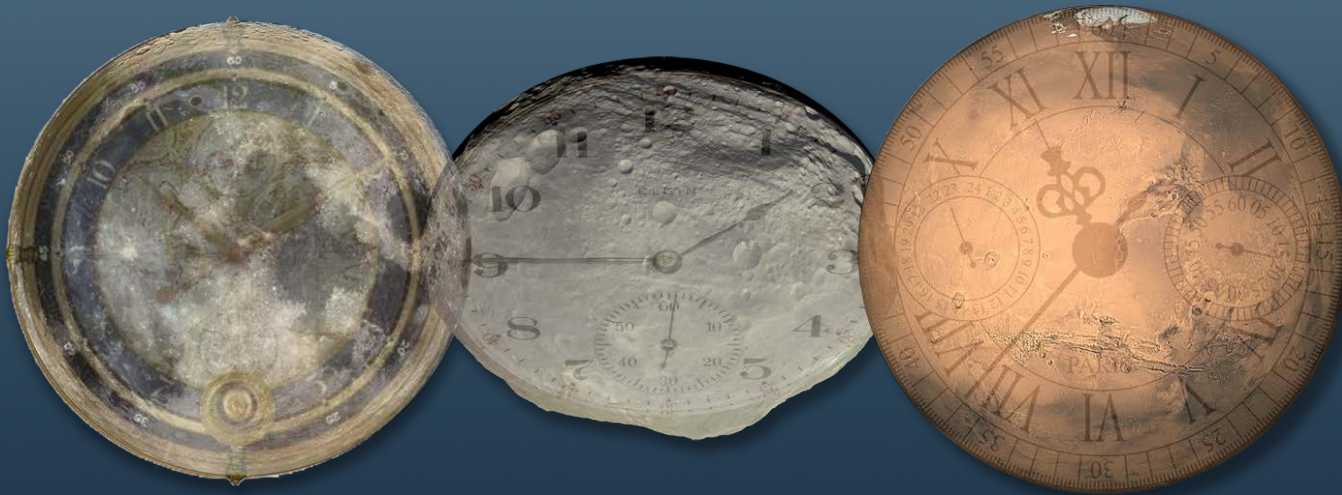


- Feasible New Frontiers-class missions exist that would carry a capable instrument payload to the Moon to conduct *in situ* dating with the precision to answer community-identified science goals
 - NASA investments in *in situ* dating instruments make a feasible payload, including dating by multiple corroborating methods and extensive characterization to give confidence in results
 - Remote-sensing work, geologic mapping, and site evaluation efforts have expanded the locations where safe landing sites can access lithologies of interest
 - Compelling cases can be made for specific science questions to be answered using targeted single-site landers at the Moon and Mars.
- Such missions would also be able to conduct a broad suite of geologic investigations
 - Geologic site investigations, geomorphology, ground truth
 - Major, minor, and trace-element analyses
 - Volatile element analyses, atmospheric monitoring
 - Organic molecule analysis
 - Soil properties, geotechnical properties
 - Long-lived monitoring (weather, space weather, etc)
 - Radio science and laser retroreflectors
- Smaller missions (e.g. Discovery, CLPS) would not be capable of making the full suite of desired measurements, but cases could be made to address well-bounded questions using smaller payloads (e.g., single method of radiometric dating, downsized characterization suite)

Conclusions and Recommendations



- *In situ* geochronology is a feasible way to address cross-cutting, big-picture, community-identified science goals at the Moon, Mars, and Vesta
- We suggest that the Decadal Survey should focus on science goals for New Frontiers missions, but not require specific architectures (e.g., sample return) to allow different approaches and enable creative implementation solutions
- We ask the Moon & Mercury panel to advocate for a mission in the New Frontiers list to answer compelling science questions about Solar System Chronology at the Moon (and/or the Vesta and/or Mars) with flexibility in implementation to meet them either by sample return or by *in situ* dating



Backup



- Team membership
- Candidate sites for Vesta and Mars
- Payload Maturity
- Payload conops, power, and data
- Mission engineering trades and drivers

Geochronology PMCS team



Science Definition Team	Institution	Research expertise
Barbara Cohen (PI)	GSFC	Geochronology, mission operations
Kelsey Young (DPI) *	GSFC	Geochronology, human missions
Nicolle Zellner	Albion College	Geochronology
Kris Zacny	Honeybee Robotics	Sample acquisition and handling
R. Aileen Yingst	PSI	Imaging, mission operations
Ryan Watkins *	PSI	Remote sensing
Sarah Valencia *	GSFC	Lunar samples
Tim Swindle	U of Arizona	Geochronology
Stuart Robbins *	SwRI	Crater chronology
Noah Petro	GSFC	Site analysis, remote sensing
Dan Moriarty *	GSFC	Remote sensing
Katherine Joy	Manchester University	Geochronology
Stephen Indyk	Honeybee Robotics	Sample acquisition and handling
Juliane Gross	Rutgers University	Lunar samples, petrology
Jennifer Grier	PSI	Crater chronology, EPO
John Grant	Smithsonian	Geology, mission operations
Caleb Fassett	MSFC	Geomorphology, crater chronology
Ken Farley	Caltech	Geochronology, mission operations
Bethany Ehlmann *	Caltech	Geology, spectroscopy, habitability
Darby Dyar	PSI	Spectroscopy, sample analysis
Natalie Curran *	GSFC	Lunar samples
Carolyn van der Bogert	University Westfalische	Crater chronology
Ricardo Arevalo *	U of Maryland	Mass spectrometry, trace elements
Scott Anderson	SwRI	Geochronology

*Early-career scientists

GSFC Engineering Team: Michael Amato, Gerry Daelemans, Richard Lynch, Cameron Jerry, Tony Nicoletti, Amani Ginyard, GSFC Mission Design Lab

Geochronology

Science

Payload

Mission

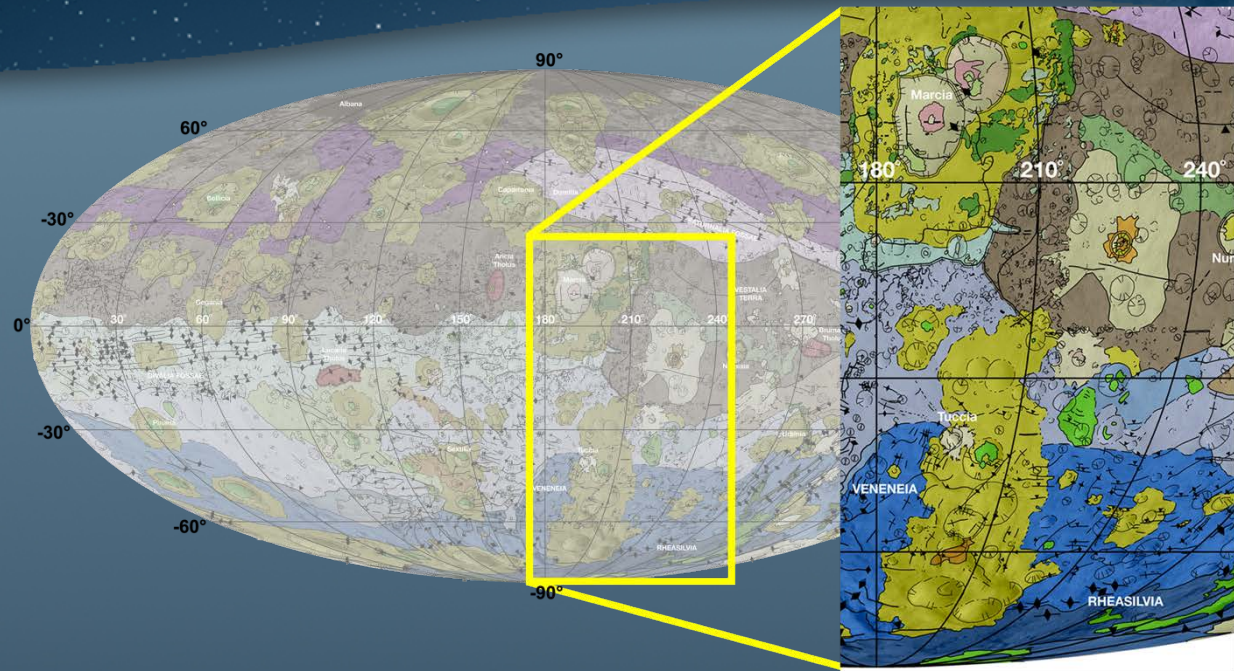
Cost

Recommendations

Vesta candidate sites



- Establish the radiometric ages of Vestan samples with well-established provenances
- Site geology at <50 m scale not resolved – probably need an orbital phase - however, landing precision not a hard constraint



Rheasilvia central peak

- Flat, high-standing plateau means resurfacing should be minimal, good location to derive crater age
- Deep-seated material brought to the surface also yields information about internal structure and composition (e.g., potential mantle material)

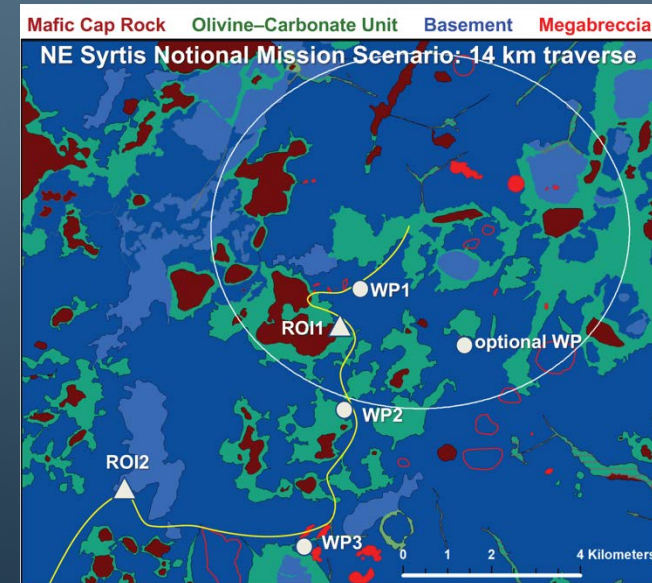
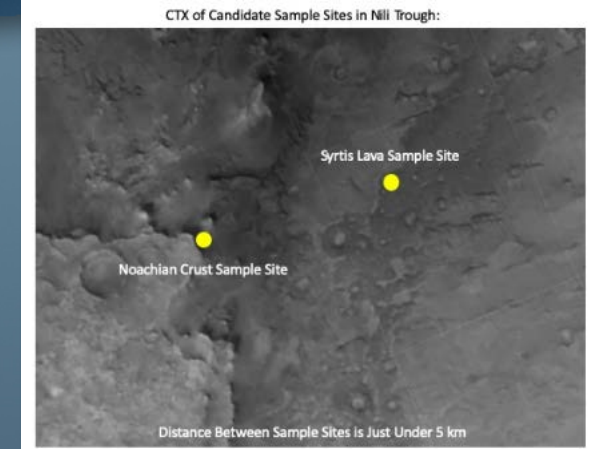
Marcia Crater

- Several unique geologic units have been mapped within a few km area, providing an opportunity to date much of the vestan stratigraphy.
- Dark material represents a key stratigraphic marker, possibly formed by fluids

Mars candidate sites



- Constrain Martian habitability and volcanic activity by investigating both ancient but potentially habitable (Noachian) crust and young (Hesperian) lavas
- Take advantage of significant engineering and scientific research expended on potential landing sites for previous, current and future landed missions
- Nili Fossae Trough
 - Provides access to representative sections of widely distributed units
 - Noachian units with clay minerals and Hesperian lavas
 - Ability to place into context via geochronology dating
- Mawrth Vallis
 - Provides access to representative sections of widely distributed units.
 - Access to widespread Noachian clay-bearing stratigraphies
 - Hesperian dark mantling materials that cap the section may or may not be volcanic
- NE Syrtis
 - Provides access to representative sections of widely distributed units.
 - Access to a range of Noachian and Hesperian materials: clays, carbonates, sulfates, lavas
 - Ability to place into context via geochronology dating
- Lots of other sites globally that are interesting!

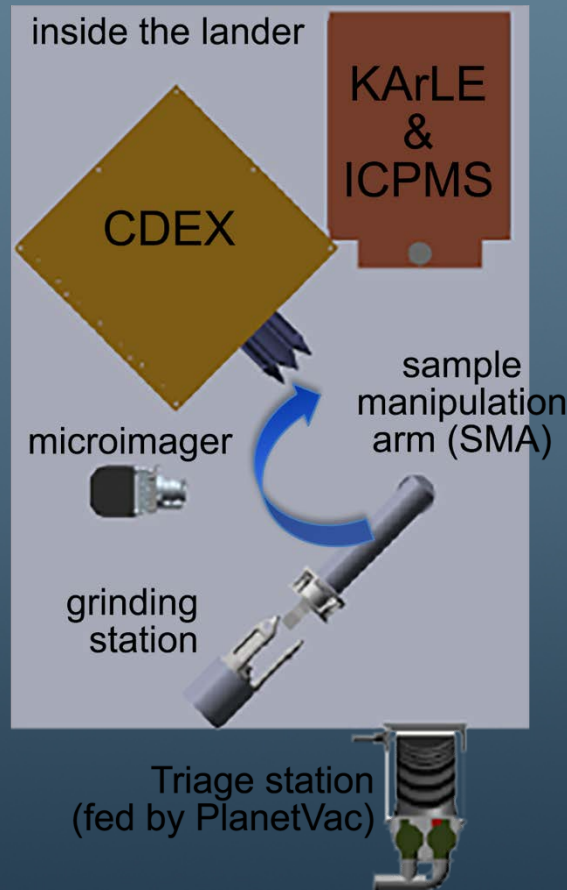


Instrument layout / functional requirements



- Instrument positioning is flexible and can adapt to lander configuration

- PlanetVac dislodges, transports, and sieves samples of correct size, regolith falls out a screen
- Samples fall into triage station for characterization by mast instruments
- SMA grabs a sample and delivers it to internal stations for analysis
- KArLE and ICPMS share an internal sample handling carousel



on a mast

UCIS

- Panoramic spectroscopy
- Spectroscopy of samples in the triage station
- Spectroscopy of area around lander footpads

Stereo Imagers

- Panoramic imaging
- Image soil around lander footpads

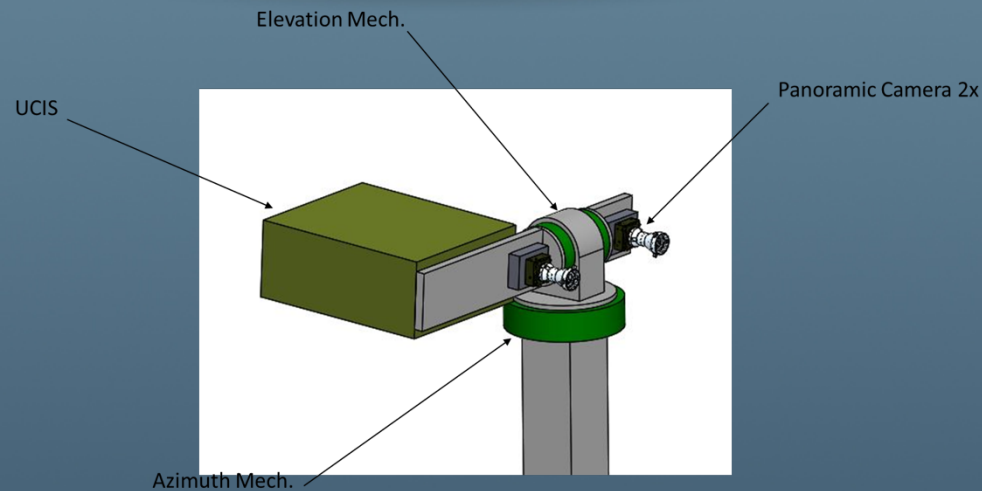
Microimager

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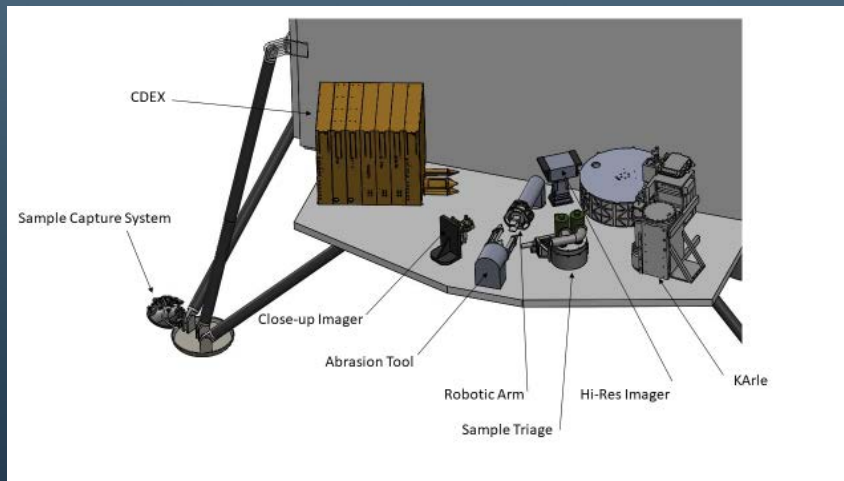
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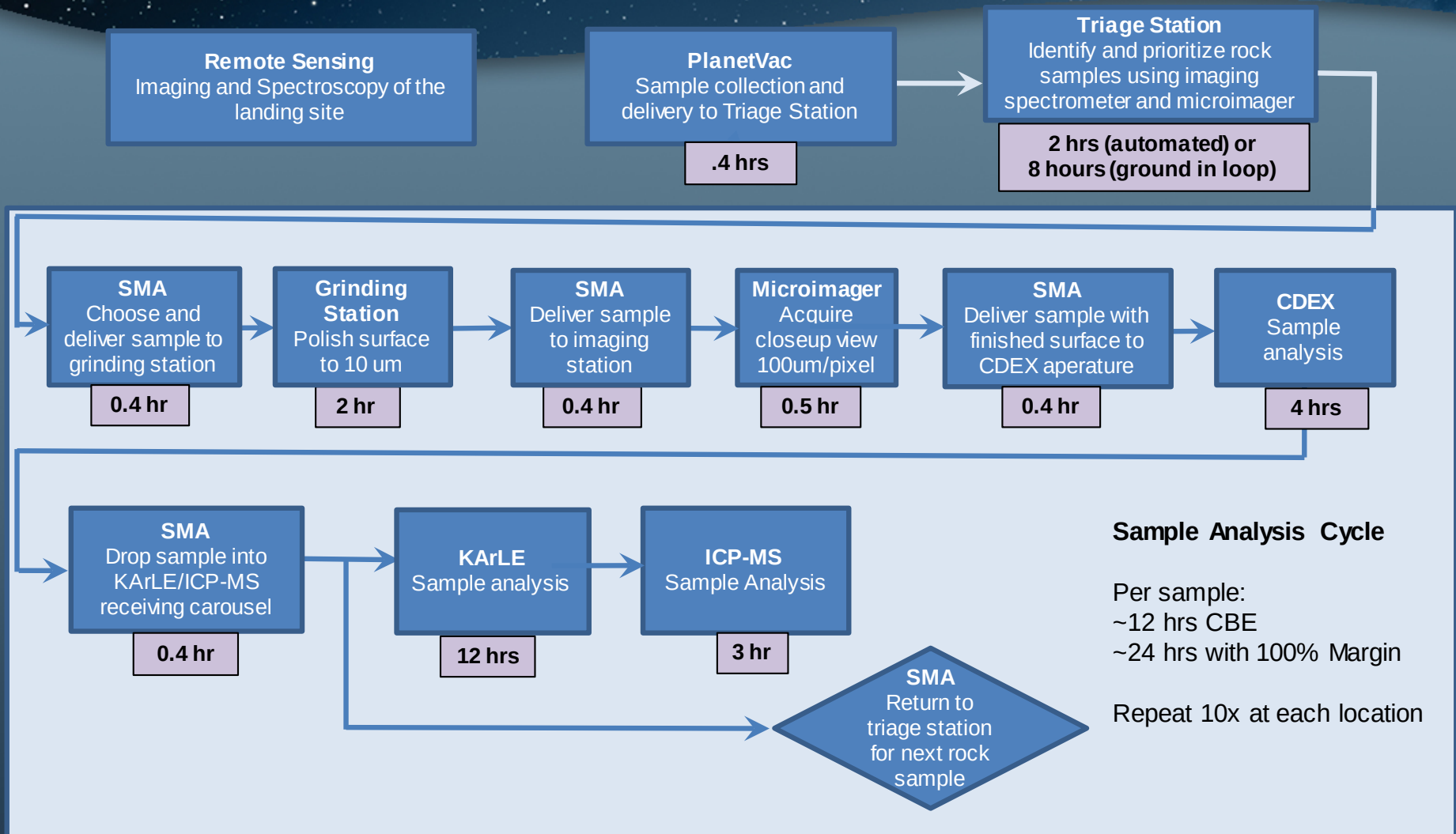
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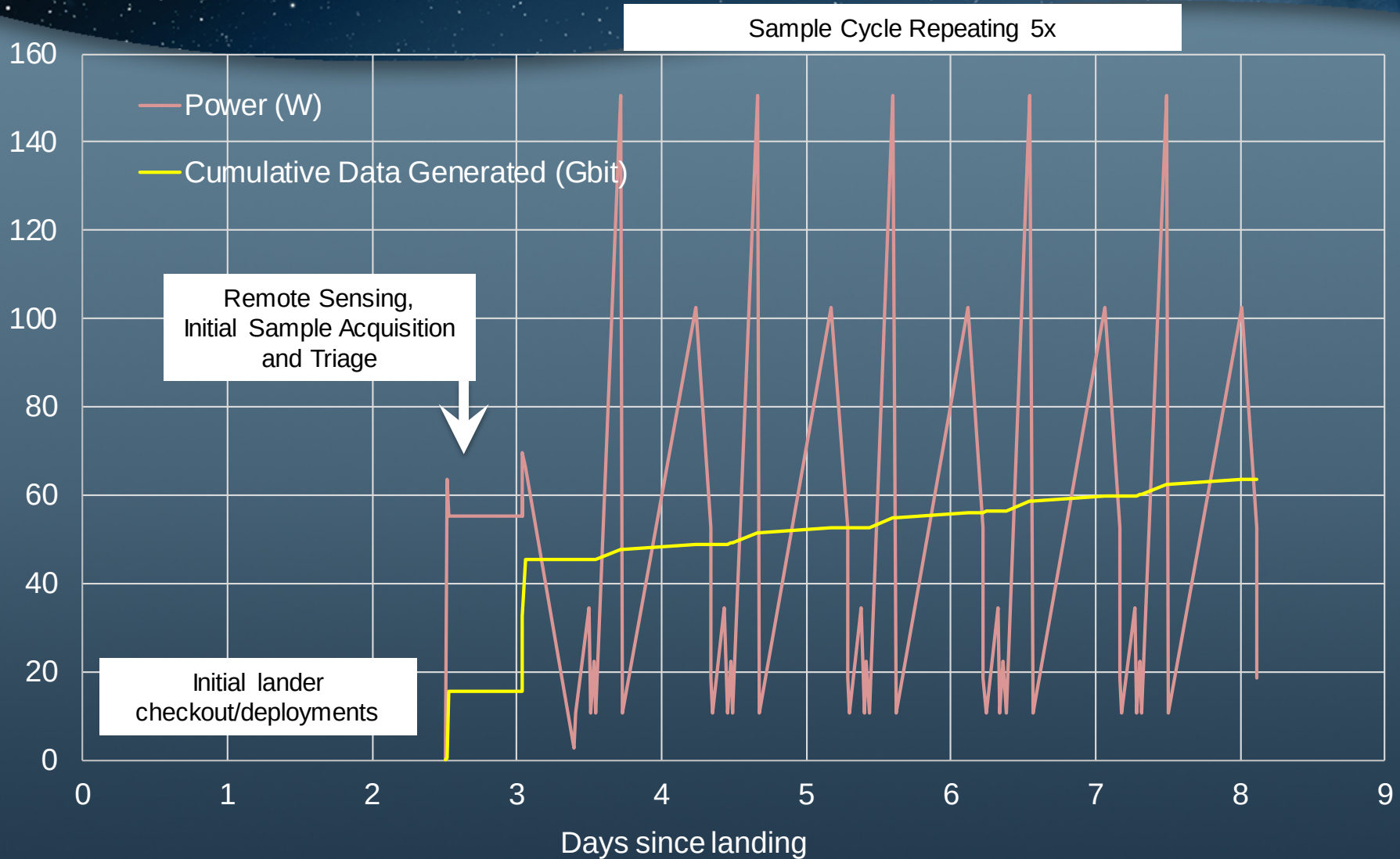
- Image samples in the triage station



Surface operations concept



Payload power and data profile (lunar)



Mission Drivers & Requirements



Mission Requirement (Top Level)	Mission Design Requirements	Lander Requirements	Ground System Requirements	Operations Requirements
Mission Lifetime of at least 6 months	Launch Vehicle Falcon 9 with 5m fairing	Deliver [170] kg of science instruments to lunar surface	34m DSN Antenna at Ka at 100 Mbs	Manage time correlations
Conduct sample analysis at 2 different sites on each planetary body	Less than 1 m/s velocity at 1 m above surface during Landings	Land Safely with clearance for 0.5m boulder	Receive house keeping & science data telemetry	Monitor Lander state of health
Reliability Category 2, Class B		Provide interfaces for instruments	Provide commanding	Implement contingency procedures
		Collect, triage, and analyze 10 0.5-2 cm sized samples at each site	Plan and transmit command sequences	Implement science sequences Inventory data & re- transmit if needed
		Image the landing site from the lander to the horizon to create spatially contiguous maps at two different sun angles	Record/Archive science data	Perform opssim testing
		Image the workspace around the landing legs to provide sample context	Provide critical event telecom coverage: Launch thru Sep, TLI, [LOI], Landing, S/A Deployment, Instrument Deployments, Hop (takeoff and landing)	
		Data Storage [350 Gbits]	Perform Lander Health and Safety checkout, then monitor SOH	
		Return at least [200 Gbits] per lunar day		
		28 V power System		
		Provide [250] W power to the science instruments		
		0.1 ms timing accuracy with 10 ⁻⁶ stability relative to ground station		
		Execute stored command sequence		
		Monitor instruments execution of stored commands		
		Place instruments in safe state and notify Ground of any faults		
		Continue operating instruments that do not have faults		