COW-1

Cosmic Origins Wayfinder
Comet 46P/ Wirtanen
Team 1

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Team Members

Mission Manager	Ramon Becerra-Orozco
Launch/ Propulsion/Power Systems	Gianluca Chaux
Navigation/Attitude Control/Communication	Michael Gunnarson
Structures/Thermal/Materials	Duha Bader
Ground Operations/ Telerobotics / Entry, Descent, Landing	Shuchen Ye
Science Instruments /Planetary Science	Natasha Evans
Space Environment /Sample Return Technology	David Martindelcampo

Mission Overview

Introduction & Motivation

COW-1 is a Comet Rendezvous and Sample Return Mission. This two part mission will conduct in situ analysis of Comet 46P/ Wirtanen and aim to return a physical sample for in lab analysis.

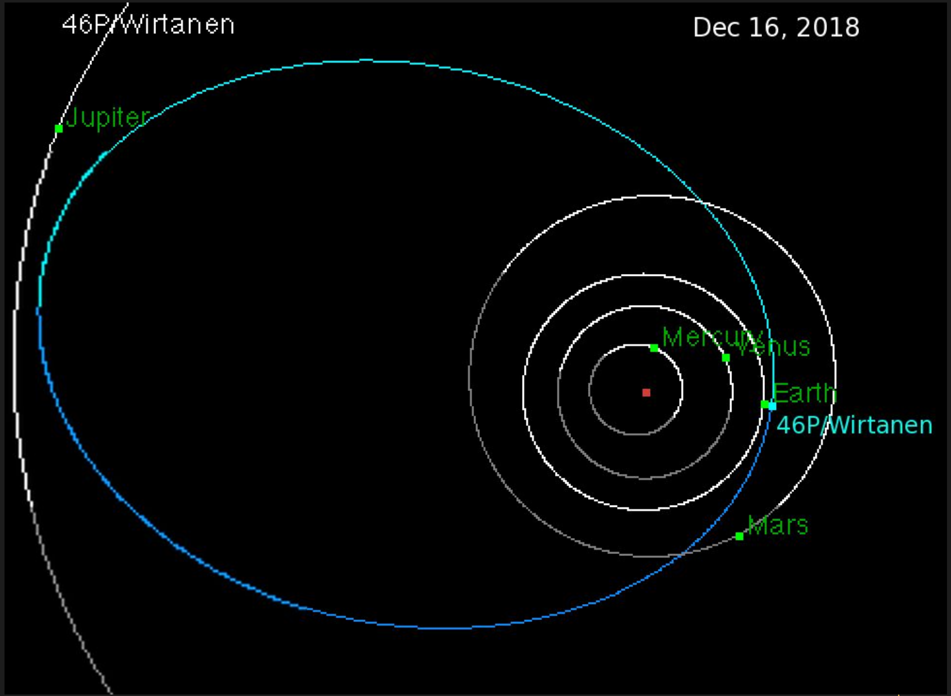
In response to the NASA Planetary Science and Astrobiology Decadal Survey, this mission aims to shed more light on cometary analysis and its influence on solar system formation.

This mission will characterize the magnetic, thermal, and mechanical properties of Comet 46P/Wirtanen, as well as its mass, bulk properties, and composition. This analysis can provide information about nebula accretion and dispersion, lifetime of the Solar System, as well as further the understanding of how comets contributed to the formation and evolution of planets.

[View of Comet 46P from Earth]

Comet 46P/ Wirtanen

Orbit Characteristics	
Family	JFC, Short Period
Eccentricity	.6587
Inclination	11.74759°
Perihelion	1.05535 AU
Aphelion	5.13 AU
Period	5.439 Years
Mean anomaly	.012467°
Mean motion	.181215°/day
Argument of perihelion	356.34°



Decadal Survey Priority Science Questions

Table 3	Priority Science Questions											
Mission Name	1	2	3	4	5	6	7	8	9	10	11	12
Mars Sample Return												
Uranus Orbiter and Probe												
Enceladus Orbilander												
Endurance-A												
Mars Life Explorer												
Centaur Orbiter/Lander												
Ceres Sample Return												
Comet Sample Return												
Enceladus Multi-Flyby												
Lunar Geophys. Network												
Saturn Probe												
Titan Orbiter												
Triton OWS												
Venus In Situ Explorer												

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Mission Requirements

Mission-Level Requirements and Science Questions

Science Objectives

Science Objective		Significance
SO1	Characterize the magnetic properties of Comet 46P	Provides key information and evolution of our Solar System. Constrains the idea of exoplanet formation.
SO2	Determine the mass and bulk density of Comet 46P	The determination of cometary mass and and bulk density is a fundamental objective in order to assess the validity and accuracy of various cometary models.
SO3	Determine the mechanical and thermal properties of the upper surface of Comet 46P	The determination of cometary mechanical and thermal properties are fundamental objective in order to assess the validity and accuracy of various cometary models.
SO4	Characterize the surface and subsurface composition of the comet by determining elemental and isotopic ratios, organic compounds present, and noble gases present (in-situ, sample return for laboratory analysis)	Provides key information in the cometary role in the delivery of water and volatiles to Earth. Constrains current models of solar system formation.

Mission Requirements

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	Minimum Requirement	Extended Requirement	Science Questions
Phase 1 - Rendezvous and Reconnaissance			
R1	The S/C should rendezvous near aphelion	N/A	S1, S2, S3, S4
R2	The S/C should maintain an orbit (altitude wrt comet) within 60 km of the comet to obtain an accurate mass estimate when the comet is near aphelion	Mass estimate of the comet shall be determined after sublimation to determine difference in physical composition	S3
R3	The entire surface of the comet must be mapped in the visible light spectrum using a wide-angle camera on approach, and volume estimate should be obtained	Entire surface of the comet shall be mapped after sublimation to determine difference in physical composition	S1, S2, S3, S4
R4	High-resolution imaging of landing sites of interest on the comet using a narrow-angle camera shall be performed to provide several options for a safe and scientifically valuable landing site	High-res imaging of the entire surface	S1,S2, S3, S4
Phase 2 - Surface Analysis & Sample Collection			
R5	Surface chemical composition at the landing site(s) must be determined in situ	N/A	S4
R6	At least one surface sample (minimum 500 cc) shall be obtained from comet 46P	N/A	S2, S3, S4
R7	At least one subsurface sample (minimum volume: 500 cc, minimum depth of sample: 10 cm) shall be obtained from a depth of 1 meter or below from comet 46P	N/A	S1, S2, S3, S4
R8	Surface and sub-surface samples shall not be mechanically or thermally altered by the extraction and storing process (stratigraphy should be maintained for sub-surface samples)	N/A	S1,S2, S3, S4
R9	S/C or Lander shall measure the magnetic field through the altitude ranges 0m - 10m (with accuracy of +/-.5m) with an accuracy of +/- .010 nT at a single location	S/C shall measure Plasma characteristics (values and parameters TBD) Must be sublimating.	S1
Phase 3 - Sample Return			
R10	The samples shall be preserved cryogenically at the same relative temperature and shall stay within approximately +/- 5K	N/A	S1, S2, S3, S4

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Phase 1 - Rendezvous and Reconnaissance

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Concept Level Trade Space

Orbiter/ Lander Configurations

Configuration	Concept	Pros	Cons
1 Orbiter and 1 Lander	Orbiter deploys Lander on Comet 46P	• Lowest complexity • Separates two different phases	• No S/C redundancy • One vehicle failure can lead to mission failure
2 Orbiter and 1 Lander	Double the Orbiters and Lander Same concept as 1 Orbiter and 1 Lander	• Increased potential for accomplishing more requirements • Increased redundancy	• Increase Mass and Volume constraints • Limits launch provider options
1 Orbiter/Lander hybrid	Similar to Osiris Rex's Touch and Go Sampling	• Touch and Go is well defined • No vehicle deployment • Single Propulsion System	• Increased complexity due to increased depth of sample • Highest Complexity • Combines phases 2 & 3

Lander Configurations

Configuration	Concept	Pros	Cons
Stationary	Sticks to one location in the comet	• Reduced complexity	• Small room for Redundancy • Immobile
Mobile Rover	Can move to multiple different location	• Allows for more locations for science	• Increased complexity • Hard to move due to low gravity

Sample Return Capsule Configurations

Configuration	Concept	Pros	Cons
Lander SRC	Lander collects the sample and returns it	• Reduced complexity (simply lander and orbiter) • Some heritage	• Two propulsion systems • Requires a detachable lander
Deployable SRC	Attached to Lander and deploys when sample is collected	• Has heritage (NASA VIPER) • Removes the need for a detachable Lander	• Increased risk of failure (small propulsion needed to reach Orbiter) • Increased GNC, ADCS complexity
Orbiter SRC	Orbiter is both the Lander and SRC	• Least Complex for SR • One propulsion system	• Highest risk of failure • No Heritage for this type

SRC - Sample Return Capsule

Number of Launches/ Packages

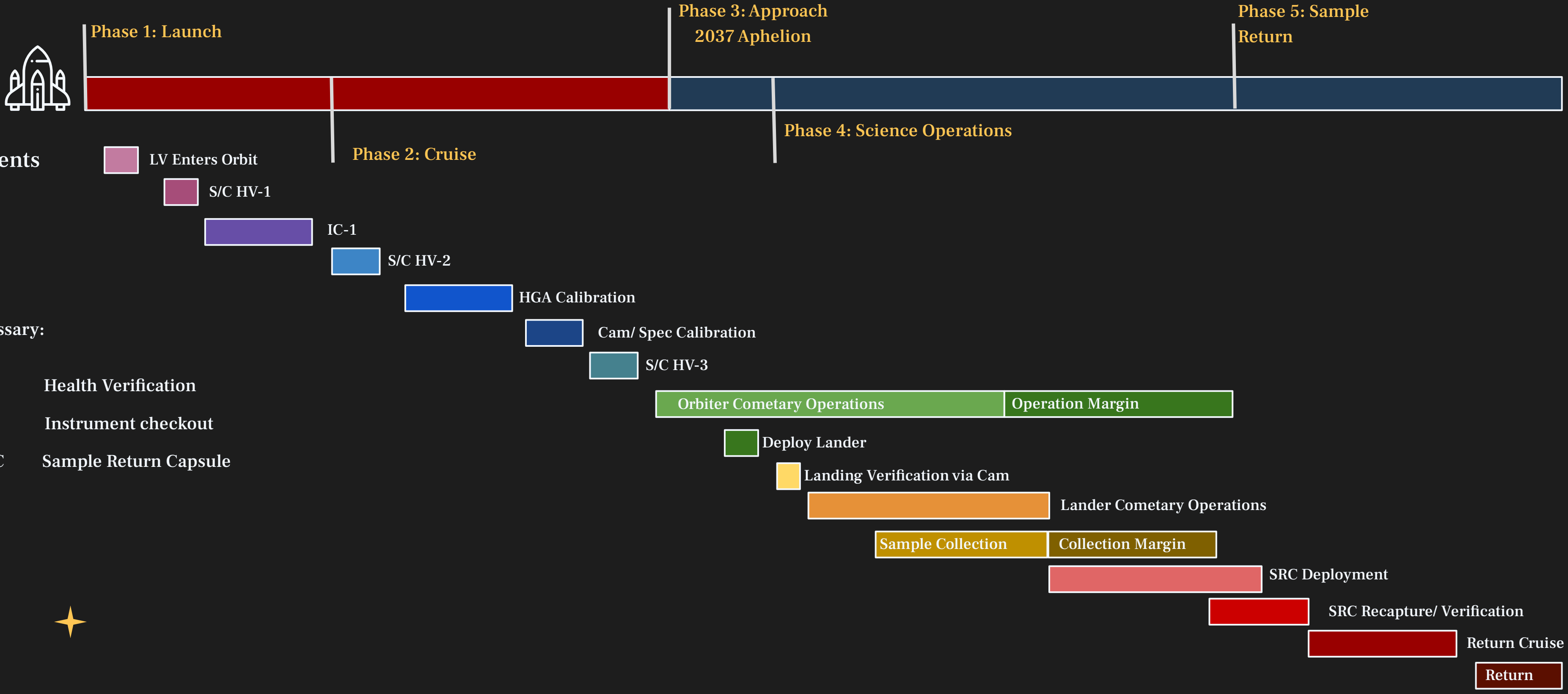
Configuration	Concept	Pros	Cons
Single	Sticks to one location in the comet	• Reduced complexity	• Small room for Redundancy • Immobile
Deployable SRC	Attached to Lander and deploys when sample is collected	• Has heritage (NASA VIPER)	• Increased risk of failure (small propulsion needed to reach Orbiter) • Increased GNC, ADCS complexity
Mobile Rover	Can move to multiple different location	• Allows for more locations for science	• Increased complexity • Hard to move due to low gravity

Full System Overview

Full System Overview

- 1 Orbiter, 1 Lander, 1 Sample Return Capsule
    - All with propulsion capabilities
- Orbiter completes Phase 1 & 3 Mission Requirements
- Lander completes Phase 2 Mission Requirements
- Lander: Stationary

Mission Timeline

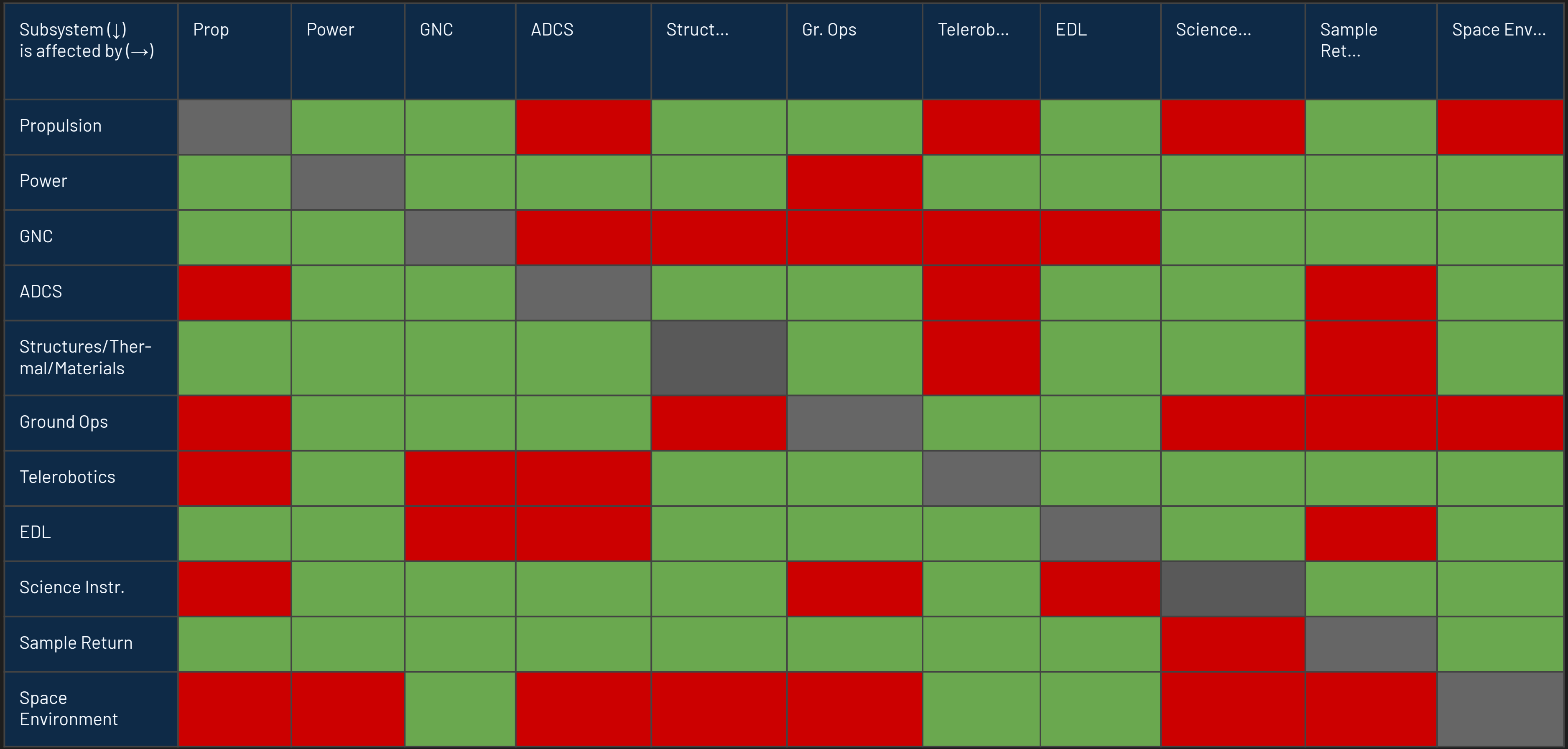


Glossary:

HV	Health Verification
IC	Instrument checkout
SRC	Sample Return Capsule

Subsystem Dependency Matrix

Affected | Unaffected



Mission Environment

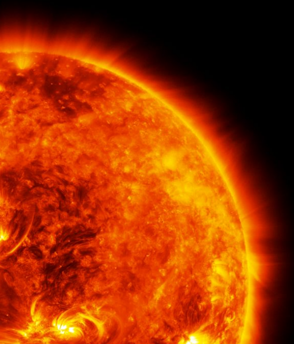
General Overview

This mission will only be influenced by the environments of:

- Earth/Moon
- Sun
- Interstellar radiation/particles
- Comet 46P

No gravitational slingshot maneuvers are currently planned and distances from other planets are significant, therefore their influences on environmental conditions can be neglected for this mission

Solar Irradiance



Earth/Moon:

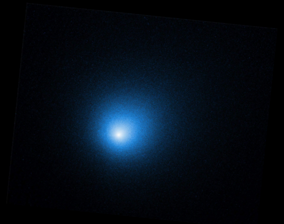
Solar Flux: 1361.0 W/m^2

Earth:

Albedo 0.306

Moon:

Albedo: 0.11



Comet 46P:

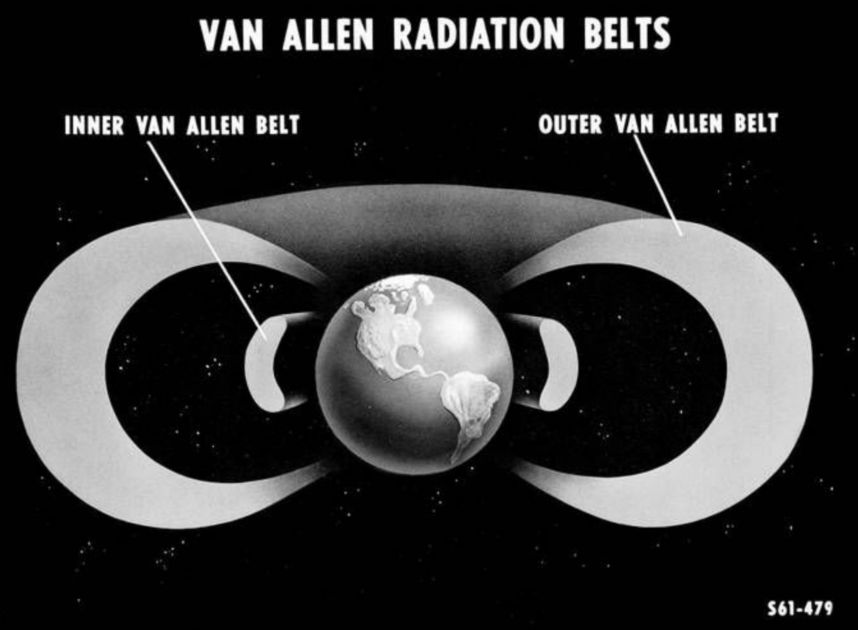
Max Solar Flux: 1239.7 W/m^2
(Perihelion)

Min Solar Flux: 52.46 W/m^2
(Aphelion)

Albedo: NA

Radiation

- Solar
  - Normal Activity
  - Solar Flares
- Particles stuck in Magnetic fields (Earth)
  - Van Allen Belts
- Cosmic Rays



As solar radiation decreases, cosmic radiation increases, as it constantly a back and forth "pressure" both fighting each other

Particle Impact Risk

The major area of concern for particle collisions are near the comet, as all other environments the risk of impacts are significantly lower

However as the spacecraft will be traveling at approximately the same velocity when it approaches the comet, particle impacts risks can be negligible and dedicated shielding isn't required. This was the case for the Rosetta Mission.

Comet Surface

Comet are fairly porise (not densely packed) and have a thin layer of dust of a few centimeters covering a much more harder soil underneath (discovered by the Rosetta Mission)

The landscape is scattered with boulders and has very drastically varying heights, leading to very steep train at locations

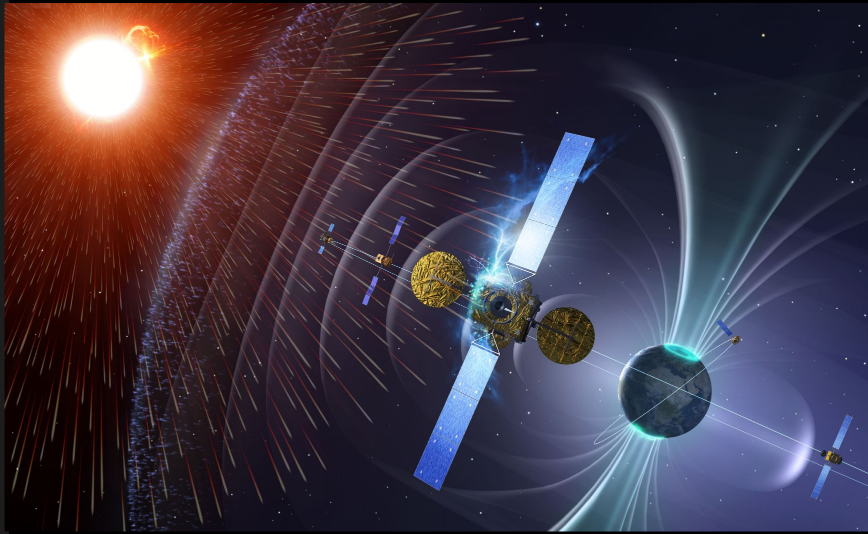
We don’t know much about the shape or physical qualities of Comet 46P, so we must plan for a very unpredicted landscape

Environmental Conclusion

Overall for all systems, components must be able to survive Earth's environment and the environment of deep space.

This frees up the opportunity for many heritage missions to pull from, as all non Earth space missions were designed with these conditions in mind

Only the lander must worry about additional environmental factors, as it will be interacting with the surface of the comet. Mostly how it interacts with dust and avoiding large objects upon landing



Launch, Propulsion and Power

Launch

- Delivers spacecraft from Earth's surface into orbit
- Upper stage will provide significant amount of ΔV necessary to reach Comet 46P
- Must accommodate spacecraft's weight and dimensions, while maintaining safe launch environment inside fairing
- Dependencies: Spacecraft Volume, Mass, and Structure

Launch Vehicle

Small lift launch vehicles ignored for this trade due to destination distance

Launch Vehicle Trade Study							
Launch Vehicle	**Atlas V**	**Delta IV**	**Vulcan Centaur**	**Falcon 9**	**Falcon Heavy**	**New Glenn**	**Ariane 6**
Payload to Mars Orbit [kg]	3,500	8,000	7,000	4,020	16,800	7,000	6,000
Maximum Axial Acceleration [g]	6	6	Unknown	8.5	8.5	6	4.6
Maximum Lateral Acceleration [g]	2	2	Unknown	3	3	2	1.8
Cost	$109 Million	$350 Million	$150 Million	$67 Million	$90 Million	N/A	$126 Million
Volumes [m^3]	64.126, 74.212, 84.307, 109.23, 154.26, and 223.65	111.29, 213.45, 311.87, and 326.05	~260 and ~392	~207 and ~333	~207 and ~333	458 and 487	166.54 and 308.19

Launch Vehicle

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Small lift launch vehicles ignored for this trade due to destination distance

Launch Vehicle Trade Study							
Launch Vehicle	**Atlas V**	**Delta IV**	**Vulcan Centaur**	**Falcon 9**	**Falcon Heavy**	**New Glenn**	**Ariane 6**
Pros	-Reliable -Highly customizable	-Large payload mass capacity -Highly customizable	-Large payload mass capacity -Large payload volume capacity	-Lower cost -Reusable -Reliable	-Largest payload mass capacity -Lower cost -Reusable -Reliable	-Large payload mass capacity -Large payload volume capacity -Reusable	-Equatorial launch location -Low static loading -Reliable
Cons	-Small payload mass capacity -Small payload volume capacity	-Expensive	- Only one available payload diameter -	-Small payload mass capacity -Only one available payload diameter -Large static loading	-Only one available payload diameter -Large static loading -Fewer launches	-No launch history - Only one available payload diameter	-No reusability increasing cost - Only one available payload diameter

Launch Vehicle: Selection and Rationale

Selection: Falcon Heavy

Rationale:

- Largest reduction in ΔV requirements for the propulsion system
- Much lower cost due to reusability
- Volume requirements still satisfied despite lack of customization
- Lack of deep space missions, however multiple are planned

Launch Site: Selection and Rationale

Selection: Kennedy Space Center, Launch Complex 39A

- Location: Cape Canaveral, Florida
- Latitude: 28.61°N
- Leased to SpaceX since April, 2014

Rationale:

- Closest available US launch site to the equator
- Has been used by SpaceX for a total of 60 launches
- Only launch site available for Falcon Heavy
- Provides all necessary launch site facilities

Propulsion

- Provides remaining ΔV necessary to reach comet 46P and return to Earth
- Conducts station keeping of orbit around 46P
- Provides thrust and attitude control needed to land on comet and return sample to the orbiter
- Dependencies: GNC, Structures, Thermal, Power, Ground Ops, EDL, and Launch Vehicle

Propulsion

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Propulsion System Trade Study							
Propulsion Technology	Specific Impulse (Isp) [s]	Thrust [N]	Power [kW]	Lifetime [h]	Total Impulse [MNs]	Efficiency [%]	Mass [kg]
Ion Thruster	2000-5000	0.001-0.1	0.1-10	30000	10-25	>90	10-15
HET	1000-3000	0.01-1	0.2-20	10000	5-35	50-60	10-50
Bipropellant	270-470	10-5,000	0.01-0.07	NA	0.09-100	NA	1-11
Monopropellant	180-235	0.2-450	0.012-0.024	NA	0.1-0.2	NA	0.3-7
Cold Gas	40-80	0.001-5	0.001-0.005	NA	<0.01	NA	0.05-0.3

Propulsion: Orbiter

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Orbiter Propulsion System Trade Study			
Type	Concept	Pros	Cons
Cold Gas	Not viable due to low thrust, specific impulse, and total impulse	- Simple and reliable - Short Impulse bit - Low power requirements	- Low total impulse - Thrust decreases as fuel is consumed
Electric	Two-three Hall Effect or Ion thrusters	- High specific impulse - Moderate total impulse - Low propellant mass	- High power requirements - Lower lifetime, requires multiple thrusters - Increased complexity of trajectory - Increased mission time
Chemical	Single bipropellant thruster	- High total impulse - High thrust - Low power requirements	- Significantly higher propellant mass - Lower specific impulse

Propulsion: Lander and Sample Return

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Lander and Sample Return Propulsion System Trade Study			
Type	Concept	Pros	Cons
Cold Gas	Multiple thrusters to grant control of 6 degrees of freedom	- Low power requirements - Simple and reliable - Short impulse bit	- Low total impulse - Thrust decreases as fuel is consumed
Electric	Same as cold gas except with resito or arcjet thrusters	- Resistojet are low cost and reliable - High efficiency - High specific impulse	- High power requirements - Low thrust - Higher thermal management requirements
Chemical	Same as cold gas except with monopropellant thrusters	- High thrust - Low power requirements - High total impulse - Low-temperature reactions	- Low specific impulse - Requires heavy catalyst bed

Propulsion: Selection and Rationale

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Orbiter Selection: Bipropellant Thruster

- Cold gas generates far to low thrust and total impulse
- Low solar flux a aphelion makes electric a difficult prospect
- Electric propulsion results in increased complexity of trajectory and mission time
- Increase in propellant mass for chemical is manageable

Lander Selection: Cold Gas Thrusters

- Electric is not viable due to low solar flux environment coupled with power prioritization of science instruments
- Increase in thrust and specific impulse of monopropellant system unnecessary and doesn't not justify increase in propulsion system mass

Sample Return Selection: Cold Gas Thrusters

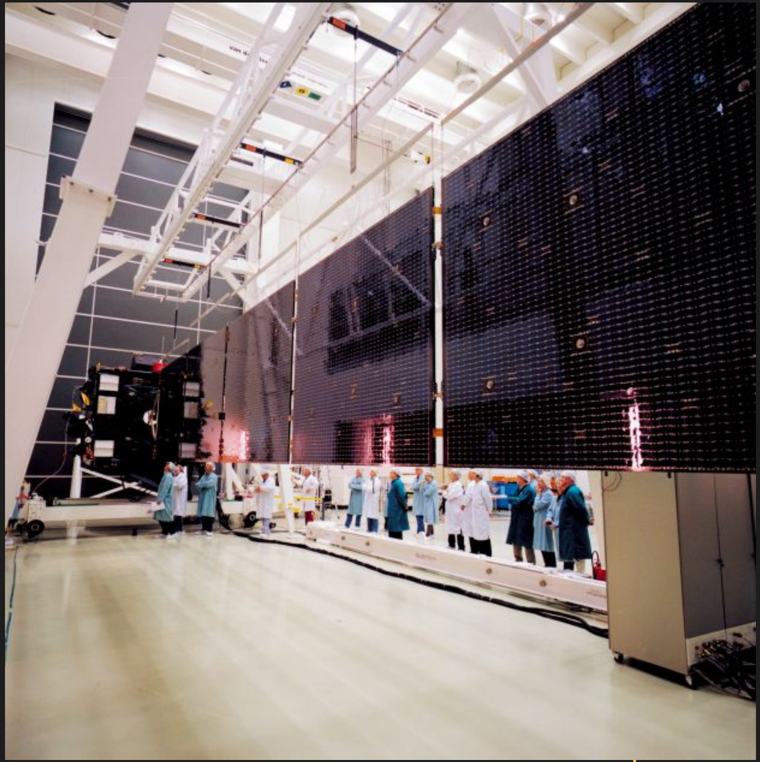
- Similar reasons for lander
- Mass budget is even more restricted for the sample return craft making the propulsion system mass increase for monopropellant unjustifiable with the increase in unnecessary thrust

Propulsion: Engines

Engines Used For Propellant Mass Calculations					
Spacecraft	Engine	Thrust [N]	Specific Impulse [s]	Valve Power [W]	Mass [kg]
Orbiter	400N Apogee	425	321	35	4.3
Lander and Sample Return	MOOG 058-118	3.6	57	30	0.023

Power

- Must provide and store reliable energy to orbiter for entire mission life
- Must provide and store reliable energy in the short term for the lander and sample return craft without utilizing a significant portion of mass budgets
- Dependencies: ADCS, Structures, Thermal, Trajectory, Mission Length, Science Instruments, Propulsion, Telerob, and Space Environment



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Power Generation

Power Generation Trade Study			
Power Technology	Power [kW]	Specific Power [W/kg]	Mission Length
Solar Array	<0.1-300	25-250	1 week - >1 year
RTG	<0.1-20	5-20	1 year - >10 years
Fuel Cells	0.1-100	30-350	1 day - 1 month
Batteries	<0.1-2	1-10,000	<10 min - 1 week

Power Generation: Orbiter

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Orbiter Power Generation Trade Study			
Type	Concept	Pros	Cons
Solar Array	2 wing GaAs (MJ) array	- Large amount of power for large arrays - High specific power - Moderate lifetime	- Much less power generation at aphelion - High volume requirements requiring in situ deployment
RTG	Single Pu 238 RTG	- Provide power independent of solar flux environment - Long lifetime - Low volume requirements	- Low specific power - Low power generation
Fuel Cells	Multiple Alkaline fuel cells	- Provide power independent of solar flux environment - High specific power - Low volume requirements	- Invalid option due to short operational lifetime - Typically low power generation

Power Generation: Lander and Sample Return

Lander and Sample Return Power Generation Trade Study			
Type	Concept	Pros	Cons
Solar Array	Body mounted solar cells	- High specific power - Moderate lifetime - Significant heritage	- Power generation depends highly on landing spot - Power generation will vary depending on comet rotation
RTG	Single Pu 238 RTG	- Provide power independent of solar flux environment - Long lifetime	- Low specific power - Low power generation - Large mass and volume for lander
Fuel Cells	Single Alkaline fuel cell	- Provide power independent of solar flux environment - High specific power	- Typically low power generation - Large mass and volume for lander
Battery	Combination of primary and secondary batteries	- Provide power independent of solar flux environment - High specific power - Significant heritage	- Need to be charged by another power source or before take off

Power Generation: Selection and Rationale

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Orbiter: Solar Array

- Fuel cells are not viable due to there very short operational lifetimes
- Low specific power and power generation of RTG's make for a poor choice
- Although power generation is reduced due to distance from the sun and degradation from mission length, power requirements will still be met
- Plenty of heritage on 5-6 AU missions

Lander: Solar Array

- RTG and fuel cells are an invalid option due to their mass and volume requirements
- Can not rely completely on battery power due to mission length on comet's surface
- Least volume and mass intense option, however land location and illumination are major concerns

Sample Return: Battery

- RTG and fuel cells are invalid for the same reasons mention for the lander
- Small operational lifetime of craft makes batteries an ideal option

Power Storage

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Power Storage Trade Study					
Type	Chemistry	Specific Energy [Wh/kg]	Volumetric Energy Density [Wh/L]	Specific Power [W/kg]	Self Discharge Rate [%/month]
Secondary	Li-Ion	100-270	250-670	250-340	1.5-2
Secondary	Ni-Cd	40-60	50-150	150	10
Secondary	Ni-MH	60-120	150-300	250-1000	0.08-2.9
Primary	Ag-Zn	60-130	100-200	1100	5
Primary	Li-SO_2	130-350	375	680	<0.2
Primary	Li-CF	500-800	1050	15	<0.05

Power Storage: Orbiter

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Orbiter Power Storage Trade Study			
Type	Chemistry	Pros	Cons
Secondary	Li-Ion	- High specific energy - High energy density	- Moderate self discharge rate - Low specific power
Secondary	Ni-Cd	- High operational temperature	- Low specific energy - High self discharge rate
Secondary	Ni-MH	- High specific power - Low self discharge rate	- Low specific energy - Moderate energy density
Primary	Ag-Zn	- High specific power	- Low specific energy - High self discharge rate
Primary	$Li\text{-}SO_2$	- High specific power - Low self discharge rate	- Moderate energy density
Primary	Li-CF	- High specific energy - Low self discharge rate	- Low specific power

Power Storage: Lander

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Lander Power Storage Trade Study			
Type	Chemistry	Pros	Cons
Secondary	Li-Ion	- High specific energy - High energy density	- Moderate self discharge rate - Low specific power
Secondary	Ni-Cd	- High operational temperature	- Low specific energy - High self discharge rate
Secondary	Ni-MH	- High specific power - Low self discharge rate	- Low specific energy - Moderate energy density
Primary	Ag-Zn	- High specific power	- Low specific energy - High self discharge rate
Primary	Li-SO_2	- High specific power - Low self discharge rate	- Moderate energy density
Primary	Li-CF	- High specific energy - Low self discharge rate	- Low specific power

Power Storage: Sample Return

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Sample Return Power Storage Trade Study			
Type	Chemistry	Pros	Cons
Secondary	Li-Ion	- High specific energy - High energy density	- Moderate self discharge rate - Low specific power
Secondary	Ni-Cd	- High operational temperature	- Low specific energy - High self discharge rate
Secondary	Ni-MH	- High specific power - Low self discharge rate	- Low specific energy - Moderate energy density
Primary	Ag-Zn	- High specific power	- Low specific energy - High self discharge rate
Primary	Li-SO_2	- High specific power - Low self discharge rate	- Moderate energy density
Primary	Li-CF	- High specific energy - Low self discharge rate	- Low specific power

Power Storage: Selection and Rationale

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Orbiter: Li-Ion

- Must be rechargeable for Earth eclipses
- Long mission lifetime requires low discharge rates
- Specific power is less significant since large discharge is unnecessary due to chemical propulsion

Lander: Li-Ion and Li-SO_2

- Low solar flux environment and shading necessitates use of primary batteries to improve robustness
- Specific energy and density most significant factors due to small volume and mass budget
- Length of travel time to comet results in necessity for low discharge rates

Sample Return: Li-CF

- Even smaller mass and power budgets result in higher significance of specific energy and density
- Few instruments and components result in small specific power requirements
- Brief operational lifetime and lack of power generation results in no need for recharability

ADCS, Navigation, and Communication

ADCS

ADCS: Attitude Determination and Control

A comet sample return mission creates unique challenges for ADCS. Besides pointing requirements for communications and navigation, unique ADCS solutions are required to get the lander safely to ground, rendezvous with the comet sample return capsule, as well as point the science instruments.

Deep space communications requires precise pointing, therefore accurate sensors and actuators.

Comet sample return capsule is limited in size, therefore actuator choice is also limited

ADCS

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Sensors Trade Study					
Sensor	Accuracy	Mass (kg)	Power (W)	Pro	Con
Gyroscope	Drifts 0.003 deg/hr to 1 deg/hr	< 0.1 to 15	< 1 to 200	Can have low power	Drifts over time
Sun Sensor	0.005 deg to 3 deg	0.1 to 2	0 to 3	Simple sensor, good with several	Lose information during eclipse
Star Tracker	0.0003 deg to 0.01 deg	2 to 5	5 to 20	Accurate and precise	Expensive, failure causes the engineers to panic
Horizon Sensor (fixed)	< 0.1 deg to 0.25 deg	0.5 to 3.5	0.3 to 5	Low power requirement	Requires a horizon
Magnetometer	0.5 deg to 3 deg	0.3 to 1.2	< 1	Simple, low power	Requires mapping of magnetic field
IMU	Drifts 0.003 deg/hr to 1 deg/hr	0.748 to 0.9	5 to 12	Integrates gyro with accelerometer	Drifts over time

ADCS

P

Sensors Trade Study: Orbiter					
Sensor	Accuracy	Mass (kg)	Power (W)	Pro	Con
Gyroscope	Drifts 0.003 deg/hr to 1 deg/hr	< 0.1 to 15	< 1 to 200	Can have low power	Drifts over time
Sun Sensor	0.005 deg to 3 deg	0.1 to 2	0 to 3	Simple sensor, good with several	Lose information during eclipse
Star Tracker	0.0003 deg to 0.01 deg	2 to 5	5 to 20	Accurate and precise	Expensive, failure causes the engineers to panic
Horizon Sensor (fixed)	< 0.1 deg to 0.25 deg	0.5 to 3.5	0.3 to 5	Low power requirement	Requires a horizon
Magnetometer	0.5 deg to 3 deg	0.3 to 1.2	< 1	Simple, low power	Requires mapping of magnetic field
IMU	Drifts 0.003 deg/hr to 1 deg/hr	0.748 to 0.9	5 to 12	Integrates gyro with accelerometer	Drifts over time

ADCS

P

Sensors Trade Study: Lander					
Sensor	Accuracy	Mass (kg)	Power (W)	Pro	Con
Gyroscope	Drifts 0.003 deg/hr to 1 deg/hr	< 0.1 to 15	< 1 to 200	Can have low power	Drifts over time
Sun Sensor	0.005 deg to 3 deg	0.1 to 2	0 to 3	Simple sensor, good with several	Lose information during eclipse
Star Tracker	0.0003 deg to 0.01 deg	2 to 5	5 to 20	Accurate and precise	Expensive, failure causes the engineers to panic
Horizon Sensor (fixed)	< 0.1 deg to 0.25 deg	0.5 to 3.5	0.3 to 5	Low power requirement	Requires a horizon
Magnetometer	0.5 deg to 3 deg	0.3 to 1.2	< 1	Simple, low power	Requires mapping of magnetic field
IMU	Drifts 0.003 deg/hr to 1 deg/hr	0.748 to 0.9	5 to 12	Integrates gyro with accelerometer	Drifts over time

ADCS

P

Sensors Trade Study: Sample Return Capsule					
Sensor	Accuracy	Mass (kg)	Power (W)	Pro	Con
Gyroscope	Drifts 0.003 deg/hr to 1 deg/hr	< 0.1 to 15	< 1 to 200	Can have low power	Drifts over time
Sun Sensor	0.005 deg to 3 deg	0.1 to 2	0 to 3	Simple sensor, good with several	Lose information during eclipse
Star Tracker	0.0003 deg to 0.01 deg	2 to 5	5 to 20	Accurate and precise	Expensive, failure causes the engineers to panic
Horizon Sensor (fixed)	< 0.1 deg to 0.25 deg	0.5 to 3.5	0.3 to 5	Low power requirement	Requires a horizon
Magnetometer	0.5 deg to 3 deg	0.3 to 1.2	< 1	Simple, low power	Requires mapping of magnetic field
IMU	Drifts 0.003 deg/hr to 1 deg/hr	0.748 to 0.9	5 to 12	Integrates gyro with accelerometer	Drifts over time

ADCS

P

Actuators Trade Study					
Actuator	Performance	Mass (kg)	Power (W)	Pro	Con
Reaction Wheel	Max Torque: 0.01 to 1 Nm Storage: 0.4 to 3000 Nms	2 to 20	10 to 100	Accurate pointing	Lots of mass, desaturation req'd
Control Moment Gyro	Max Torque: 25 to 500 Nm	> 10	90 to 150	Withstand large torques	Requires more power than RW
Magnetorquer	1 to 4000 Am^2	0.4 to 50	0.6 to 16	Orient two axes	Requires magnetic field
Cold Gas	< 5 N	See propulsion	See propulsion	Simple implementation	Low thrust, low ISP, restricted use cases
Hot Gas	0.5 to 9000 N	See propulsion	See propulsion	High thrust capabilities	Complex, uses propellant

ADCS

P

Actuators Trade Study: Orbiter					
Actuator	Performance	Mass (kg)	Power (W)	Pro	Con
Reaction Wheel	Max Torque: 0.01 to 1 Nm Storage: 0.4 to 3000 Nms	2 to 20	10 to 100	Accurate pointing	Lots of mass, desaturation req'd
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Magnetorquer	1 to 4000 Am^2	0.4 to 50	0.6 to 16	Orient two axes	Requires magnetic field
Cold Gas	< 5 N	See propulsion	See propulsion	Simple implementation	Low thrust, low ISP, restricted use cases
Hot Gas	0.5 to 9000 N	See propulsion	See propulsion	High thrust capabilities	Complex, uses propellant

ADCS

P

Actuators Trade Study: Lander					
Actuator	Performance	Mass (kg)	Power (W)	Pro	Con
Reaction Wheel	Max Torque: 0.01 to 1 Nm Storage: 0.4 to 3000 Nms	2 to 20	10 to 100	Accurate pointing	Lots of mass, desaturation req'd
Control Moment Gyro	Max Torque: 25 to 500 Nm	> 10	90 to 150	Withstand large torques	Requires more power than RW
Magnetorquer	1 to 4000 Am^2	0.4 to 50	0.6 to 16	Orient two axes	Requires magnetic field
Cold Gas	< 5 N	See propulsion	See propulsion	Simple implementation	Low thrust, low ISP, restricted use cases
Hot Gas	0.5 to 9000 N	See propulsion	See propulsion	High thrust capabilities	Complex, uses propellant

ADCS

P

Actuators Trade Study: Sample Return Capsule					
Actuator	Performance	Mass (kg)	Power (W)	Pro	Con
Reaction Wheel	Max Torque: 0.01 to 1 Nm Storage: 0.4 to 3000 Nms	2 to 20	10 to 100	Accurate pointing	Lots of mass, desaturation req'd
Control Moment Gyro	Max Torque: 25 to 500 Nm	> 10	90 to 150	Withstand large torques	Requires more power than RW
Magnetorquer	1 to 4000 Am^2	0.4 to 50	0.6 to 16	Orient two axes	Requires magnetic field
Cold Gas	< 5 N	See propulsion	See propulsion	Simple implementation	Low thrust, low ISP, restricted use cases
Hot Gas	0.5 to 9000 N	See propulsion	See propulsion	High thrust capabilities	Complex, uses propellant

ADCS: Orbiter

The orbiter will include:

- 12 sun sensors, two per face
- 2 IMU's, one for redundancy
- 1 star tracker
- 4 reaction wheels, pyramidal configuration
- Cold gas thrusters

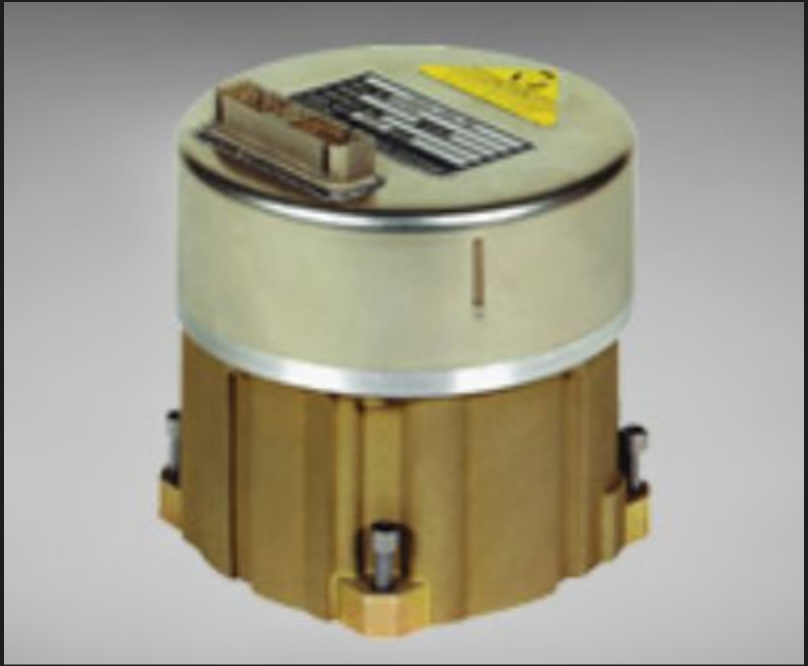
This configuration is inspired by Psyche:

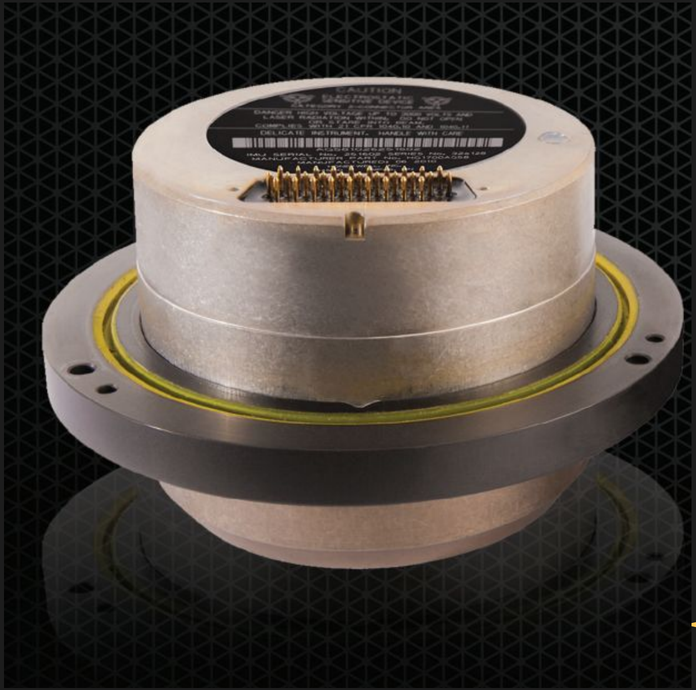
- 1 star sensor assembly
- 1 inertial reference unit
- 12 coarse sun sensors
- 12 cold gas thrusters
- 4 Honeywell HR 16-100 reaction wheels, pyramidal configuration

NP

ADCS: Orbiter [NOT PRESENTED]

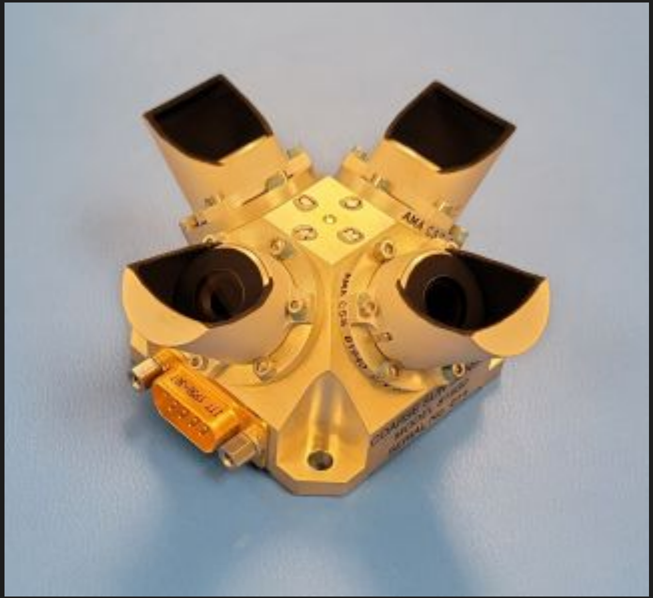
Possible IMUs: Northrop Grumman LN-200S vs Honeywell HG1700

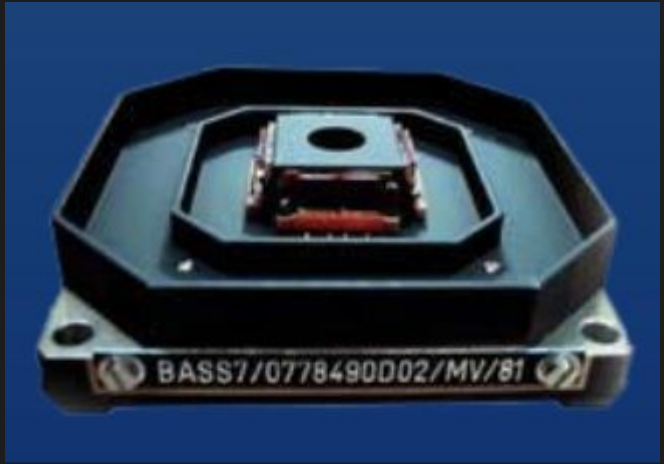




ADCS: Orbiter [NOT PRESENTED]

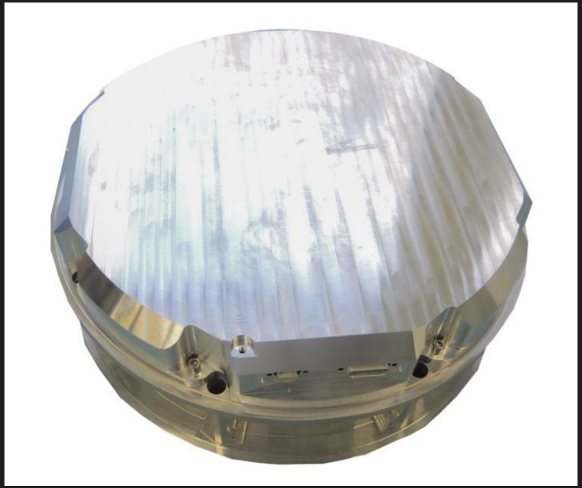
Possible Sun Sensors: Redwire Coarse Sun Sensor Pyramid vs Avionics Bass Bi-Axis Sun Sensor





ADCS: Orbiter [NOT PRESENTED]

Possible Reaction Wheels: Honeywell Constellation Series Reaction Wheels vs. Astrofein Reaction Wheels



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ADCS: Orbiter [NOT PRESENTED]

We choose the Northrop Grumman LN-200S, the Avionics Bass Coarse Bi-Axis Sun Sensor, and Astrofein Reaction Wheels for our components. We chose the LN-200S for its heritage in deep space, the Avionics Sun sensor for its small mass, and the Astrofein Reaction Wheels for its heritage.

The datasheets for each component allows us to predict mass, power, and volume budgets for ADCS. Important data is on the slide that follows.

ADCS: Orbiter [NOT PRESENTED]

Component	Mass	Volume	Power
LN-200S	0.748 kg	8.89 cm diameter, 8.51 cm height	Nominal 12 W
Avionics Bass Sun Sensor	65 g	70x82x23 mm^3	0 W (passive)
Astrofein RW 800	6 kg	250x250x100 mm^3	Nominal 25 W
Total	26.28 kg	0.02711 m^3	87 W

ADCS: Lander

The lander will include:

- 1 IMU
- 1 short range LIDAR to use as altimeter
- Cold gas thruster array

ADCS: Lander

IMU (BMI 160) and LIDAR (LIDAR Lite v3: Mars Helicopter heritage

ADCS: Lander [NOT PRESENTED]

Important specs:

Component	Mass	Volume	Power
Lidar-Lite v3	22 g	40x48x20 mm^3	1.3 W
BMI 160	0.2 g	2.5x3.0x0.8 mm^3	3.5 mW
Cold Gas (see propulsion)	0.3 kg	Unknown, estimate 1 m^3	5 W
Total	0.3222 kg	1.00004 m^3	6.335 W

NP

ADCS: Sample Return Capsule [NOT PRESENTED]

The Sample Return Capsule (SRC) requires orientability in order to appropriately rendezvous with the orbiter. We also want to minimize mass, volume, and power required to operate. To this end, we have decided to offload the computing requirements of the SRC to the orbiter. The commands will come from the orbiter through the capsule's low gain antenna from the orbiter's low gain antenna. For Attitude Determination, the orbiter and lander both will use their communication systems as radar to triangulate the sample capsule's position/velocity and use this information to determine the capsule's orbit. For Attitude Control, we will utilize three reaction wheels. This configuration comes with a lot of risk since the mission has no heritage. To minimize risk, a secondary mission to the moon as a hardware demonstration should be considered to test out communication triangulation and capsule control.

NP

ADCS: Sample Return Capsule [NOT PRESENTED]

Reaction wheel decision: due to heritage with cubesats and smallsats, we have chosen the Astrofein RW 35 reaction wheels.

Component	Mass	Volume	Power
Astrofein RW35	0.5 kg	102x102x58 mm^3	9 W
Total	1.5 kg	0.00181 m^3	27 W

Communications

Deep space communications creates unique challenges with respect to pointing requirements, band usage, and power requirements. These are deeply intertwined with distance, spacecraft eclipses, and antenna type.

In order to perform accurate mass estimations on the comet, the communications subsystems will need to operate using S band and X band radio frequencies.

Rosetta's pointing requirements was about 0.5 degrees for a similar distance.

Communications

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Antenna Shape Trade Study			
Antenna	Use	Pro	Con
Parabolic Reflector	Focus Signal	High EIRP	Bulky
Helix	Low frequency	Smaller than parabolic reflector	Higher complexity if deployed
Horn	Wide coverage area	Simple	Low gain use
Array	Electronic beam steering	High aperture efficiency	High cost and weight

Communications

P

Antenna Shape Trade Study: Orbiter			
Antenna	Use	Pro	Con
Parabolic Reflector	Focus Signal	High EIRP	Bulky
Helix	Low frequency	Smaller than parabolic reflector	Higher complexity if deployed
Horn	Wide coverage area	Simple	Low gain use
Array	Electronic beam steering	High aperture efficiency	High cost and weight

Communications

P

Antenna Shape Trade Study: Lander			
Antenna	Use	Pro	Con
Parabolic Reflector	Focus Signal	High EIRP	Bulky
Helix	Low frequency	Smaller than parabolic reflector	Higher complexity if deployed
Horn	Wide coverage area	Simple	Low gain use
Array	Electronic beam steering	High aperture efficiency	High cost and weight

Communications [NOT PRESENTED]

NP

Antenna Shape Trade Study: Sample Return Capsule			
Antenna	Use	Pro	Con
Parabolic Reflector	Focus Signal	High EIRP	Bulky
Helix	Low frequency	Smaller than parabolic reflector	Higher complexity if deployed
Horn	Wide coverage area	Simple	Low gain use
Array	Electronic beam steering	High aperture efficiency	High cost and weight

Communications

Gain Trade Study			
Gain	Use	Pro	Con
HGA	Large distance or lots of data	Fast downlink	Higher power consumption
MGA	Solid backup	Less power than HGA	Slower downlink than HGA
LGA	Omnidirectional	Low power	Smaller effective range

Communications

P

Gain Trade Study: Orbiter			
Gain	Use	Pro	Con
HGA	Large distance or lots of data	Fast downlink	Higher power consumption
MGA	Solid backup	Less power than HGA	Slower downlink than HGA
LGA	Omnidirectional	Low power	Smaller effective range

Communications

P

Gain Trade Study: Lander			
Gain	Use	Pro	Con
HGA	Large distance or lots of data	Fast downlink	Higher power consumption
MGA	Solid backup	Less power than HGA	Slower downlink than HGA
LGA	Omnidirectional	Low power	Smaller effective range

Communications: [NOT PRESENTED]

NP

Gain Trade Study: Sample Return Capsule			
Gain	Use	Pro	Con
HGA	Large distance or lots of data	Fast downlink	Higher power consumption
MGA	Solid backup	Less power than HGA	Slower downlink than HGA
LGA	Omnidirectional	Low power	Smaller effective range

Communications: Orbiter

The orbiter will have:

- 1 high gain parabolic antenna, About 2 meters diameter
- 1 medium gain antenna, for redundancy
- 2 Omnidirectional low gain antennas (horn)

This configuration takes inspiration from Rosetta:

- 1 2.2M diameter parabolic HGA (S or X)
- 2 MGA's (one S, one X. HGA redundancy)
- 2 LGA's (S-band)

Communications: Orbiter

Based on Rosetta communications design, we find the following uplink and downlink speeds.

Band	Uplink (MHz)	Downlink (MHz)
S	2000	2300
X	7200	8400

We can also estimate the mass of the HGA to be about 45 kg. The HGA transponder uses 28.5 watts.

NP

Communications: Orbiter [NOT PRESENTED]

Since we have chosen to model the communications system after Rosetta, we will use their mass and power estimations.

Component	Mass	Volume	Power
HGA	45	2.2 m diameter, about 1 m focal distance	See transponder power
MGA	0.880 kg	300 mm diameter, 75.8 mm height	See transponder power
LGA	< 250 g	285 mm length, 55 mm diameter	10 W
Transponder	6.25 kg	254x184x160 mm^3	28.5W
Total	46.38 kg	3.817 m^3	28.5 W (only use one antenna at a time)

Communications: Lander

The lander will have one low gain antenna to communicate with the orbiter. This antenna will be omnidirectional to reduce pointing requirements for successful communication. Mass estimations are currently unknown but the power requirements are 10 Watts and 250 grams if we use the Rosetta orbiter LGA information

NP

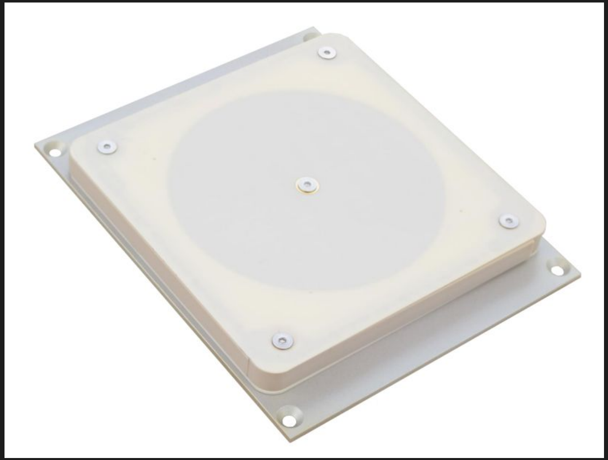
Communications: Sample Return Capsule [NOT PRESENTED]

We have chosen the GOMSpace S-band Patch antenna and NanoCom AX100 configurable transceiver. Important specifications are below:

Component	Mass	Volume	Power
Antenna	110 g	98x98x20.1 mm^3	11.25 W
Transceiver	24.5 g	65x40x6.5 mm^3	1.0 W
Total	0.1345 kg	209.94 cm^3	12.25 W

Communications: Sample Return Capsule [NOT PRESENTED]

GOMSpace S-band Patch antenna and NanoCom AX100 configurable transceiver



Navigation

Navigation has its own unique challenges with regards to orbiting an unknown comet. Calculations have to be run for the range of mass and volume estimations that we might see at Comet 46P.

In addition, comet sample return missions have to assure that an Earth return is physically realizable. This can be done through orbit phasing at return or very careful consideration of time of flight for each part of the mission.

Rendezvous with return capsule is a unique challenge due to size and orientability of said capsule.

Navigation

P

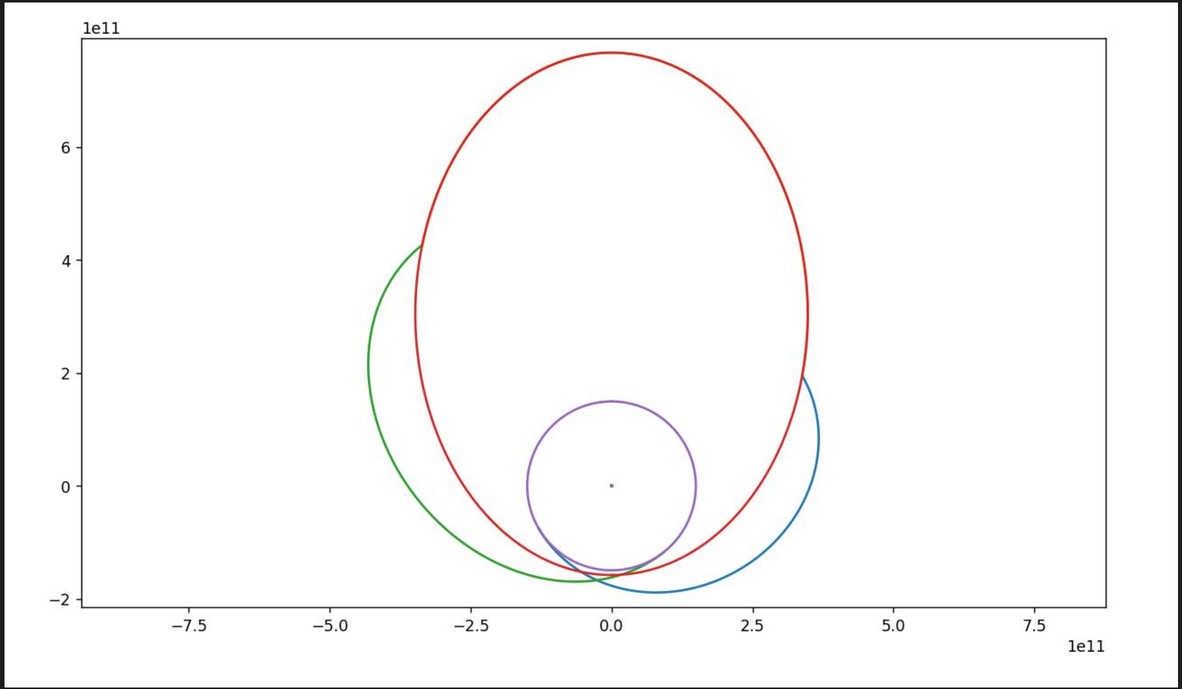
Orbits Iteration			
Maneuvers	ΔV	Pro	Con
Mars flyby, coast, interception, fast transfer departure	80 km/s	Instrument calibration	Earth is not there when you arrive
Mars flyby, interception, fast transfer departure, orbit phasing	130 km/s	You actually make it home	Prohibitive ΔV
Fast transfer to comet, fast transfer from comet	60 km/s	Lower ΔV	Unable to accurately time return to Earth, would require further phasing
Elliptical transfer from comet, elliptical transfer to comet	38 km/s	Lowest ΔV thus far	Earth is where you expect it to be

Navigation

P

Orbits Iteration			
Maneuvers	ΔV	Pro	Con
Mars flyby, coast, interception, fast transfer departure	80 km/s	Instrument calibration	Earth is not there when you arrive
Mars flyby, interception, fast transfer departure, orbit phasing	130 km/s	You actually make it home	Prohibitive ΔV
Fast transfer to comet, fast transfer from comet	60 km/s	Lower ΔV	Unable to accurately time return to Earth, would require further phasing
Elliptical transfer from comet, elliptical transfer to comet	38 km/s	Lowest ΔV thus far	Earth is where you expect it to be

Navigation



Navigation: Orbit Breakdown

Maneuver	Maneuver Type	ΔV	TOF	Distsance from Sun
Escape Earth	Oberth	4.75 km/s	26.37 days	1 AU
Cruise	Elliptical, intercept at 46P's True Anomaly at 120 deg	0 m/s	443.00 days	1 to 2.61 AU
Comet Capture	Hyperbolic to Circular	9.60 km/s	3.40 seconds	2.61 AU
Comet Maneuver	90 deg plane change	< 0.2 m/s	3.80 years	2.61 to 5.13 AU
Comet Escape	Oberth	9.18 km/s	678.65 seconds	3.63 AU
Return Cruise	Elliptical, depart at 218 deg	0 m/s	643.45 days	3.63 to 1 AU
Earth Capture	Hyperbolic to Circular	14.62 km/s	0.55 days	1 AU
Total	N/A	38.16 km/s	6.85 years	N/A

Navigation

Future work:

- Electric propulsion
- Flyby implementation
- Reduce Delta V to increase feasibility of mission

Structures/Thermal/ Materials

Specialty Overview

Structures

Spacecraft structures enclosed, protect, and support other subsystem. They provide attachment points and shield other components from environment, static, dynamic, and vibrational load.

Thermal

Thermal system controls the heat transfer throughout the spacecraft. It also focuses on protecting the spacecraft and its payload from the hot atmospheric reentry.

Materials

What Alloys has reliably flown and how we can benefit from exploiting intrinsic/extrinsic properties for specific subsystems and mission goals

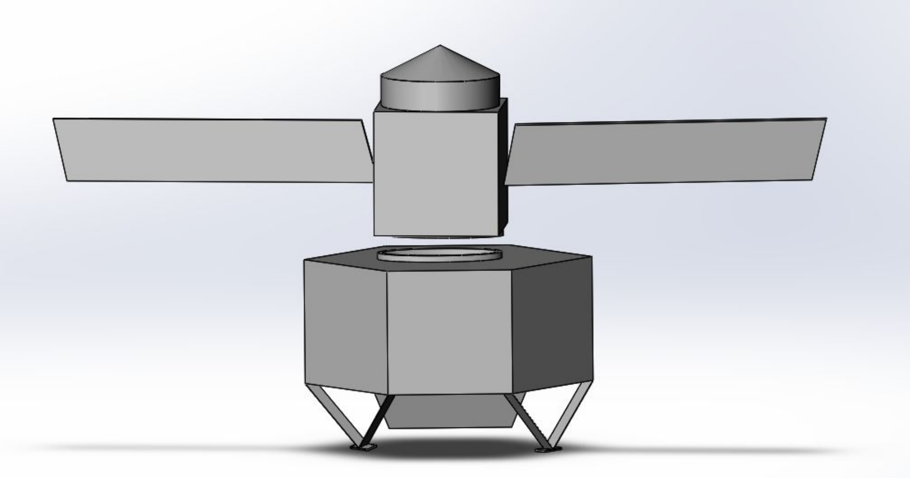
Structures: Spacecraft Attachment Mechanism

Structures

- Vibrational loads during launch
- Structure geometry
- Material selection
- Stability

Design is based off of the VIPER, DART, and Perseverance spacecrafts

Current Dimensions of Lander: 3m x 2m x 5m



Thermal

Keeping the Spacecraft warm/cool	Keeping the instrumentation under temperature control
• Uses Passive Systems • MLI blanket on spacecraft • Lander legs and bottom of lander will have a coating in the form of adhesive tape to reduce degradation while operating on the comet • Radiators on side panels to dissipate extra heat	• Uses Active Systems • Kapton heaters for the instrumentation • Thermoelectric coolers to keep some instrumentation cool such as IR Sensors and spectrometers

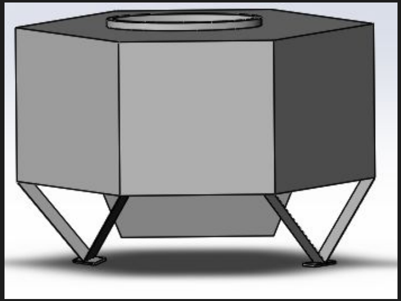
Thermal: Orbit + Surface Operations

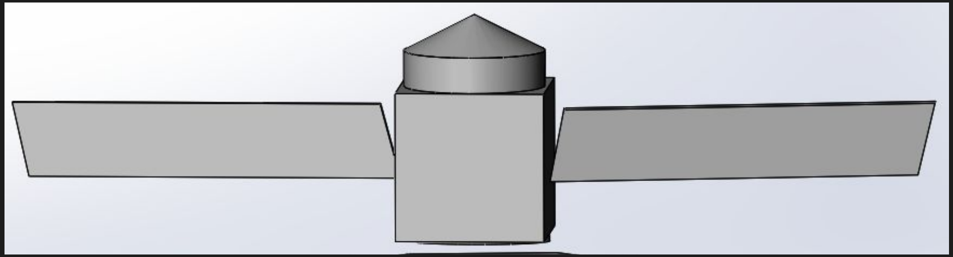
Thermal: EDL

Option	Application/Info	Pros	Cons
Ablative Heat Shield			

Materials

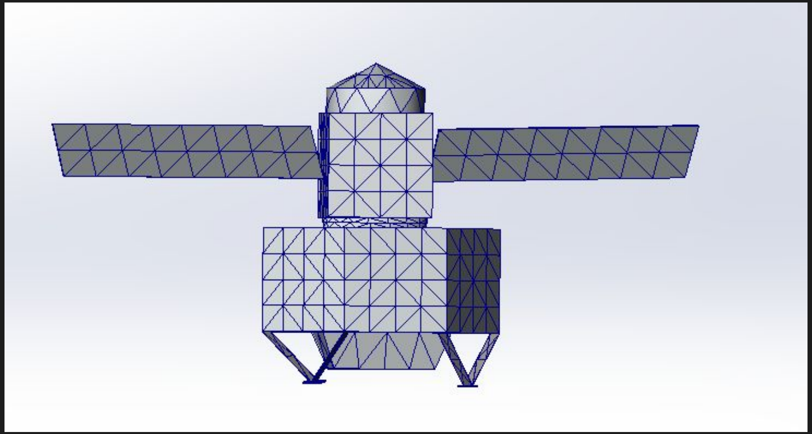
- Lander
  - Structure: Al T6-6061
  - Legs: Titanium 6AL-4V
  - Clamp-band: Steel
- Orbiter
  - Structure: Al T6-6061
  - Solar Panels: Gallium Arsenide - GaAs

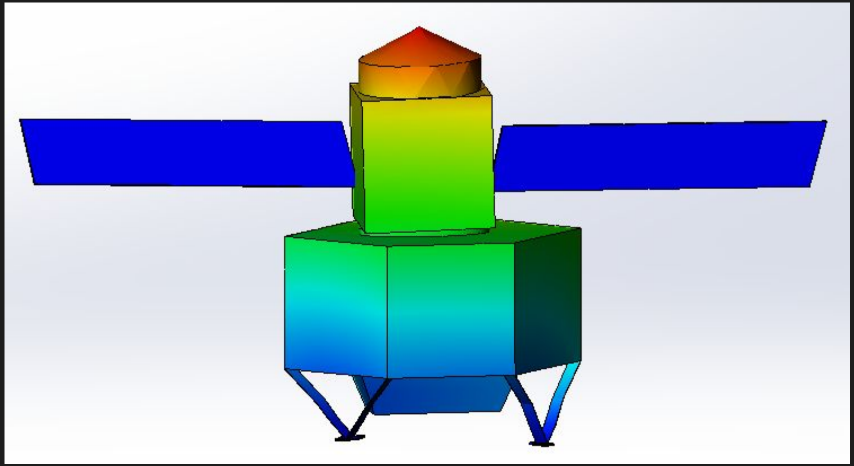




Analysis

- FEA tools for Static, vibrational, and thermal loads





Science Instruments

Overview, Rationale, Trade Studies

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Science Instruments Overview

Instrument	Description	Requirements Satisfied
Orbiter Instruments		
Radar	Uses existing X-band telecommunications system and Doppler shift from gravitational acceleration to estimate mass of Comet 46P.	R1
LIDAR	Uses laser pulses to measure distance to comet surface to characterize surface topography and comet shape.	R3, R4
Camera Suite (WAC & NAC)	Obtains broad-context images of the entire comet surface, as well as high-resolution images of sites of interest.	R3, R4
Gamma Ray / Neutron Spectrometer (GRNS)	Measures gamma rays and neutrons emitted from surface and subsurface materials to determine chemical composition.	R5
Visible / IR Mapping Spectrometer (VIMS)	Observes light spectrum emitted by comet in visible and infrared wavelengths to determine chemical composition throughout an entire image.	R4, R5
Lander Instruments		
Sample Verification Camera	Verify that sample collection was successfully completed.	R6, R7
Magnetometer	Measure magnetic field of comet as lander descends.	R9
Seismometer	Study seismic events, internal structure, and mechanical properties of comet.	R6

Gravity Science

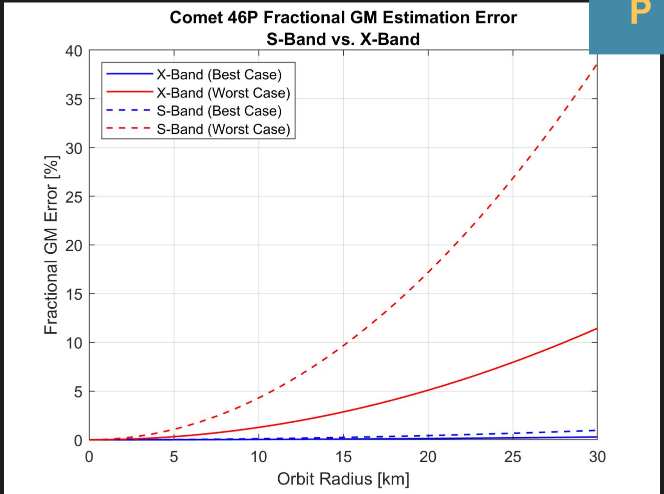
How It Works: the spacecraft's radio system will be used to measure comet mass using Doppler shift. The comet's gravity affects spacecraft motion, resulting in a frequency shift in communications between the spacecraft and Earth.

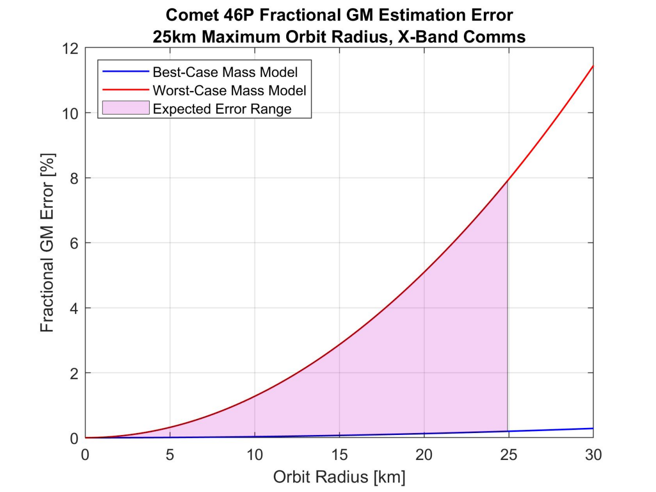
Mission Parameters:

- Orbit Radius = 25 km
- X-Band Communications
- Comet 46P Density CBE = 200 - 1000 kg / m^3
- Comet 46P Radius CBE = 500 - 1000 m

Expected Results:

- Worst-Case Mass Model: 8% accuracy
- Best-Case Mass Model: 0.2% accuracy

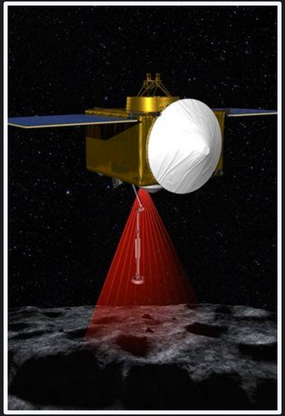




LIDAR

Objective: obtain high-resolution topographical map of Comet 46P's surface in order to scout a safe landing location.

LIDAR Trade Space						
Name	Size	Mass	Power	Other Specs	Pros	Cons
MOLA *Mars Global Surveyor*	0.15 m^3	26.18 kg	28.74 W	Range: 787 km Resolution: 37.5 cm Accuracy: 100 cm	Large range	High mass; low accuracy; no scanning
OLA *OSIRIS-REx*	270 x 320 x 230 mm (head) 265 x 250 x 142 mm (electronics)	21.4 kg	59 W	Range: 1.2 - 9.0 km Resolution: 1.1 - 2.6 cm Accuracy: 6 - 31 cm	Fine resolution; scanning; long- and short-range modes	High power; range smaller than orbit radius
LIDAR *Clementine*	n/a	2.37 kg	6.8 W	Range: 500 km Resolution: 40 m	Large range; low mass and power	Low resolution
NLR *NEAR - Shoemaker*	374 x 229 x 216 mm	5 kg	16.5 W	Range: 50 km Resolution: 31.48 cm Accuracy: 32 cm	Large range; low mass and power	No scanning



OLA

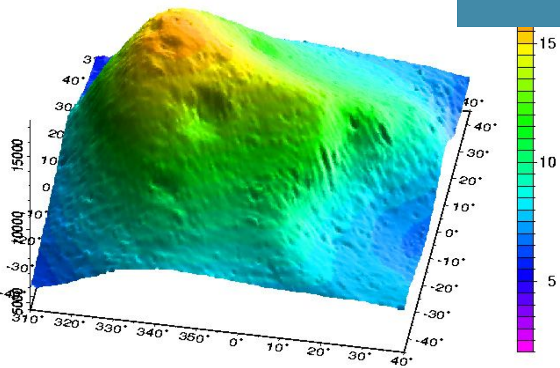
LIDAR

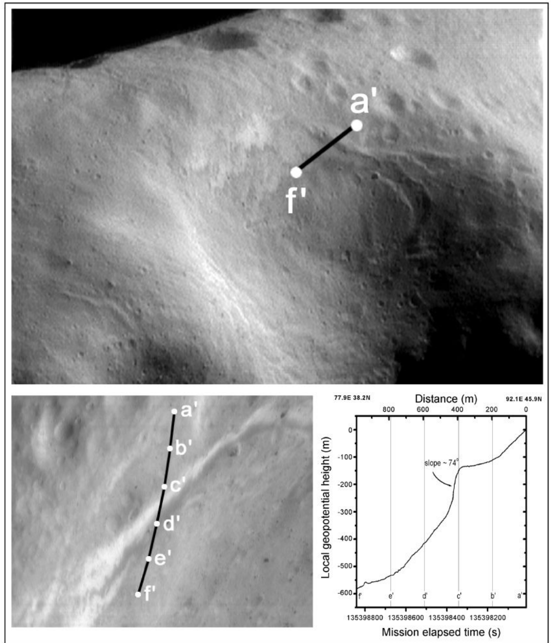
Selected Instrument: NEAR Laser Rangefinder (NLR)

Rationale:

- Low mass and power requirements
- Heritage on an orbiter/lander mission
- Includes in-flight calibration mechanism (optical fiber)
- Specs allow for accurate landing site measurements
  - Maximum range (50 km) > orbit radius (25 km)
  - Relatively high accuracy and resolution

Upper Right: topographical map of asteroid Eros' surface using NLR.
Lower Right: detection of a steep cliff on Eros using NLR.





Camera Suite: WAC + NAC

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Objective: map entire comet in visible light spectrum (WAC), and obtain high-resolution images of landing sites of interest (NAC).

Camera Suite Trade Space							
Suite	Size	Mass	Power	WAC Specs	NAC Specs	Pros	Cons
OSIRIS *Rosetta*	n/a	23.1 kg	32.4 W	Resolution: 101 μrad/px FOV: 11.35 x 12.11° Wavelength: 240-720 nm	Resolution: 18.6 μrad/px FOV: 2.20 x 2.22° Wavelength: 250-1000 nm	Heritage on comet mission; doors to protect from dust	No pivoting
MDIS *Messen-ger*	n/a	7.9 kg	10 W	Resolution: 179 μrad/px FOV: 10.5 x 10.5° Wavelength: 395-1040 nm	Resolution: 25 μrad/px FOV: 1.5 x 1.5° Wavelength: 725-783 nm	1-DOF pivoting; low mass	Monochrome NAC
ISS *Cassini*	95 x 40 x 33 cm (NAC) 55 x 35 x 33 cm (WAC)	57.83 kg	26.2 W (NAC) 19.4 W (WAC)	Resolution: 60 μrad/px FOV: 3.5° x 3.5° Range: 380-1100 nm	Resolution: 6 μrad/px FOV: 0.35° x 0.35° Wavelength: 200-1100 nm	High resolution; proven long-duration use	No pivoting
LROC *LRO*	15.8 x 23.2 x 32.3 cm (WAC) 118 x 27 cm (NAC)	16.4 kg (NACs) 0.9 kg (WAC)	6.4 W (NAC) 2.6 W (WAC)	Resolution: 1500 μrad/px FOV: 91.9° (monochrome), 61.4° (color) Range: 321 - 689 nm	Resolution: 10 μrad/px FOV: 2.85° x 2.85° Wavelength: 400 - 750 nm	Redundant NAC; low power	Low WAC resolution; no pivoting

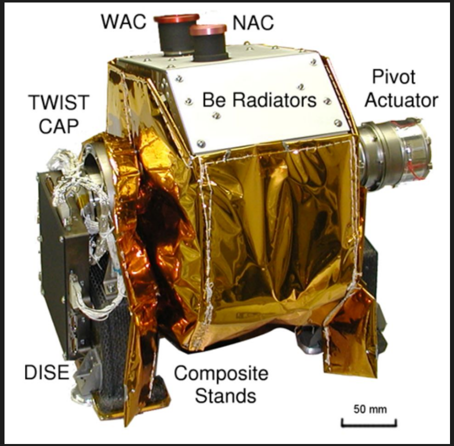
Camera Suite: WAC + NAC

P

Selected Instrument: Mercury Dual Imaging System (MDIS)

Rationale:

- Reasonable mass and power requirements
- Can be rotated independently of spacecraft to ease ADCS requirements
  - Also allows cameras to be rotated inward, acting as a "shielding" mechanism without additional mass
- WAC FOV allows entire comet surface to be imaged from planned orbit radius



Upper Right: MDIS instrument.

Lower Right: craters of Mercury imaged using MDIS NAC.

Camera Suite: Sample Verification Camera

P

Objective: obtain images of comet surface from lander, and images of sample tube to verify that a sample was successfully collected.

Camera Suite Trade Space						
Name	Size	Mass	Power	Specs	Pros	Cons
SamCam *Osiris-Rex*	n/a	0.6 kg	32.2 W	FOV: 20.8º Resolution: 354 µrad/px	Ranged focus (2-30 m); redundant filters in case of damage	Low resolution
Rolis *Philae*	90 x 63 x 86 mm	0.405 kg	2.2 W	FOV: 57.7º Resolution: 980 µrad/px	Designed for imaging in both descent & sampling; low power	Low resolution; only 2 focus options (> 1.4 m, 30 cm).
CacheCam *Perserverance*	74 x 88 x 143 mm	0.397 kg	3.0 W	FOV: 50mm circle Resolution: 12.5 µm/px	High resolution; low mass	Narrow FOV; fixed-focus
MAHLI *Curiosity*	4 cm (camera lens) 22 x 12 x 10 cm (electronics)	2.718 kg	9.0 W	FOV: 38.5º Resolution: 402 µrad/px	Autofocus from 2.1 cm to infinity; includes dust cover	High mass

CacheCam view of sample tube

Camera Suite: Sample Verification Camera

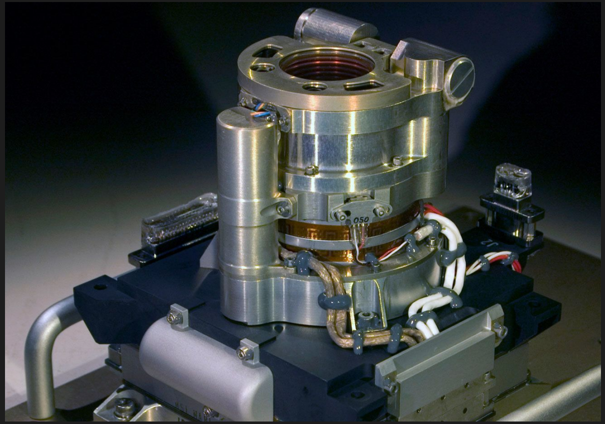
Selected Instrument: Mars Hand Lens Imager (MAHLI)

Rationale:

- Autofocus is useful for lander which cannot directly and immediately communicate with operators on Earth
- Protected from dust and debris
- Reasonable resolution, FOV, and power requirements
- Can be used for high-resolution surface images

Upper Right: MAHLI camera head.

Lower Right: high-resolution MAHLI image of zinc ore sample.



Gamma Ray / Neutron Spectrometer

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Objective: determine chemical composition by detecting gamma rays and neutrons emitted from particles on and slightly beneath the comet surface, including hydrogen (for water detection) and a wide range of other elements (such as O, Mg, Al, Si, Ca, Fe, K, Th, Cl, and U).

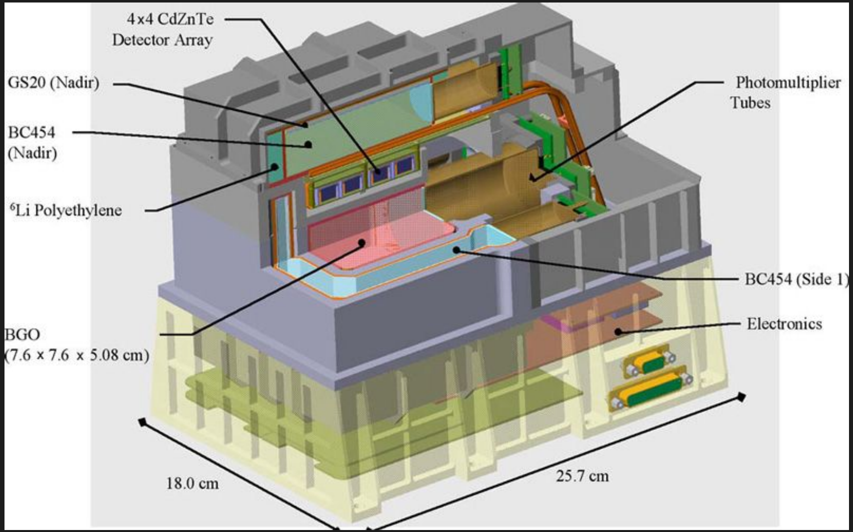
Camera Suite Trade Space						
Name	Size	Mass	Power	Specs	Pros	Cons
GRAND *Dawn*	25.7 x 18.0 x 20.3 cm	9.4 kg	9 W	Range: 0.3 - 10 MeV Resolution: 3% FWHM @ 662 keV Depth: 1 m	High resolution; no boom	High power
GRNS *Messenger*	GRS: 31 cm cylinder NS: 2 x (80 x 6.35 cm) paddle shapes	13.1 kg	4.5 W	Range: 60 keV - 9 MeV Resolution: 8% FWHM @ 662 keV Depth: 10 cm (GR), 40 cm (NS)	No boom	High total volume
GRS & NS *Lunar Prospector*	116.7 x 55.4 cm cylinder	8.6 kg	3 W	Range: 0.3 - 9 MeV Resolution: 10.5% @ 662 keV Depth: 20 cm (GR), 50 cm (NS)	Low mass & power	Low resolution; requires boom
XRS-GS *NEAR*	n/a	26.9 kg	24 W	Range: 0.3 - 10 MeV Resolution: 8.5% @ 662 keV Depth: 10 cm	Includes X-ray spectrometer	No neutron spectrometer; high mass & power

Gamma Ray / Neutron Spectrometer

Selected Instrument: Gamma Ray and Neutron Detector (GRAND)

Rationale:

- Low mass and volume
- Reasonable power requirement
- Highest resolution of selected spectrometers
- Lack of boom simplifies structural design and ADCS requirements



GRaND

Visible-IR Mapping Spectrometer

P

Objective: determine chemical composition, specifically looking for water, organics, and carbon-bearing molecules; provide functional redundancy for camera system.

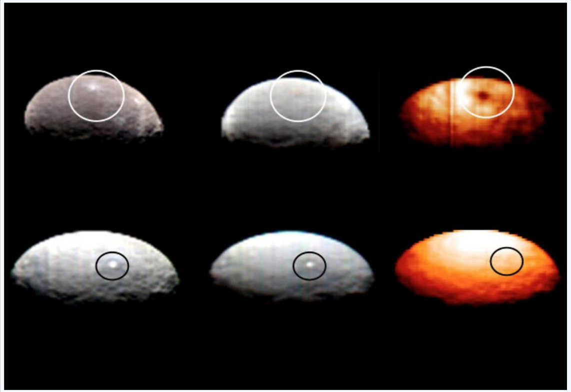
Visible-IR Mapping Spectrometer Trade Space						
Name	Size	Mass	Power	Specs	Pros	Cons
VIRTIS *Rosetta*	-	29.9 kg	38.8 - 41.8 W	Spectral Range: 0.25 - 5 μm Spectral Resolution: 1.89 (M-V), 9.47 (M-IR), 0.6 nm (H) Spatial Resolution: 250 μrad	Separate channels for imaging (M) and high-resolution (H) spectra; VIRTIS-M can rotate about one axis	Low spatial resolution
VIR *Dawn*	-	20 kg	52 W	Spectral Range: 0.25 - 5.0 μm Spectral Resolution: 1.8 nm (V), 9.8 nm (IR) Spatial Resolution: 250 μrad	Offers similar performance to VIRTIS with lower mass; derived from VIRTIS-M (flight heritage)	High power consumption; pointing unconfirmed
MISE *Europa Clipper*	0.63 x 0.74 x 1.1 m	50.4 kg	51.7 W	Spectral Range: 0.8 - 5.0 μm Spectral Resolution: 10 nm Spatial Resolution: 251 μrad	Can rotate about one axis (+/- 30°)	Large mass and volume; no flight heritage
CRISM *MRO*	77.4 x 56.7 x 39.1 cm	32.92 kg	47.3 W	Spectral Range: 0.362 - 3.920 μm Spectral Resolution: 6.55 nm Spatial Resolution: 61.5 μrad	High spatial resolution (useful for scouting landing site); can rotate about one axis (+/- 60°)	Gimbal behavior deteriorates with age; limited IR range

Visible-IR Mapping Spectrometer

Selected Instrument: Visible and Infrared Mapping Spectrometer (VIR)

Rationale:

- Offers mapping capabilities of similar spectrometers with reduced mass
- Extensive flight heritage (Rosetta and Dawn)
- Sufficient spectral range to discern materials of interest, including minerals expected to be on a comet as well as water and organics



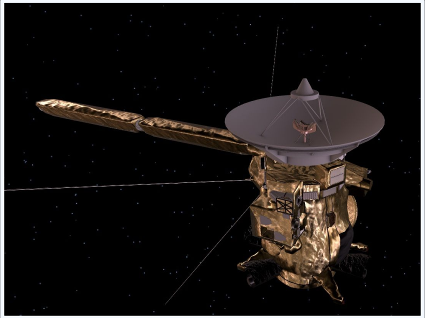
Upper Right: VIR optical head
Lower Right: VIR images of Ceres in visible, IR, and thermal IR

Magnetometer

P

Objective: map magnetic field strength of Comet 46P through a range of altitudes as lander descends.

Magnetometer Trade Space						
Name	Size	Mass	Power	Specs	Pros	Cons
ROMAP *Rosetta*	Boom: 0.60 m	No boom: 850 g With boom: 930 g	0.9 W	Range: +/- 2000 nT Resolution: 0.010 nT Noise: 0.005 nT / $Hz^{1/2}$	Includes plasma monitor to characterize solar wind; low power	Small range
MAG *Messen-ger*	Boom: 3.6 m	No boom: 1.43 kg With boom: 4.09 kg	4.2 W	Range: +/- 1530 nT Resolution: 0.047 nT Noise: 0.020 nT / $Hz^{1/2}$	Redundant sampling channels in electronics	Small range; high mass
FGM *Cassini*	Boom: 11 m (moun-ted halfway)	No boom: 440 g With boom: 3 kg	3.1 W	Range: +/- 40 to 44,000 nT Resolution: 4.9 to 5400 nT Noise: 0.005 nT / $Hz^{1/2}$	Large range; redundant power supplies and processing systems	Low resolution; long boom
MAG *Psyche*	Boom: 2.15 m	2x 896 g	2x 2.2 W	Range: +/- 80,000nT Resolution: 0.012 nT Noise: 0.030 nT / $Hz^{1/2}$	Large range; 2 sensors for redundancy + reduced noise	Has not flown (but has heritage from another mission)



Cassini with magnetometer boom

Magnetometer

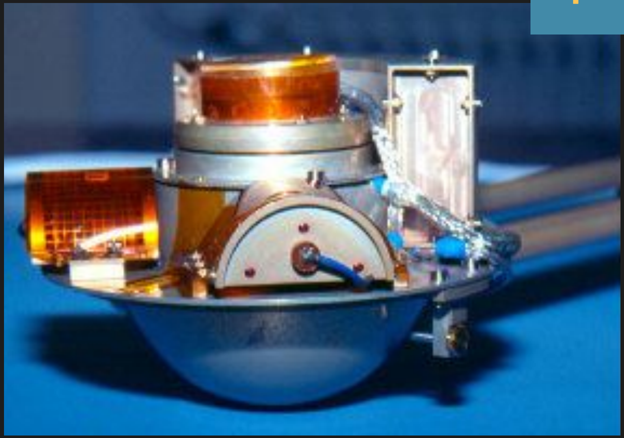
Selected Instrument: Rosetta Magnetometer and Plasmamonitor (ROMAP)

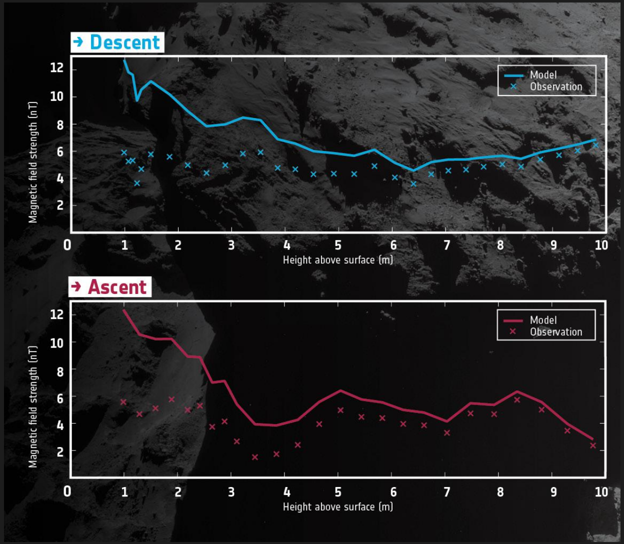
Rationale:

- Enables extended science (plasma characterization)
- Small range is sufficient for expected comet magnetic field based on previous missions
- Low mass and power requirement
- Heritage on comet lander

Upper Right: ROMAP instrument

Lower Right: Rosetta measurements showing a weaker magnetic field than model predictions at comet surface.





Seismometer

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Objective: listen for seismic events (such as from thermal stress or impacts) and study comet mechanical properties and internal structure on the surface.

Seismometer Trade Space						
Name	Size	Mass	Power	Specs	Pros	Cons
SEIS *InSight*	42 cm radius	29.5 kg	8.5 W	Range: 0.01 - 50 Hz	Includes wind & thermal shield; includes pressure & wind sensors	Must be deployed away from s/c
CASSE *Rosetta*	101 mm diameter	550 g	1.25 W	Range: < 100 Hz (seismic) 100 Hz - 10 kHz (acoustic sounding)	Attached to feet of lander; passive & active modes to evaluate material properties	Relies on lander thermal control
PSE *Apollo 16*	Housing: 23 x 29 cm cylinder Thermal shroud (deployed): 75 cm radius	11.5 kg	7.1 W	Range: 0.004 - 20 Hz	Includes thermal shield; extensive heritage from previous moon missions	Noise with temperature fluctuations; must be deployed away from s/c

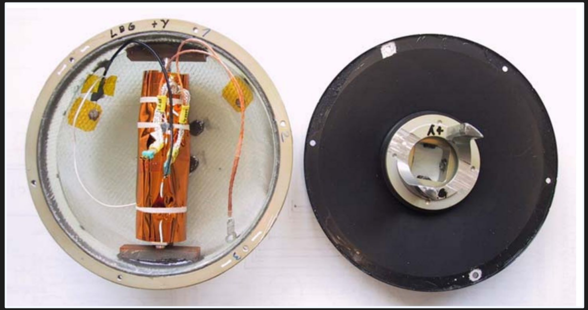
SEIS

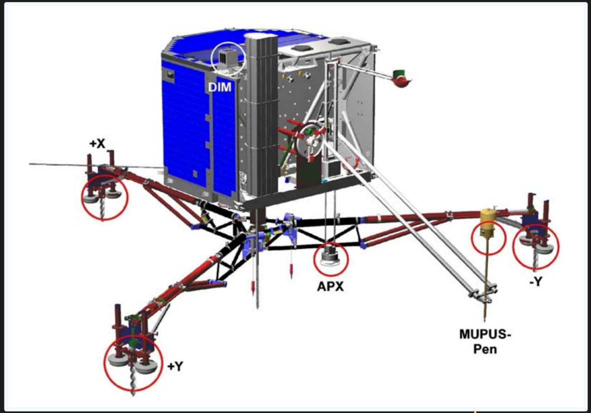
Seismometer

Selected Instrument: Cometary Acoustic Surface Sounding Experiment (CASSE)

Rationale:

- Heritage on comet mission
- Compact, lightweight design built into lander reduces mass, volume and complexity
- Low power requirement
- "Active" sounding mode allows detection of layers and material properties (E and ν)





Upper Right: CASSE transmitter sole (left) and cover (right)
Lower Right: Philae lander (CASSE on feet)

Science Operations: General Timeline

Spacecraft	ORBITER			LANDER	
Mission Phase	Approach	Sample Site ID	Additional Science	Descent	Surface
Gravity Science					
LIDAR					
WAC					
NAC					
GRNS					
VIMS					
Magnetometer					
Seismometer					
Sample Camera					

Science Operations: Landing Site Selection

Step	Purpose	Instrument
1	Low-resolution imaging of entire surface to identify safe landing sites based on lighting and visual inspection of topography.	WAC
2	Imaging of entire surface using mapping spectrometer to determine distribution of chemical composition to identify scientifically interesting sample sites.	VIMS
GROUND OPS: SELECT A FIRST BATCH OF LANDING SITES (~10)		
3	High-resolution imaging of selected landing sites for additional inspection of lighting and topography.	NAC
4	Ranging to landing sites using LIDAR for high-resolution topography information (crevasses, boulders, inclination, etc).	LIDAR
5	Refine chemical composition measurements using both spectrometers.	GRNS VIMS
GROUND OPS: NARROW TO FINAL BATCH OF LANDING SITES (~3-5)		
6	Additional high-resolution imaging of selected landing sites with NAC for additional inspection of lighting and topography at different times and camera angles.	NAC
GROUND OPS: SELECT FINAL LANDING SITE		

Science Operations: In-Flight Calibration Plan

In addition to ground calibrations, it is useful to calibrate science instruments in-flight in case performance changes over the mission duration or due to the space environment (such as low gravity or radiation).

MAHLI onboard calibration target.

Instrument	Calibration Plan
Gravity Science	In tandem with telecommunications calibration.
LIDAR	Periodically calibrate in-flight using an onboard spool of optical fiber of known length.
WAC + NAC	Image known stars during cruise to determine changes in camera parameters such as focal length, distortion coefficients, and responsivity.
Sample Cam	Periodically turn on during cruise for health check; image onboard calibration target.
GRNS	Turn on periodically during cruise to verify that instrument is alive and measure background noise (such as cosmic rays and s/c itself).
VIMS	Periodically image known light sources onboard s/c to verify life and performance over time.
Magnetometer	Conduct calibration maneuvers during cruise to characterize magnetic field induced by s/c.
Seismometer	Measure vibrations in cruise induced by other lander actuators during checkouts.

Sample Collection

P

Trade Study of Plausible Sampling Options

Method	Application	Sample collected	Pros	Cons
Standard Dry Drilling	Planned for future mission at scale	All material types	• Relatively simple • Commonly used and reliable	• Contamination from other layers • Slight thermal generation • **Mechanically Alterations to Sample**
Standard Dry Coring	Use on current missions at smaller scale	Most material types, not usually loose grains	• Relatively simple • Preserves structure of sample	• Slight thermal generation • Has to be broken off to collect sample
Thermal Coring	On Earth	Ice	• Easier than standard dry coring	• More energy intensive than standard dry coring • Has to be broken off to collect sample • **Thermal Alterations to Sample**
Chainsaw "Coring"	On Earth	Ice/Soil	• Preserves structure of sample	• Contamination from other layers • Decent thermal generation • Need separate structure to remove sample from ground
Jackhammer Insertion	On Earth	Soil	• Relatively simple • Preserves structure of sample	• Major vibrational impact on spacecraft • May affect structure of sample but not mechanically
Ram Insertion	On Earth	Soil	• Relatively simple • Little to none mechanical parts	• Requires spacecraft to travel at high speeds towards ground • High risk of failure to mission • High unpredictability of collision behavior
Lazar coring	On Earth/Experimental	Ceramics/Metals	• Minimize vibrational impacts • Minimize physical mechanical points of failure • Could take advantage of sublimation properties	• Major energy use • Need separate structure to remove sample from ground • **Thermal Alterations to Sample**

Combining Methods

Standard Dry Drilling

TRIDENT Drill

- Currently in preparation for the **PRIME1** and **VIPER** missions
- Is designed to drill to 1m in depth
- Digs in 10 cm increments to reduce heat generation/power consumption
- Has additional included instruments to measure ejected material

Standard Dry Coring

Perseverance Rover

- Actively collecting core samples from rocks
- Uses a coring drill to collect rock samples
- Samples are broken off after collection and transported to within the rover

*Both were developed by or with Honeybee Robotics

Note: Other drills used in space were either too old to be relevant for this application or too small, severely limiting heritage options

Sample Drill Bit Specifications

External Diameter: 60 mm

Perseverance Drill: 27 mm

TRIDENT Drill: 25.4 mm

Sample Internal Volume: 170 cc

Perseverance Drill: 2.7885 cc

Sample Internal Diameter: 38 mm

Perseverance Drill: 13 mm

Sample Internal Length: 155 mm

Perseverance Drill: 66mm

Length: 20 cm

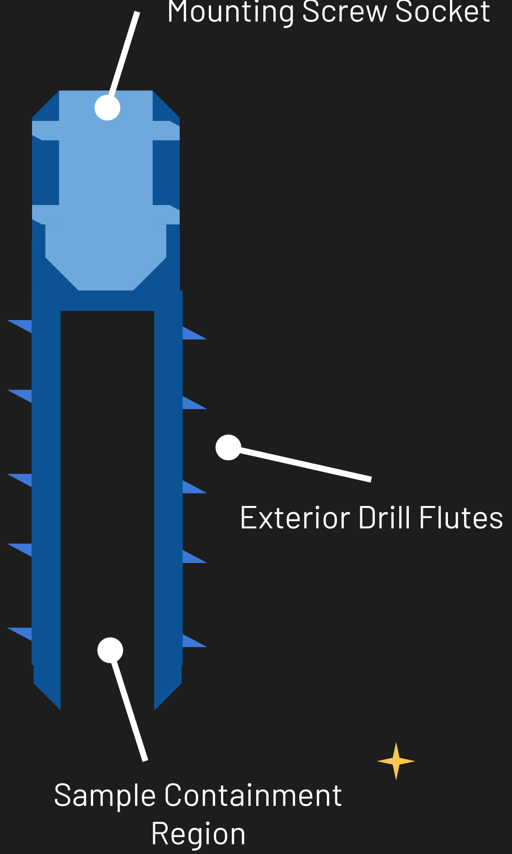
Cutting Material: Carbide

Number of Bits: 8

3 for Surface Samples

3 for 1m Deep Samples

2 for Redundancy



Sample Drill Bit Volume Trade Space

Method	# of Holes	Sample Diameter (mm)	Sample Length (mm)	Sample Volume (cc)
Perseverance Drill	1	13	66	2.79
	180	13	66	502.2
Perseverance Drill Size w/ needed Diameter (fixed Length)	1	**98.21**	66	500
	2	**69.45**	66	500
	3	**56.70**	66	500
Perseverance Drill Size w/ needed Length (fixed Diameter)	1	13	**3766.98**	500
	2	13	**1883.49**	500
	3	13	**1255.66**	500

Sample Drill Bit Volume Trade Space pt2

Method	# of Holes	Sample Diameter (mm)	Sample Length (mm)	Sample Volume (cc)
Perseverance Drill Size Scaled x2	1	26	132	70.08
	8	26	132	560.66
Perseverance Drill Size Scaled x2.5	1	32.5	165	136.88
	4	32.5	165	547.52
Custom 1	3	30	230	500.46
Custom 2	3	42.1	120	501.14
Custom 3	3	38	155	527.36

Sample Collection Collective Specifications

Volume: 0.140 m^3

TRIDENT Drill: 0.115 m^3

- Expected estimated increase comes from addition of sample drill bit retrieval system

Mass: 35 kg

TRIDENT Drill: 25.4 kg

- Expected estimated increase comes from addition of sample drill bit retrieval system and drill size

Power: 250 W (Average)

TRIDENT Drill: 87W (Average)

- Expected power usage was scaled by diameter Increase of the drill to account for increase in torque needed

Note: May need to be scaled quadratically instead of linearly to match increase in surface area

Drill Diameter: 6 cm

TRIDENT Drill: 2.54 cm

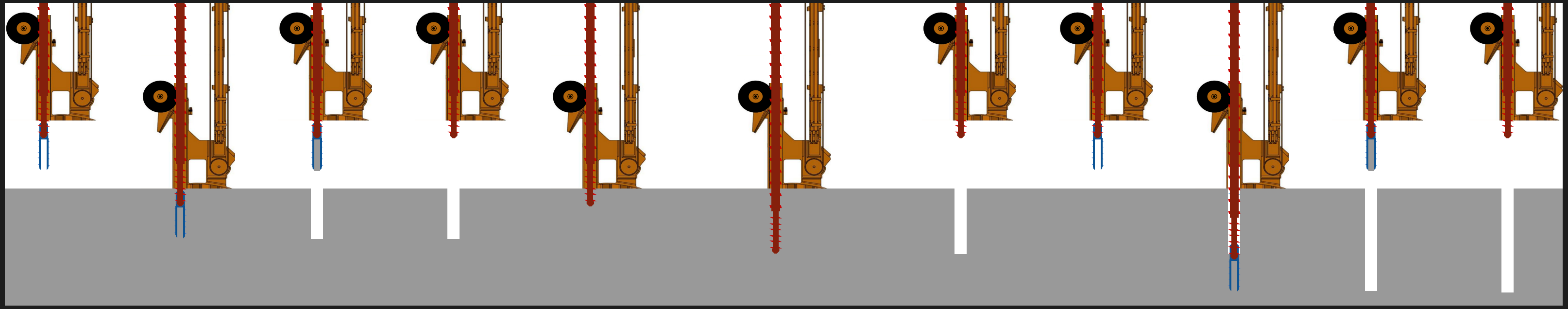
- Accounts to match increase in sample drill bit diameter as well as provides additional drill strength

Drill Length: 1.20 m

TRIDENT Drill: 1.02 m

- Slight increase to help account for off nominal alignment of the lander with the ground if needed

Method of Drilling Holes



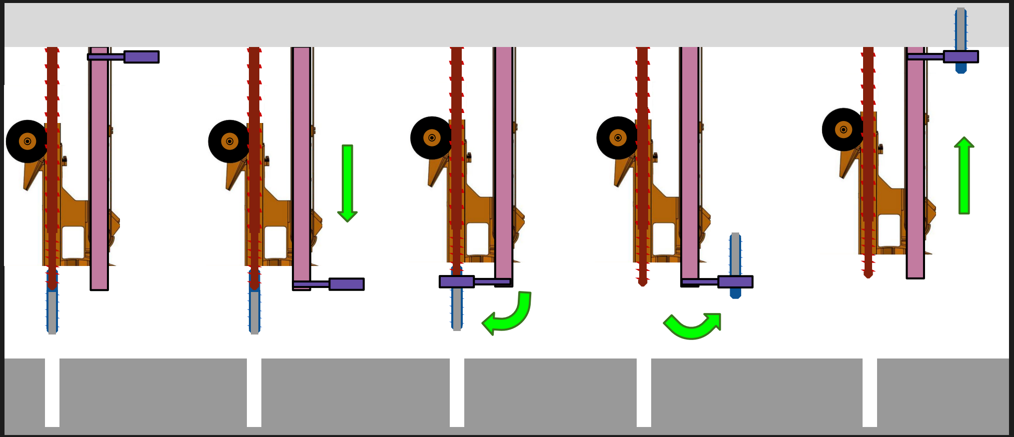
Surface Sample

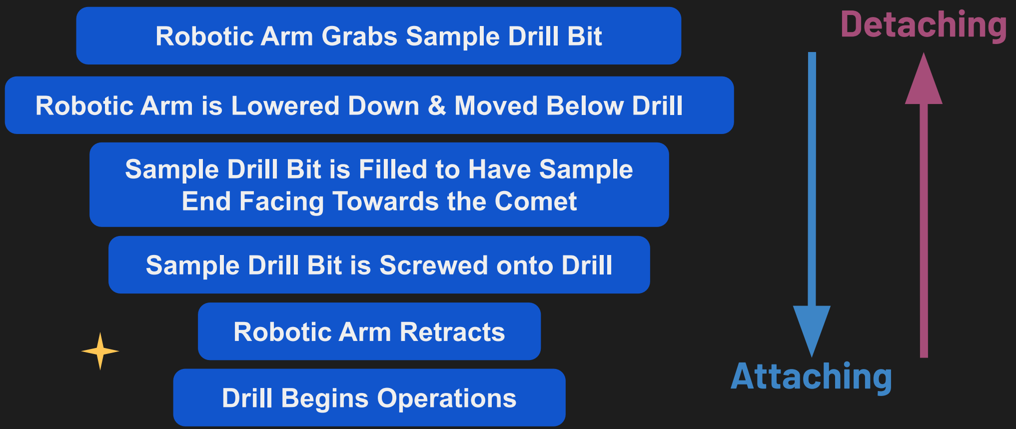
- Sample Drill Bit Attached by Robotic Arm
- Drills Down to Collect Sample
- Retracted Back to the Surface
- Drill Bit Exterior is Cleaned off by Brushes
- Sample Drill Bit Detached by Robotic Arm and Stored Away

1m Deep Sample

- Main Drill Bores 10 cm
- Retracted Back to the Surface and Cleaned by Brushes
- Repeat 10 Times

Sample Drill Bit Attachment





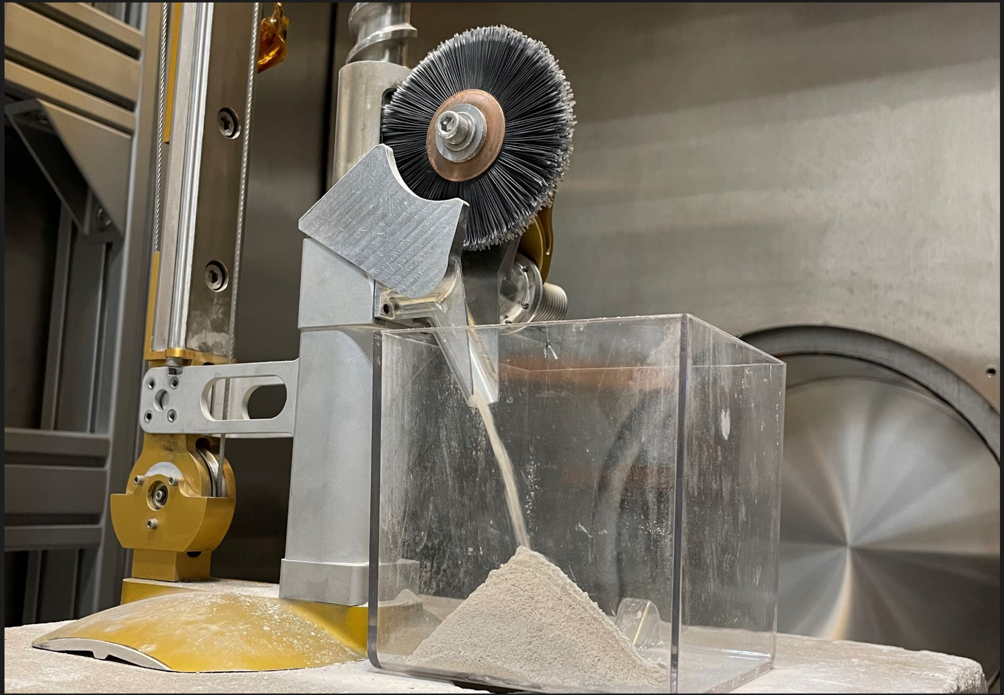
The robotic arm's vertical actuator and motors can be copied from the TRIDENT Drills existing versions, reducing complexity and simplifying manufacturing

Other Benefits of the TRIDENT Drill

Sensors are installed to find:

- Regolith Strength
    - Uses penetration rate and power consumption
- Thermal Conductivity
    - Uses heater and thermal sensor to measure downhole temp

The drill is designed to operate at sample temperatures as low as 100K, ideal for the cryogenic conditions needed



Advantages and Shortcomings

Advantages

- Heritage missions
- Samples several location
- Redundancy for collection drill lost
- Redundancy for sample size variation
- Reasonable samples sizes for handling
- Accounts for the off nominal lander orientation

Shortcomings

- Crucial elements must be modified
- Failure of mission if drill or robotic arm fails
- Can't gather all needed samples in one drilling session
- Particulate interference potentially with sample drill bit attaches
- Reverification of systems needed
- Sample drill bit attachment method has never been tried in space

Ground Ops / Telerobotics / EDL

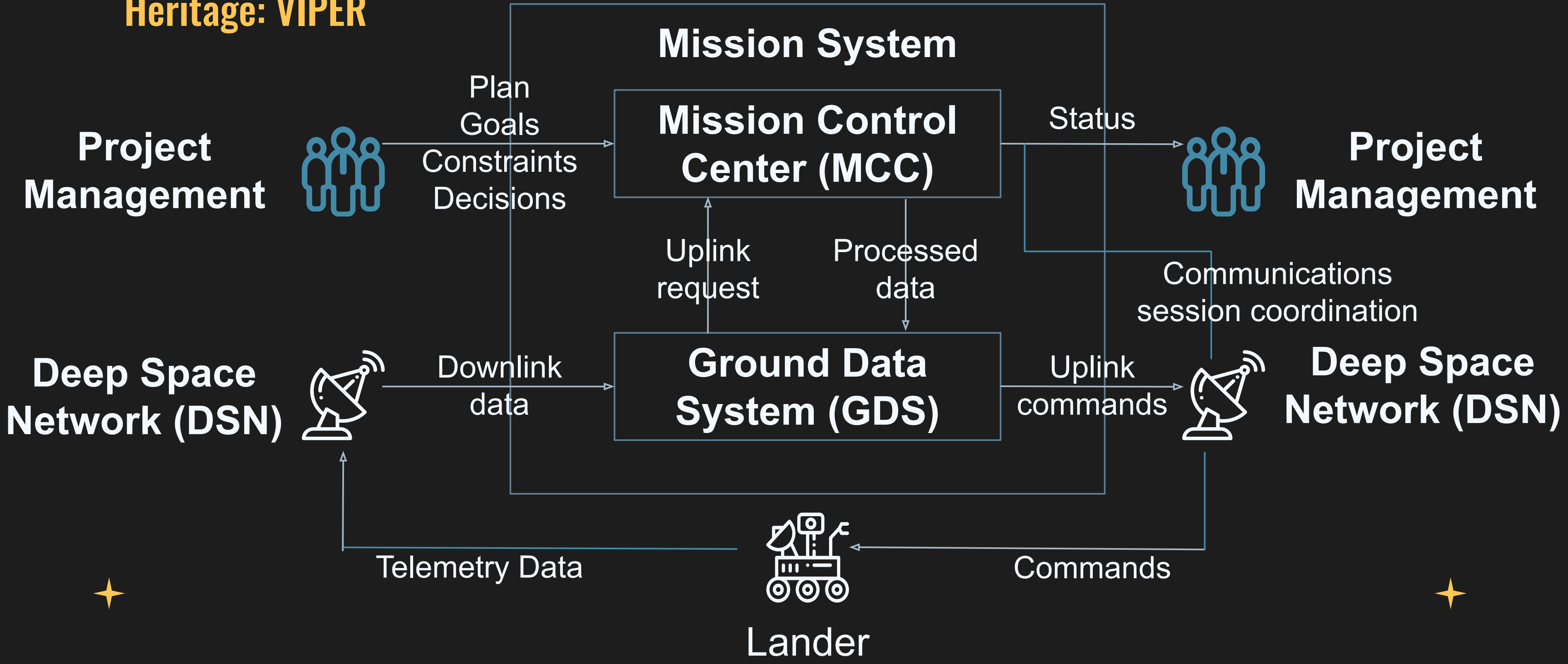
Overview, Rationale, Trade Studies

Ground Operations Overview

	COW-1	Heritage
Ground-based Communication Network	Deep Space Network (DSN)	Rosetta Stardust Hayabusa2 OSIRIS-REx
Communication Bands	S-band & X-band (for communication with spacecraft)	
Antenna Style	Parabolic dish & High Gain	

Ground System Architecture

Heritage: VIPER



Ground Operations Data Budgets

Assumptions:

- Mission Durations: ~ 7 years
- Data Rates: 1Mbps
- Mission Operations: 8 hours/day
- Contact Time: 4 hours/day

Data Budgets:

Daily Data Volume: 4,000 megabits (500 megabytes)

Annual Data Volume: 182,500 megabytes (182.5 gigabytes)

Software for Landing Site Selection

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Software Selection					
Type	Description	Software	Pros	Cons	Heritage
Geographic Information Systems (GIS)	- Gives various geospatial data layers - Identifies potential landing sites based on geological features	**ArcGIS (Esri)**	- Robust data integration capabilities - Interactive maps and 3D visualization	- Hard to learn - Time consuming	Curiosity
		QGIS (Quantum GIS)	- Open source & user friendly interface - Frequent update - Cross-platform compatibility	- Smaller ecosystem of plugins and extensions - Less comprehensive documentation	Specific missions were not be directly attributed to QGIS
Remote Sensing Image Analysis Software	- Gives remote sensing data, including images - Identifies potential landing sites based on surface features (composition, morphology, etc.)	**ENVI**	- Integration with GIS for spatial analysis and visualization - Wide range of sensor data	- Hard to learn - High hardware requirements and memory usage	Terra Aqua
		MultiSpec	- Multiple image formats and spectral data analysis - Free and open-source - User-friendly interface	- Limited advanced analysis tools - Compatibility issues with some image formats	Specific missions were not be directly attributed to MultiSpec

Software for Landing Site Selection

P

Software Selection (Continued)					
Type	Description	Software	Pros	Cons	Heritage
Simulation and Modeling Software	- SimulateS the trajectory and dynamics of the orbiter and lander - Identifies potential landing sites based on landing constraints, navigation, and terrain characteristics	**Systems Tool Kit (STK)**	- Integration of various data sources - Extensive library of pre-built models and scenarios for space missions	- Hard to learn - High hardware requirements and memory usage	- Mars Exploration Rovers (MER) - Lunar Reconnaissance Orbiter (LRO)
		SPICE (Spacecraft Planet Instrument C-matrix Events)	- Standardized framework for handling and accessing mission geometry and instrument calibration data - Precise time and space coordinate calculations - Interoperability with various software tools and mission planning systems	- Hard to learn - Limited visualization and analysis capabilities	- Mars rovers (Spirit, Opportunity, Curiosity) - Voyager - Cassini

Systems Tool Kit (STK): Landing site selection

SPICE: Landing site targeting

- Precise navigation and geometric calculations

Software for Landing Site Selection

P

Software Selection (Continued)					
Type	Description	Software	Pros	Cons	Heritage
Data Visualization and Collaboration Tools	- Enables collaboration and decision-making among ground operators	**OpenMCT**	- Integration of diverse data sources and formats. - Interactive interface - Real-time data sharing among team members	- Requires development and customization based on specific mission requirements - Relies on the availability of data feeds and interfaces for integration	Curiosity VIPER
		Worldview	- Web-based tool for visualizing and exploring Earth science data. - Access to a wide range of NASA satellite imagery and datasets - Interactive tools for data exploration and analysis - Real-time data updates and overlays of multiple datasets	- Primarily focused on Earth science data and may not be directly applicable to all space missions - Limited customization options	Terra Aqua Suomi NPP

Capsule Subsystem Overview

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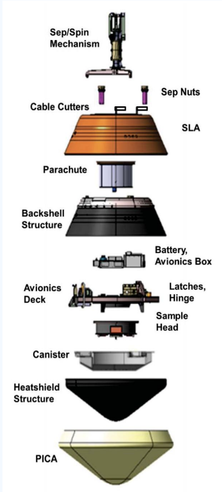
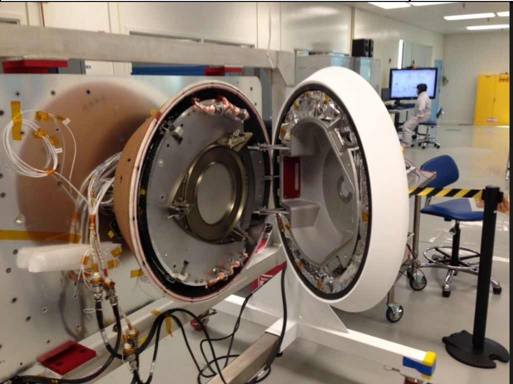
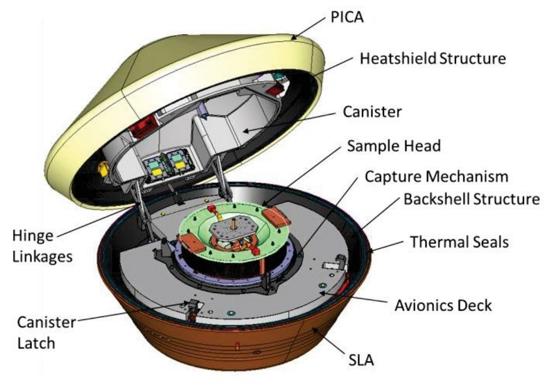
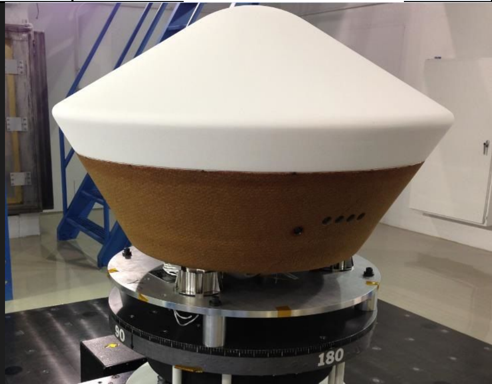
Subsystem	Description	Heritage
Sample container	holds the collected samples from the comet's surface, providing protection and isolation during the return journey to Earth	OSIRIS-REx
Battery & Electronic and Sensors housing	houses the necessary electronics, sensors, and power supply, including batteries, that enable the operation and control of various functions within the sample return capsule, such as temperature monitoring, telemetry, and command execution	
Heat shields	shields the sample return capsule from the intense heat generated during re-entry into Earth's atmosphere, ensuring the samples remain intact and safe during the high-speed descent	
Parachutes	slows down the descent of the sample return capsule after re-entry	
Landing mechanisms	landing legs or other mechanisms designed to absorb the impact forces upon landing	
Drill (sample collection)	extracts samples from the comet's surface by drilling into the desired location	

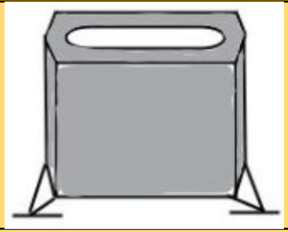
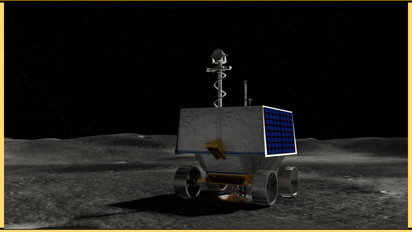
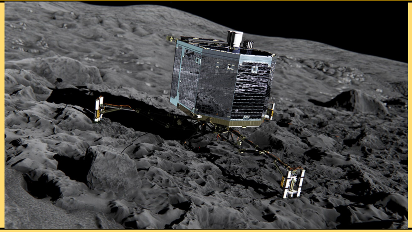








Lander Operations: Overview

Lander Operations Approach Overview			
			
	COW-1 Lander	**VIPER**	**Philae**
Comms	**Intermittent**	Continuous	Intermittent
Environment	**Unstructured**	Unstructured	Unstructured
Approach	**Command sequences**	Waypoint commands	Command sequences

Lander Operations: Selections & Rationales

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Communications Selection: Intermittent

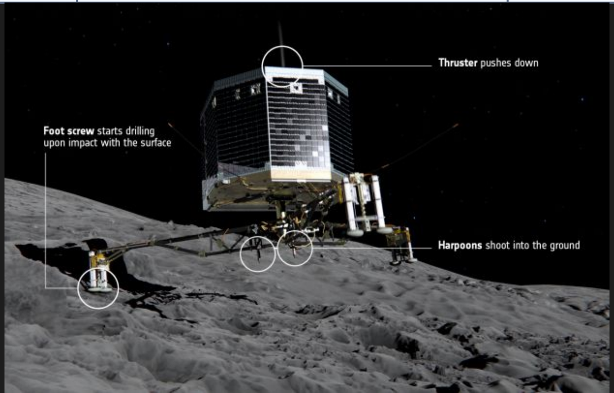
- Allows for more flexibility in managing resources
- Reduces the dependency on continuous communication
- Conserves power and data transmission resources
- Can store data locally and transmit it to the orbiter when communication is reestablished

Approach Selection: Command sequences

- Allows the lander to perform tasks according to a predefined sequence without requiring real-time input from the orbiter
- Reduces the need for constant communication between the orbiter and the lander
- Enables the lander to perform complex operations efficiently and reliably
- Can execute its tasks without waiting for specific instructions from the orbiter
- Can be designed and tested on Earth before the mission

Landing Mechanisms

Landing Mechanisms Trade Space				
Type	Concept	Pros	Cons	Heritage
Legs	Provide stability and absorb the impact of landing	- Simple - Reliable	Add weight and complexity to the lander design	Sojourner Spirit Opportunity Curiosity
Harpoons	Penetrate the surface upon landing, securing it in place	Reliable and robust method for anchoring the lander to the surface, even in challenging terrains	Require careful design and control to ensure successful deployment and avoid potential damage to the lander or the surface	Philae



Landing Mechanisms: Selection & Rationales

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Landing Mechanism Selection: Legs

- Stable and reliable landing mechanism
- Can absorb the impact and provide cushioning during landing, ensuring a soft touchdown
- Allow for adjustable height
  - Accommodate uneven terrain → flexibility of landing site
- Heritage: Apollo lunar landers, Mars Rovers (Curiosity, Spirit, Opportunity)
- Stable during drilling operations
  - Reduce risk of the lander toppling over & Ensure successful sample collection

Why not choosing Harpoons?

- Additional complexibility
  - Increase the risk of malfunctions or failures

Entry, Descent, Landing Overview

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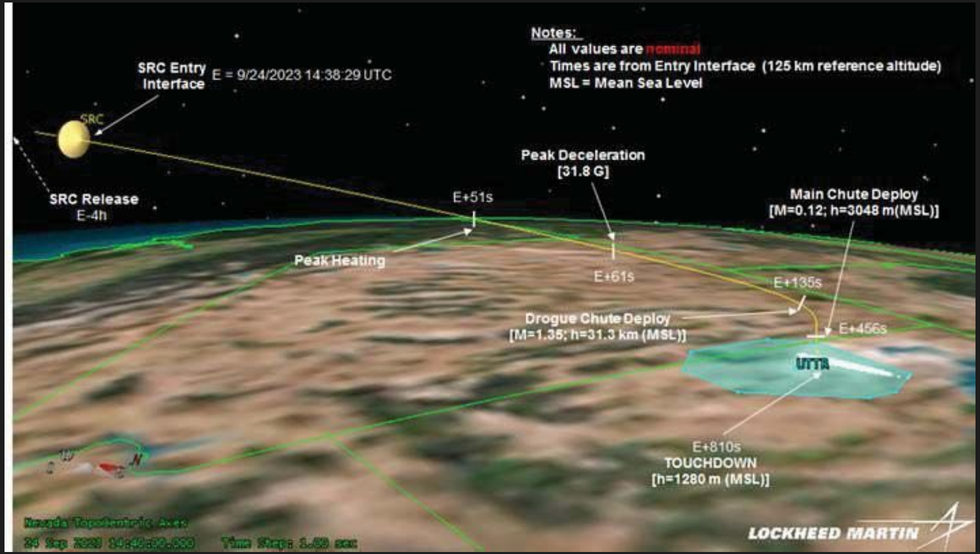
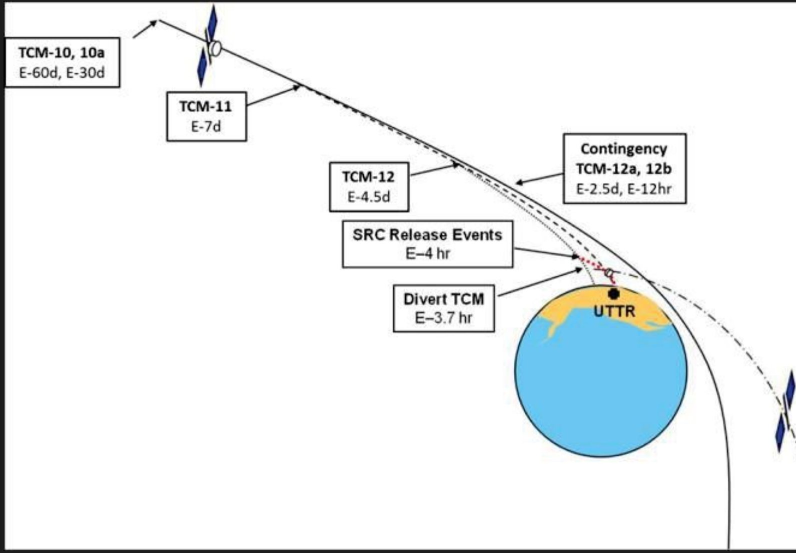
Entry, Descent, Landing (EDL) Overview			
	Entry Type	**Descent / Landing Type**	**Heritage**
Earth	Ballistic	Parachute	OSIRIS-REx
Comet	Orbiter drops lander to surface	Rely on comet gravity and landing mechanisms	Rosetta



OSIRIS-REx Landing Profile



OSIRIS-REx Return Trajectory

Earth EDL Selection & Rationales

Angle of Entry: 5 ~ 10 degrees

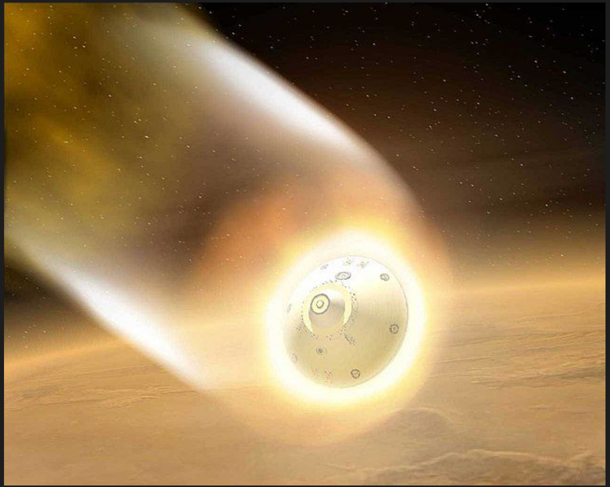
- balance the trade-off between managing re-entry forces and achieving a feasible landing location

Survival Speed: 12.4 km/s (27,700 miles/hour)

Entry Type: Ballistic

Descent / Landing Type: Parachute

- Safe sample recovery
- Sample integrity
- Reliability: OSIRIS-REx heritage
- Sample preservation
- Precision landing
- Simple landing system → Reduce complexity, mass, and cost



Comet EDL Selection & Rationales

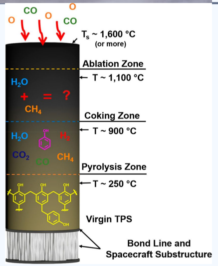
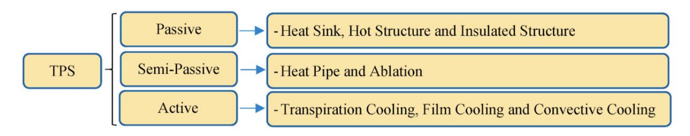
Heritage: Rosetta

Entry Type: Orbiter drops lander to surface

Descent / Landing Type: Rely on comet gravity and landing mechanisms

- Low fuel consumption
- Low risk of damage
    - Handle rough surface conditions
- Protect science instruments
    - Low vibrations & disturbances

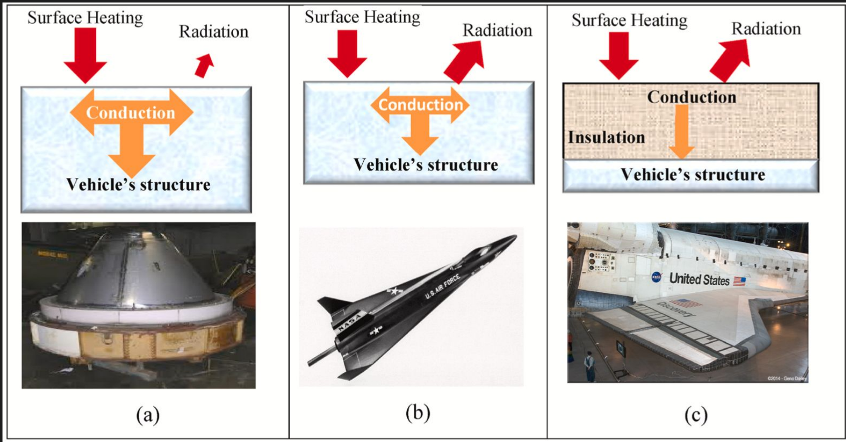
Heat Shields

Heat Shields Trade Space				
Type	Concept	Pros	Cons	Heritage
Ablative	Gradually burn away and dissipate the heat generated during re-entry through sacrificial material layers	- Effective at high-temperature protection - Can handle high-speed re-entry	- Needs to be replaced after each use - Complex - Expensive	Apollo 
Ablative: Phenolic Impregnated Carbon Ablator (PICA)	Lightweight and heat-resistant material that ablates and dissipates heat	- Excellent thermal protection - Lightweight - Enhanced reusability compared to traditional ablative materials	- Requires careful manufacturing and inspection processes	Stardust 
Thermal Protection System (TPS)	Combination of insulating materials and heat-resistant tiles	- Excellent thermal protection - Reusable - Flexible design and application	- Heavy - Complex	SpaceX Dragon 

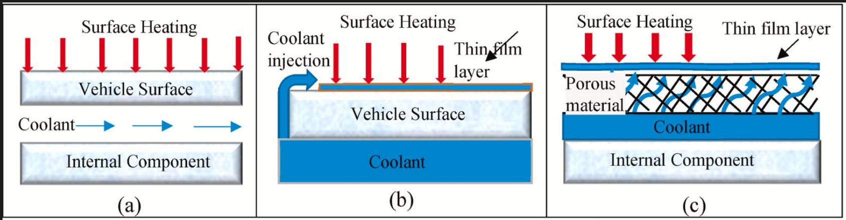
Heat Shields: Selection & Rationales

Heat Shields Selection: Thermal Protection System (TPS)

- Reusability
  - Cost saving
  - Sustainability
- Heritage proved reliability & effectiveness
- Flexibility
  - Customize according to specific mission requirements and spacecraft configuration
- Effective thermal protection



Schematic of passive TPS methods: (a) Heat sink (b) Hot structure (c) Insulated Surface



Schematic of active TPS methods: (a) convective cooling, (b) film cooling and (c) transpiration cooling

Overall Mission

Requirements Fulfilled: Orbiter

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	Minimum Requirement	Extended Requirement	Science Questions
Phase 1 - Rendezvous and Reconnaissance			
R1	The S/C should rendezvous near aphelion	N/A	S1, S2, S3, S4
R2	The S/C should maintain an orbit (altitude wrt comet) within 60 km of the comet to obtain an accurate mass estimate when the comet is near aphelion	Mass estimate of the comet shall be determined after sublimation to determine difference in physical composition	S3
R3	The entire surface of the comet must be mapped in the visible light spectrum using a wide-angle camera on approach, and volume estimate should be obtained	Entire surface of the comet shall be mapped after sublimation to determine difference in physical composition	S1, S2, S3, S4
R4	High-resolution imaging of landing sites of interest on the comet using a narrow-angle camera shall be performed to provide several options for a safe and scientifically valuable landing site	High-res imaging of the entire surface	S1,S2, S3, S4
Phase 2 - Surface Analysis & Sample Collection			
R5	Surface chemical composition at the landing site(s) must be determined in situ	N/A	S4
R6	At least one surface sample (minimum 500 cc) shall be obtained from comet 46P	N/A	S2, S3, S4
R7	At least one subsurface sample (minimum volume: 500 cc, minimum depth of sample: 10 cm) shall be obtained from a depth of 1 meter or below from comet 46P	N/A	S1, S2, S3, S4
R8	Surface and sub-surface samples shall not be mechanically or thermally altered by the extraction and storing process (stratigraphy should be maintained for sub-surface samples)	N/A	S1,S2, S3, S4
R9	S/C or Lander shall measure the magnetic field through the altitude ranges 0m - 10m (with accuracy of +/-.5m) with an accuracy of +/- .010 nT at a single location	S/C shall measure Plasma characteristics (values and parameters TBD) Must be sublimating.	S1
Phase 3 - Sample Return			
R10	The samples shall be preserved cryogenically at the same relative temperature and shall stay within approximately +/- 5K	N/A	S1, S2, S3, S4

Requirements Fulfilled: Lander

P

	Minimum Requirement	Extended Requirement	Science Questions
Phase 1 - Rendezvous and Reconnaissance			
R1	The S/C should rendezvous near aphelion	N/A	S1, S2, S3, S4
R2	The S/C should maintain an orbit (altitude wrt comet) within 60 km of the comet to obtain an accurate mass estimate when the comet is near aphelion	Mass estimate of the comet shall be determined after sublimation to determine difference in physical composition	S3
R3	The entire surface of the comet must be mapped in the visible light spectrum using a wide-angle camera on approach, and volume estimate should be obtained	Entire surface of the comet shall be mapped after sublimation to determine difference in physical composition	S1, S2, S3, S4
R4	High-resolution imaging of landing sites of interest on the comet using a narrow-angle camera shall be performed to provide several options for a safe and scientifically valuable landing site	High-res imaging of the entire surface	S1,S2, S3, S4
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R8	Surface and sub-surface samples shall not be mechanically or thermally altered by the extraction and storing process (stratigraphy should be maintained for sub-surface samples)	N/A	S1,S2, S3, S4
R9	S/C or Lander shall measure the magnetic field through the altitude ranges 0m - 10m (with accuracy of +/-.5m) with an accuracy of +/- .010 nT at a single location	S/C shall measure Plasma characteristics (values and parameters TBD) Must be sublimating.	S1
Phase 3 - Sample Return			
R10	The samples shall be preserved cryogenically at the same relative temperature and shall stay within approximately +/- 5K	N/A	S1, S2, S3, S4

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Volume Budget

	Orbiter	Lander	Sample Return Capsule	Total
ADCS	0.02711 m^3	1.000038406 m^3	0.00181 m^3	1.0273 m^3
Comms	3.817 m^3	0.000216 m^3	0.00021 m^3	3.817426 m^3
Structure	48 m ^3	51.9 m^3	3.14 m ^3	103.04 m^3
Science	0.53 m^3	0.10 m^3	-	0.63 m^3
Power Systems	7.2 m^3	1.73 m^3	1.05m^3	9.98m^3
Sample Mechanisms	-	0.140 m^3	-	0.140 m^3
Propulsion	1.55 m^3	0.46 m^3	0.14 m^3	2.15 m^3
Total	61.12411 m^3	55.33025 m^3	4.33202 m^3	120.78638 m^3
Falcon Heavy Fairing Volume				207 m^3
Margin [% free]				41.65%

Mass Budget

	Orbiter	Lander	Sample Return Capsule	Total
ADCS	26.28 kg	.3222 kg	1.5 kg	28.1022 kg
Comms	46.38 kg	0.25 kg	0.1345 kg	46.7645 kg
Structure	610 kg	475.7 kg	45.7 kg	1131.4 kg
Science	42.3 kg	4.2 kg	0 kg	46.5 kg
Power Systems	98.8 kg	10.06 kg	1 kg	109.86 kg
Sample Mechanisms	-	35 kg	-	35 kg
Propulsion	1804.3 kg	0.68 kg	0.438 kg	1805.418 kg
Total	2628.06 kg	526.2122 kg	48.7725 kg	3203.0447 kg
Allowable				3500 - 10,000 kg
Margin [% free]				8.48 - 67.97%

Power Budget

	Orbiter	Lander	Sample Return Capsule	Total
ADCS	87 W	6.335 W	27 W	120.335 W
Comms	28.5 W	10 W	12.25 W	50.75 W
Structure	-	-	-	-
Science	87.5 W	11.15 W	-	98.65 W
Sample Mechanisms	-	250 W (AVG)	-	250 W
Total	203 W	277.485 W	39.25 W	519.735 W
Allowable	500 W	95-119 W	42 W	637 - 661 W
Margin [% free]				18.41 - 21.37%

Mission Requirement Drivers

Minimum Requirement	
R6	At least one surface sample (minimum 500 cc) shall be obtained from comet 46P
R7	At least one subsurface sample (minimum volume: 500 cc, minimum depth of sample: 10 cm) shall be obtained from a depth of 1 meter or below from comet 46P

- R6/ R7 required that we implement a sample lander and return capsule
- Defined what our drill mechanisms needed to be
- Required science instruments to scout an ideal landing site
- Required Power for a lander
- Increased Mass and Power consumption
- Had the largest impact on EDL and GNC

Engineering Design Drivers

- Science Instruments
  - Had the largest impact on other subsystems
  - Final decisions for other subsystems required finalized list of instruments
- Guidance, Navigation, and Controls
  - Delta-V → propulsion system
  - Timing of launch/return to Earth → how long we can perform operations at comet
  - Orbit Radii → how close can we get for science ops
  - Cruise Duration → when we perform checkouts, mission phases, etc

Pros and Cons of Overall Mission

Pros	Cons	Risks
Has instrumentation redundancies	No redundancy on sample collection mechanisms	SRC technology is still new
Well established technologies	Long cruise time (no guarantee that we can re-establish communication)	Lander can fail to deploy or detach SRC
Well defined orbit trajectory (Celestial body rendezvous has been well defined)	If either lander or orbiter fail, the majority of mission requirements can't be satisfied	Orbiter/ Lander can collide with Comet 46P
Landing on celestial bodies is well defined	SRC technologies not completely established	Heat Shield could fail destroying the SRC
Most subsystems have heritage	-	Orbiter can fail to attach to SRC

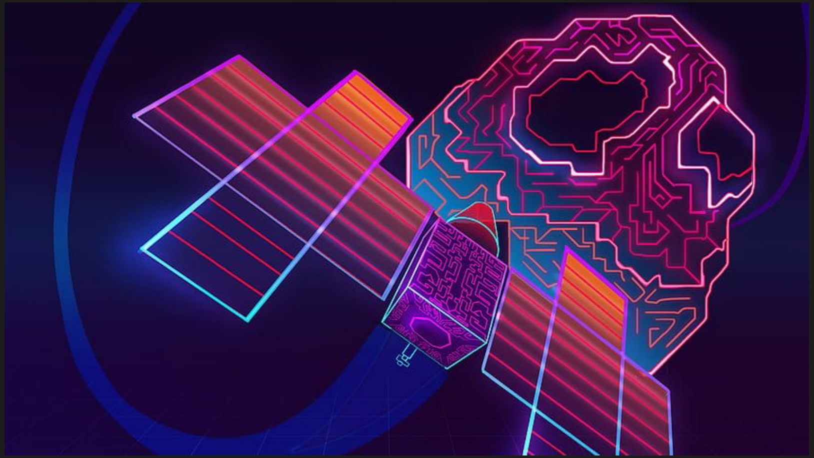
SRC - Sample Return Capsule

Mission Feasibility

Subsystem	Heritage	Risk	Mitigation
Launch, Propulsion, Power	Heritage for batteries, solar panels, and thrusters from Dawn, Rosetta, and OSIRIS-REx	Lack of Lander illumination	Primary batteries introduced to provide backup power during eclipse
Navigation, ADCS, Communication	ADCS and communication have well defined heritage, Rosetta, Psyche, ISS	Lander lack of redundancy, low power at Comet	Heritage sensors and actuators, small low power devices
Structures, Thermal, Materials	Well defined Heritage for materials, structures, thermal	Structural Fatigue, Material Corrosion	FEA Analysis on materials and thermal control systems.
Ground Operations, Telerobotics, EDL	VIPER, OSIRIS-REx, Rosetta, Mars Rovers	Ground-based image analysis and decision-making for landing site selection causes the risk of delays in identifying suitable sites	The use of advanced software tools can make efficient and informed landing site selection
Science Instruments	All instruments have heritage on planetary science missions (multiple derived from Rosetta comet mission) Extensive heritage of radar gravity science (Rosetta, Mariner II, OSIRIS-REx)	Possibility of dust accumulation on camera lenses and/or sublimation obscuring view Seismometer requires upright landing on surface	Functional redundancy for imaging (4 instruments capable of imaging) Minimum requirements can be met without seismometer
Space Environment, Sample Return	Missions to Comets have established heritage	Cometary physical sample return has no heritage	Utilize accurate environment modeling. Use well established heritage on other components

Mission Robustness

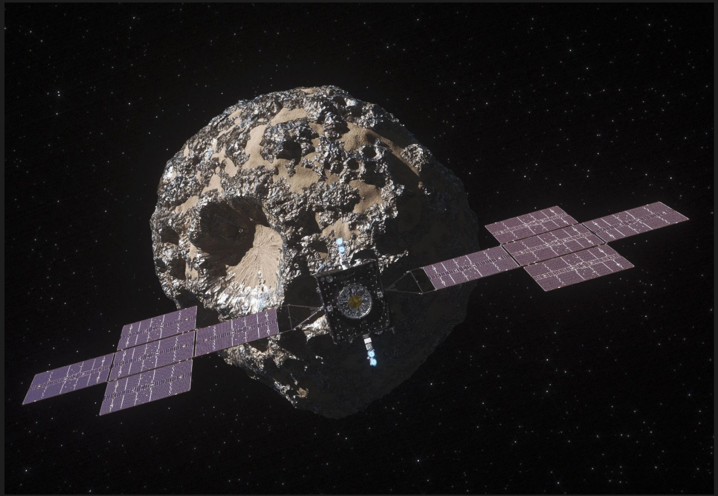
- Although there is one Orbiter, Lander, SRC, there is functional and instrumental redundancy
- Technologies for sample return have robust heritage (OSIRIS-REX, VIPER...)
- Celestial Rendezvous is well defined
- Sample Return missions have been well established



NASA Psyche

Future Iterations/ Work

- It would be beneficial to have redundancy into the Orbiter/ Lander/ SRC configurations. A lot rides on the success of each individual vehicle
- Choosing an orbit trajectory to maximize payload mass would prove beneficial
- Attempt to define a more complex mission, satisfying more of the extended mission requirements
- Increasing propulsion capabilities for re-rendezvous capabilities of the same or different celestial bodies



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THANK YOU!

Questions & Comments?

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Backup Slides

Spectrometer Selection

Question: why does COW-1 carry two spectrometers with four types of detection?

Answer: each detection mechanism enables detection of different substances.

1. **Gamma Rays** reveal the presence of a wide range of elements, including O, Mg, Al, Si, Ca, Fe, K, Th, and Cl from cosmic ray impacts, as well as radioactive elements K, Th, U from radioactive decay.
2. **Neutrons** are useful for detecting water (via hydrogen) and rare earth elements.
3. **Visible Light** reveals carbon-bearing molecules and fragments of complex organic molecules, as well as C/N isotopic ratios which may be useful in comparisons to Earth.
4. **Infrared Light** can be used to detect organic molecules (as well as water and ammonia).

Additional benefits include:

- Mapping spectrometer produces full images → functional redundancy for the WAC and NAC
- GR/NS can detect subsurface composition → useful for scouting subsurface sample sites

Expected Chemical Composition

The following molecules are likely to be found at Comet 46P; therefore, the selected spectrometers should be able to detect most of these wavelengths.

Table 3. Fundamental bands of potential comet molecules in the 2.5–5 μm region

σ (cm^{-1})	λ (μm)	Band	g-factor (s^{-1})	Molecule	σ (cm^{-1})	λ (μm)	Band	g factor (s^{-1})	Molecule
2062.2	4.849	ν_3	2.5×10^{-3}	OCS	3017.0	3.315	ν_4	5.5×10^{-4}	CH_3D
2077.0	4.815	ν_3	2.0×10^{-5}	HC_3N	3019.5	3.312	ν_3	4.0×10^{-4}	CH_4
2138.0	4.677	ν_3	2.3×10^{-5}	CH_3CCH	3047.9	3.281	ν_{12}	2.0×10^{-4}	C_6H_6
2143.2	4.666	1–0	2.6×10^{-4}	CO	3105.3	3.220	ν_9	1.4×10^{-4}	CH_2CH_2
2157.8	4.634	ν_3	2.2×10^{-5}	C_2N_2	3212.9	3.112	ν_1	6.2×10^{-4}	H_2O+
2200.0	4.545	ν_2	2.2×10^{-5}	CH_3D	3259.0	3.068	ν_3	2.4×10^{-3}	H_2O+
2272.0	4.401	ν_2	1.1×10^{-4}	HC_3N	3294.8	3.035	ν_3	1.7×10^{-4}	CHCH
2289.9	4.367	ν_3	1.0×10^{-2}	OC_3O	3311.5	3.020	ν_3	3.5×10^{-4}	HCN
2349.1	4.257	ν_3	2.6×10^{-3}	CO_2	3327.0	3.006	ν_1	8.6×10^{-4}	HC_3N
2727.0	3.667	ν_1	6.5×10^{-5}	HDO	3333.7	3.000	ν_4	1.5×10^{-4}	HCCCCH
2782.5	3.594	ν_1	3.9×10^{-4}	H_2CO	3335.1	2.998	ν_1	2.5×10^{-4}	CH_3CCH
2843.3	3.517	ν_5	4.6×10^{-4}	H_2CO	3337.0	2.997	ν_1	3.4×10^{-5}	NH_3
2844.0	3.516	ν_3	1.5×10^{-4}	CH_3OH	3444.0	2.904	ν_3	2.0×10^{-5}	NH_3
2901.0	3.447	ν_3	4.7×10^{-4}	CH_3CH_2OH	3519.4	2.841	ν_3	5.8×10^{-3}	H_3O+
2941.0	3.400	ν_2	1.0×10^{-4}	CH_3CCH	3568.0	2.803	1–0	6.0×10^{-5}	OH
2942.0	3.399	ν_2	1.9×10^{-4}	HCOOH	3569.0	2.802	ν_1	3.6×10^{-4}	HCOOH
2945.0	3.396	ν_1	3.3×10^{-5}	CH_3D	3607.0	2.772	ν_1	1.0×10^{-4}	H_2O_2
2954.0	3.385	ν_1	1.5×10^{-5}	CH_3CN	3608.0	2.772	ν_5	6.0×10^{-4}	H_2O_2
2970.0	3.367	ν_9	3.5×10^{-4}	CH_3OH	3657.0	2.734	ν_1	1.8×10^{-5}	H_2O
2971.0	3.366	ν_2	3.9×10^{-4}	CH_3CH_2OH	3660.0	2.732	ν_1	1.0×10^{-4}	CH_3CH_2OH
2980.9	3.355	ν_6	8.5×10^{-5}	CH_3CCH	3681.0	2.717	ν_1	1.3×10^{-4}	CH_3OH
2988.6	3.346	ν_{11}	7.3×10^{-5}	CH_2CH_2	3707.0	2.698	ν_3	1.9×10^{-4}	HDO
2999.0	3.334	ν_2	1.9×10^{-4}	CH_3OH	3755.9	2.662	ν_3	2.6×10^{-4}	H_2O

NP

Cometary Mass Estimation: Mass Models

Comet 46P Mass Models from Existing Observations Assuming a Spherical Body

Parameter	Small Model	Large Model	Average Model
Radius (m)	500	1000	700
Density (kg /m^3)	200	1000	500
Mass (kg)	1.05×10^{11}	41.9×10^{11}	7.18×10^{11}

Cometary Mass Estimation: Doppler Shift

When a spacecraft's velocity changes due to forces on the spacecraft, a frequency shift in the radio carrier with respect to the predicted shift is induced (upper left).

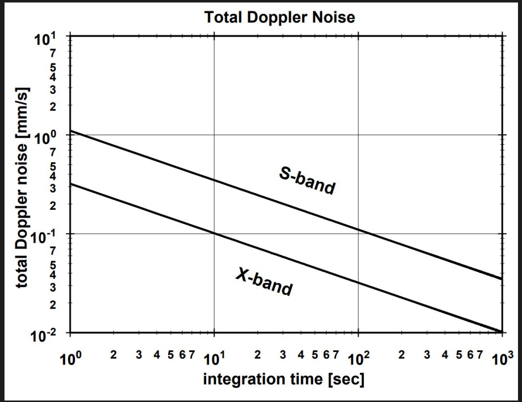
Doppler velocity error affects the accuracy of these measurements, and can be modeled as a function of integration time (upper right).

X-band has less error than S-band (lower left/right).

$$\Delta f = -\frac{f_0}{c} \cdot \frac{\Delta R}{\Delta t}$$

$$\sigma_{\mathrm{v}}(\Delta t) = \sigma_{\mathrm{v}_0} \frac{1}{\sqrt{\Delta t}}.$$

	Doppler velocity error σ_{v}	
	S-band	X-band
Phase error (thermal and ground station contribution)	1.0 mm/s	0.3 mm/s
Transponder quantisation error in frequency	0.4 mm/s	0.1 mm/s
Transponder quantisation error in phase	0.01 mm/s	0.004 mm/s
Total error (coherent mode)	1.08 mm/s	0.32 mm/s



Cometary Mass Estimation: Accuracy

Using the models and equations from previous slides, the mass estimation error can be predicted.

$$\frac{\sigma_{GM}}{GM} = \frac{r^2}{GM}\frac{1}{T}\sigma_{\mathrm{v}}(\Delta t).$$

σ_{GM} / GM = fractional error
r = orbit radius (m)
$\sigma_v(\Delta t)$ = Doppler error
G = gravitational constant (6.672 x 10^{-11} m^3 kg^{-1} s^{-2})
M = mass (kg)
T = tracking pass duration (s)