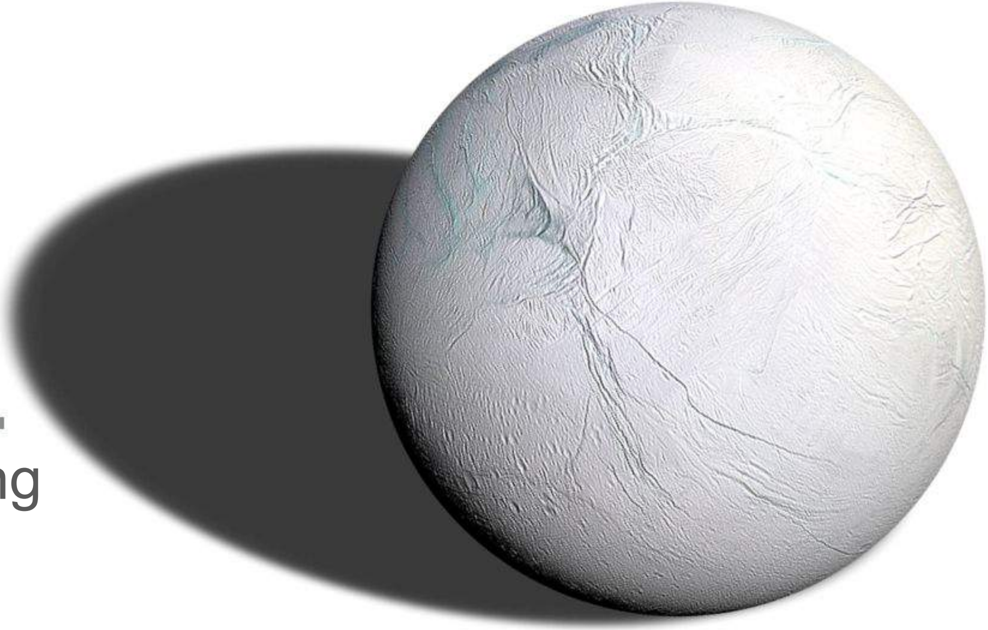
ELDER

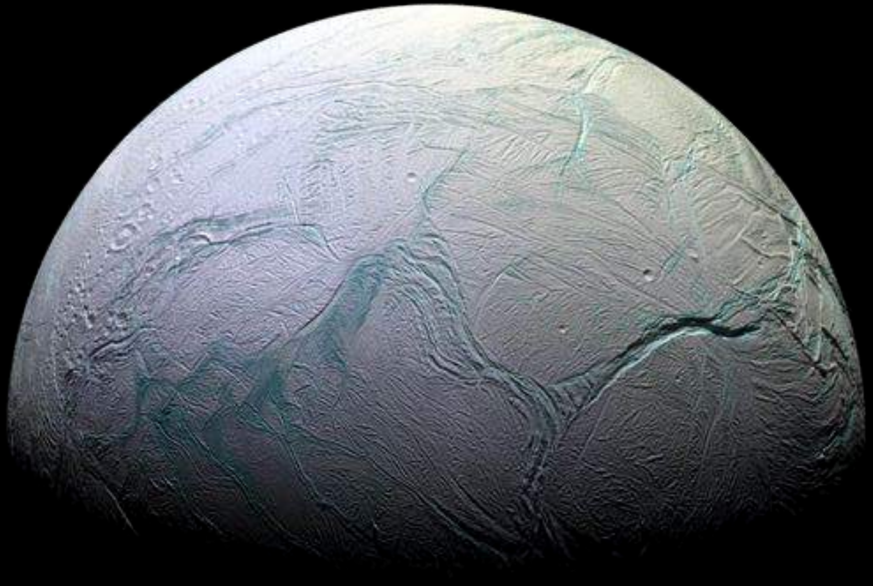
Enceladus Life Detection, Exploration and Reconnaissance
Critical Design Review



16.83 Space Systems Engineering
7 May 2019

Are We Alone?

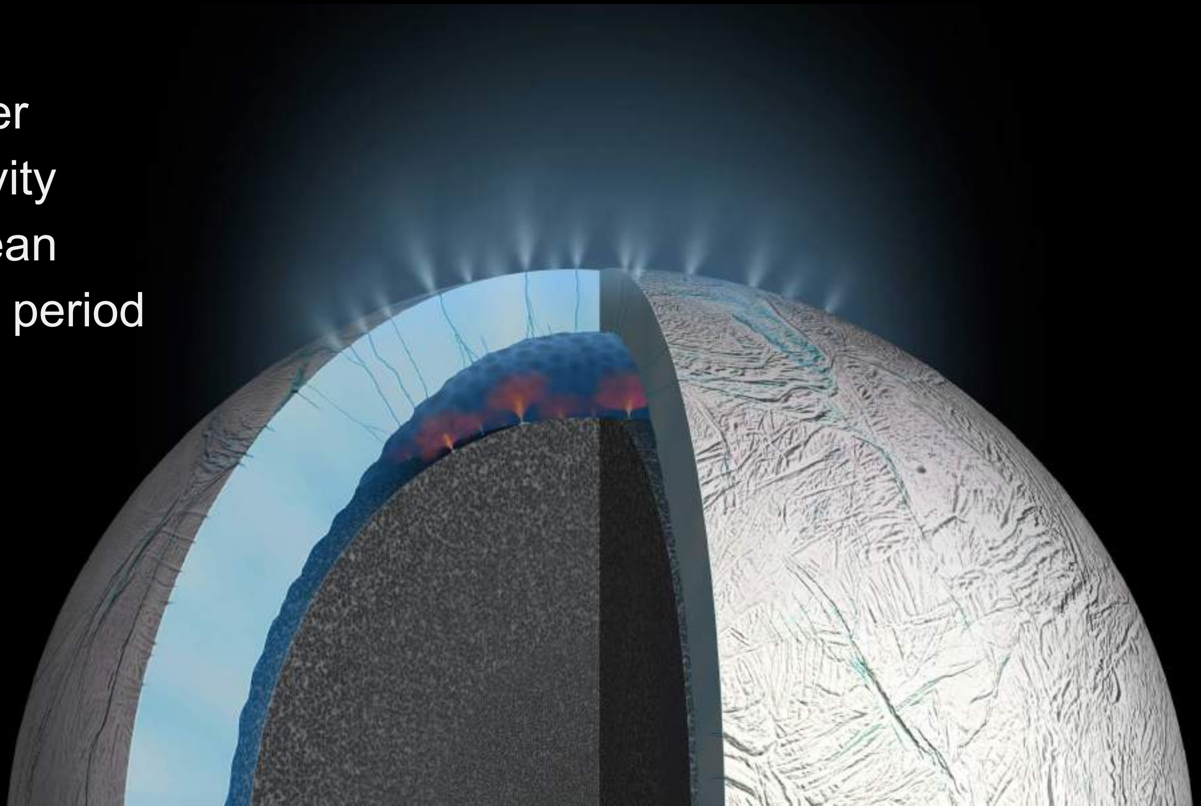
Enceladus, an ocean world.



Enceladus, an ***Active World***

One that could support life...

500 km diameter
1% Earth's gravity
Subsurface ocean
1.37 day orbital period
around Saturn



The Legacy of Cassini

ELDER Mission Team

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Niyati Desai

Science and Mission Objectives

Decadal Survey: “Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?” [LD1]

A. Characterize the habitability of Enceladus' subsurface ocean

- What are the conditions of the subsurface ocean?
- What is the nature of the energy source sustaining Enceladus’ ocean?

B. Search for evidence of life on Enceladus

- Is there evidence of ongoing prebiotic or biotic processes in Enceladus’ subsurface ocean?

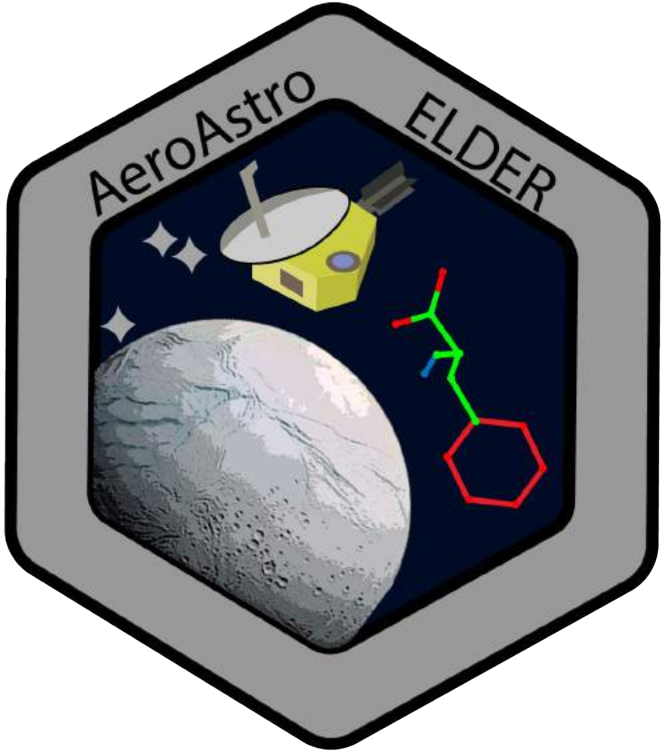
C. Communicate the importance of detecting life to the general public

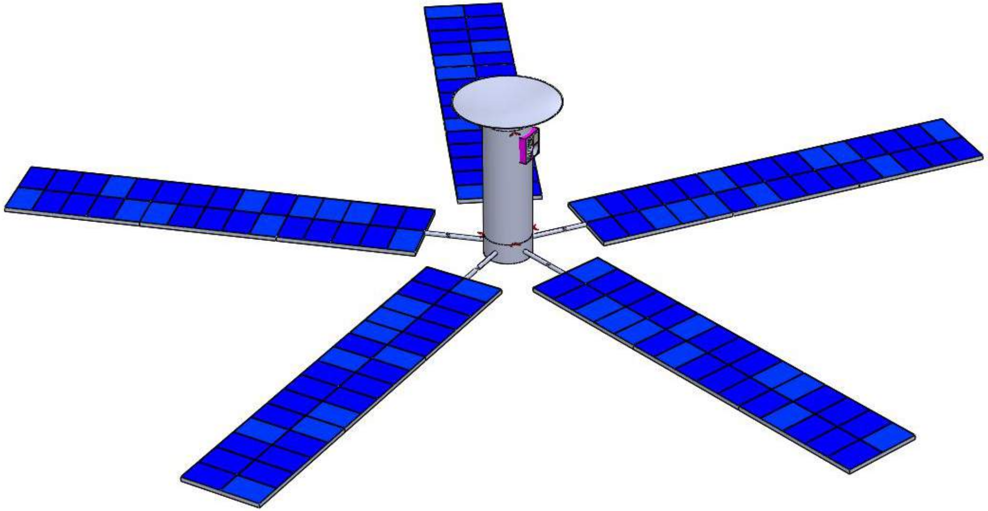
- Will be discussed in demo after CDR

Agenda

- **CONOPS**
- Science & Instrumentation
- Enceladus Operations
- Spacecraft Design: Main Stage
- Trajectory
- Spacecraft Design: Solar Electric Propulsion Stage
- System Health
- Risks
- Possible Mission Extensions
- Budgets

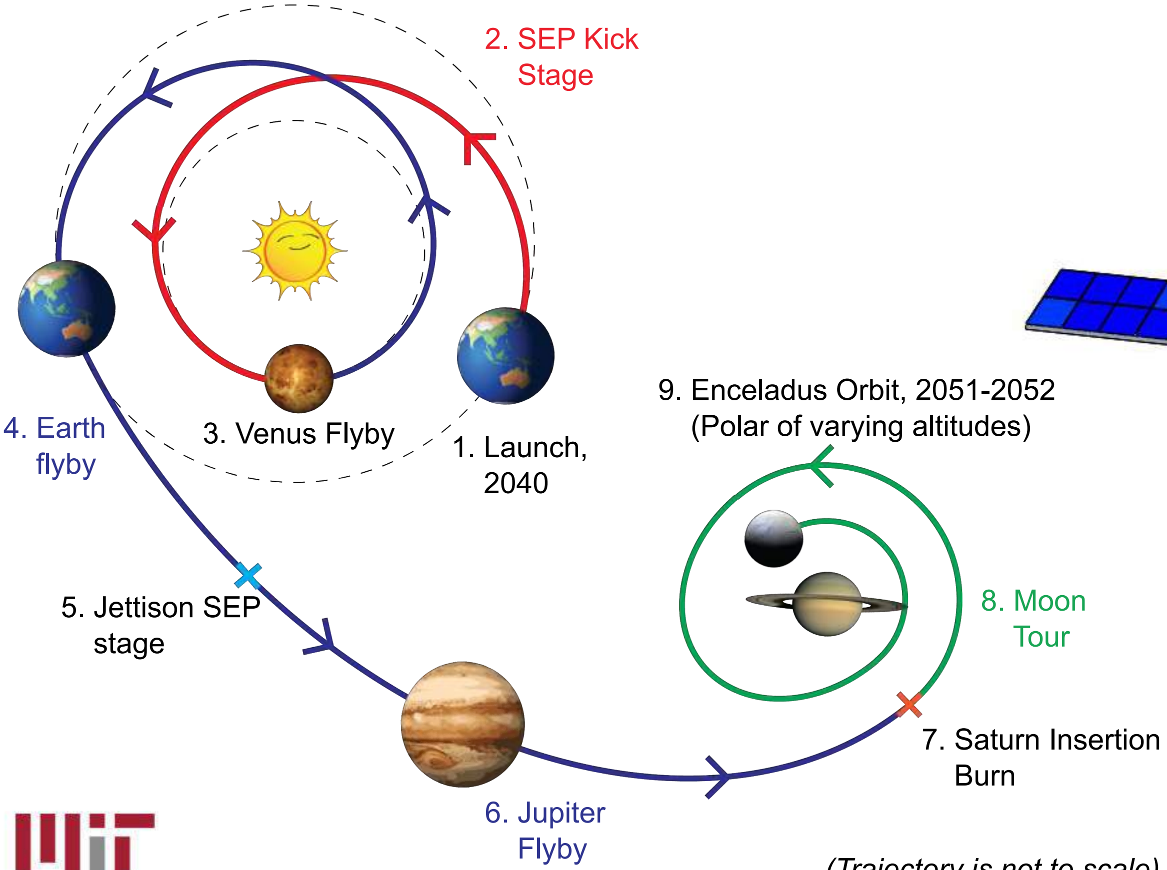
Enceladus Life Detection, Exploration, and Reconnaissance



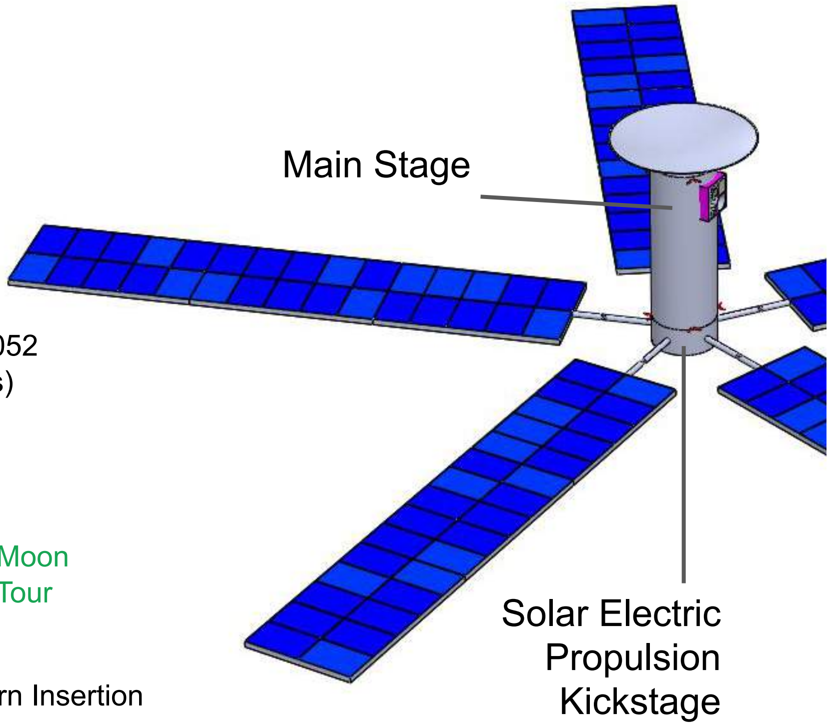


Yun Chang

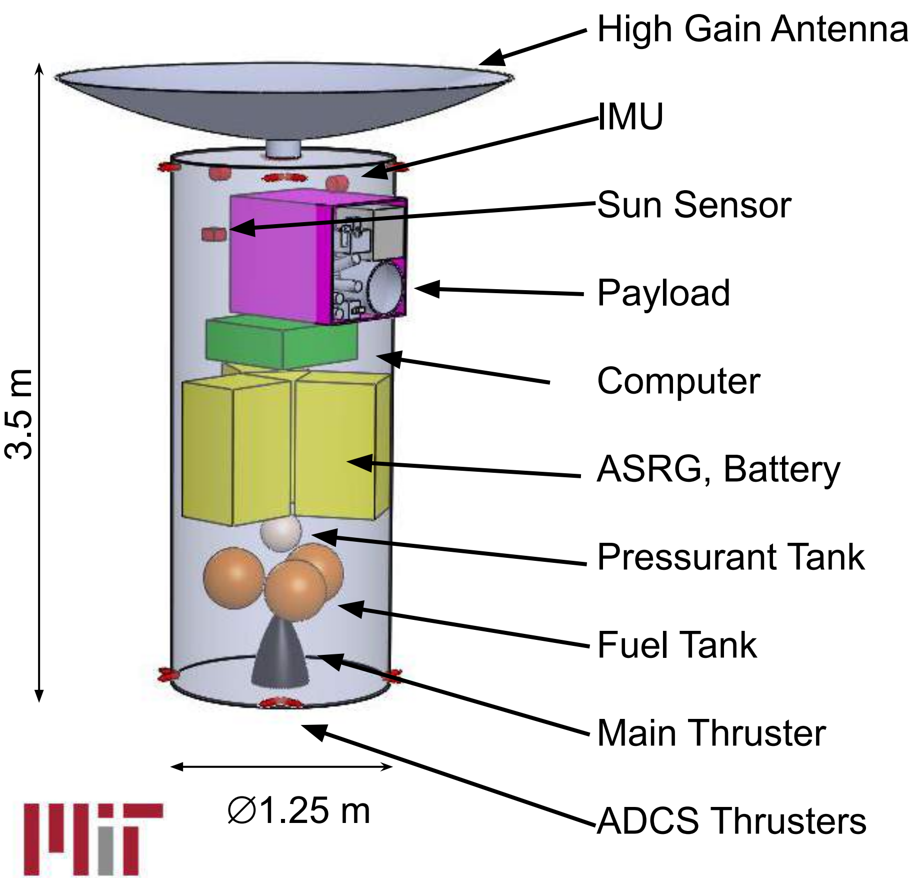
Concept of Operations

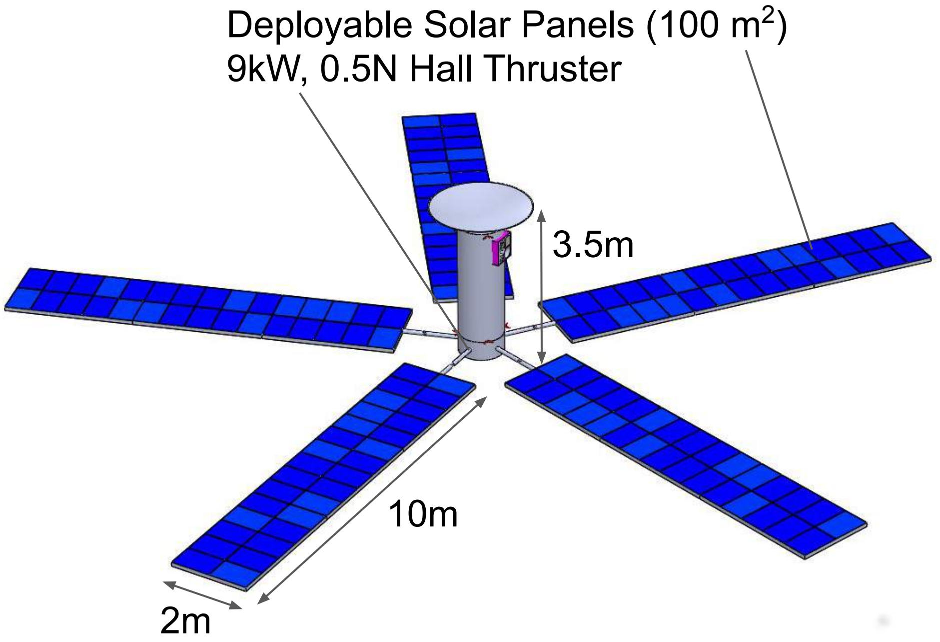


(Trajectory is not to scale)



Spacecraft Overview





Total launch mass (with margin): 2606 kg

Agenda

- Mission & CONOPS
- **Science & Instrumentation**
- Enceladus Operations
- Spacecraft Design: Main Stage
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Science Objectives

Decadal Survey: “Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?” [LD1]

A. Characterize the habitability of Enceladus' subsurface ocean

- What are the conditions of the subsurface ocean?
- What is the nature of the energy source sustaining Enceladus’ ocean?

B. Search for evidence of life on Enceladus

- Is there evidence of ongoing prebiotic or biotic processes in Enceladus’ subsurface ocean?

Science Questions: Ocean Conditions

A. Characterize the habitability of Enceladus' subsurface ocean

- What are the conditions of the subsurface ocean?
  - Determine the **salinity** of Enceladus' subsurface ocean
  - Determine the **pH** of Enceladus' subsurface ocean
  - Determine the **temperature** of Enceladus' subsurface ocean
  - Constrain the **size and depth** of the subsurface ocean

AEROASTRO

Niyati Desai

Science Questions: Energy Source

A. Characterize the habitability of Enceladus' subsurface ocean

- What is the nature of the energy source sustaining Enceladus' ocean?
  - Determine the **longevity of Enceladus' hydrothermal system**
  - Determine whether **serpentinization** is ongoing between Enceladus' subsurface ocean and rock core
  - Characterize the **tidal heating** within the interior of Enceladus
  - Constrain the **energy flux** between Enceladus' surface and its subsurface ocean

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Science Questions: Biotic Processes

B. Search for evidence of life on Enceladus

Is there evidence of ongoing prebiotic or biotic processes in Enceladus' subsurface ocean?

- Determine the extent that relevant **species are produced from biotic or abiotic processes**
- Constrain evidence of **chemical disequilibrium** as a biosignature (indicative of metabolism)
- Detect **structural preferences** conferring functions of organic molecules (chirality)

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Science Traceability Matrix: Ocean Conditions

Decadal Survey	Science Objectives	Science Questions	Science Requirements	Measurements	Instruments	Measurement Requirements	Instrument Performance	Measurement References	Instrument References
"Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?" [LD1]	A. Characterize the habitability of Enceladus' subsurface ocean	1. What are the conditions of the subsurface ocean?	1.a. Determine the salinity of Enceladus' subsurface ocean	Characterize abundance of salts and other minerals in ice grains from 20 to 50 km altitude	Enceladus Icy Jet Analyzer (ENIJA)	Mass Resolution: 200 m/Δm	Mass Resolution: 1000 m/Δm	Hsu et al., 2015 [LD19] Sherwood, 2016 [LD27]	Mitri et al., 2018 [LD2]
				Measure conductivity of Enceladus' subsurface ocean from 20 to 30 km altitude	Magnetometer	Magnetic Field Resolution: 1.0 nT	Magnetic Field Resolution: 0.2 nT	Domagal-Goldman and Wright et al., 2016 [LD1] Kriegel et al., 2011 [LD18]	MacKensie et al, 2016 [LD4]
			1.b. Determine the pH of Enceladus' subsurface ocean	Measure temperature of the plumes and fissures of Enceladus from 50 to 100 km altitude	Submillimeter Enceladus Life Fundamentals Instrument (SELFI)	Temperature Resolution: 1.0 K	Temperature Resolution: 0.1 K	Glein et al., 2015 [LD24]	Racette et al., 2019 [LD5]
				Measure CO2 abundance in plume vapor from 20 to 50 km altitude	Mass Spectrometer for Planetary Exploration (MASPEX)	Mass Resolution: 134 m/Δm	Mass Resolution: 25,000 m/Δm	Combe et al., 2019 [LD22] Glein et al., 2015 [LD24]	Brockwell et al., 2016 [LD3]
			1.c. Determine the temperature of Enceladus' subsurface ocean	Measure abundance of nitrates (N2, NH3) as measure of freezing point of ocean from 50 to 100 km altitude	Narrow Angle Camera (NAC) - UV	Wavelength: 200-205 nm	Wavelength: UV Filter: 200-205 nm	Bouquet et al., 2015 [LD11] Matson et al., 2007 [LD20]	Edwards et al., 2000 [LD9]
				Measure the isotopic ratio of oxygen (16O/18O) in water vapor from 50 to 100 km altitude	Submillimeter Enceladus Life Fundamentals Instrument (SELFI)	Frequency of Oxygen Isotopes in Water Vapor: O17 - 552.021 GHz O18 - 547.676 GHz	Frequencies: 552.021 GHz 547.676 GHz Resolution: < 100kHz	Zastrow et al., 2012 [LD25]	Racette et al., 2019 [LD5]
			1.d. Constrain the size and depth of the subsurface ocean	Measure magnetic field of Enceladus from 20 to 30 km altitude	Magnetometer	Magnetic Field Resolution: 1.0 nT	Magnetic Field Resolution: 0.2 nT	Kriegel et al., 2011 [LD18]	MacKensie et al, 2016 [LD4]

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Science Traceability Matrix: Energy Source

Decadal Survey	Science Objectives	Science Questions	Science Requirements	Measurements	Instruments	Measurement Requirements	Instrument Performance	Measurement References	Instrument References
"Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?" [LD1]	A. Characterize the habitability of Enceladus' subsurface ocean	2. What is the nature of the energy source sustaining Enceladus' oceans?	2.a. Determine the longevity of Enceladus' hydrothermal system	Measure abundances of nobles gases (e.g. Ar, Ne, He) that have leached from Enceladus' rock-core from 20 to 50 km altitude	Mass Spectrometer for Planetary Exploration (MASPEX)	Mass Resolution: 5000 m/Δm	Mass Resolution: 25,000 m/Δm	Matson et al., 2007 [LD20] Sherwood, 2016 [LD27]	Mitri et al., 2018 [LD2], LD3]
			2.b. Determine whether serpintinization is ongoing between Enceladus' subsurface ocean and rock-core	Measure the abundance of H2 in plume vapor from 20 to 50 km altitude	Mass Spectrometer for Planetary Exploration (MASPEX)	Mass Resolution: 37 m/Δm	Mass Resolution: 25,000 m/Δm	Bouquet et al., 2015 [LD11] Taubner et al., 2018 [LD21]	Brockwell et al., 2016 [LD3]
			2.c. Characterize tidal heating within the interior of Enceladus	Measure gravity field (hydrostatic equilibrium, moment of inertia) of Enceladus to ≥4th degree via Doppler shift tracking of the spacecraft at altitudes of 20 to 30 km altitude	Radio Laser Altimeter	Resolution: 10^-5 m/s (Achieved with X band)	Communication Frequencies: X & Ka bands	Iess et al., 2014 [LD16] Souček et al., 2019 [LD31]	MacKensie et al, 2016 [LD4] Souček et al., 2019 [LD31]
				Map the topography of at least 70% of Enceladus' surface from 50 to 100 km altitude	Laser Altimeter	Accuracy: 1 km	Accuracy: 30 cm	Domagal-Goldman and Wright et al., 2016 [LD1] McKinnon, 2009 [LD28]	Cavanaugh et al., 2007 [LD30]
				Map at least 70% of Enceladus' surface and image specific features of interests (e.g. ice shell fractures) from 50 to 100 km altitude	Wide Angle Camera (WAC) - VIS Narrow Angle Camera (NAC) - VIS	Spatial Resolution: 20m/px	Spatial Resolution: NAC: 0.5 m/px WAC: 10 m/px	Domagal-Goldman and Wright et al., 2016 [LD1] Hemingway and Mittal, 2019 [LD23] McKinnon, 2009 [LD28]	Lewis et al., 2016 [LD10], Soucek et al., [LD31]
			2.d. Constrain the energy flux between Enceladus' subsurface ocean and its surface	Quantify the ice/vapor ratio of plume material from 50 to 100 km altitude	Narrow Angle Camera (WAC) - UV	Wavelength: <170nm	Wavelength: UV Filter: 170nm +/- 20 nm	Saur et al., 2008 [LD12] Tian et al., 2007 [LD13]	Warren et al., 2006 [LD8] Lewis et al., 2016 [LD10]
				Measure the mass flux and velocity of ice grains out of plume vents from 50 to 100 km altitude	Narrow Angle Camera (WAC) - UV	Wavelength: <170nm	Wavelength: UV Filter: 170nm +/- 20 nm	Saur et al., 2008 [LD12] Tian et al., 2007 [LD13]	Warren et al., 2006 [LD8] Lewis et al., 2016 [LD10]
				Measure spatial distribution of ice grains in plumes from 50 to 100 km altitude	Narrow Angle Camera (WAC) - UV	Wavelength: <170nm	Wavelength: UV Filter: 170nm +/- 20 nm	Saur et al., 2008 [LD12] Tian et al., 2007 [LD13]	Warren et al., 2006 [LD8] Lewis et al., 2016 [LD10]
				Thermally map at least 70% Enceladus's surface to measure heat flux of ice shell from 50 to 100 km altitude	Wide Angle Camera (WAC) - IR	Spatial Resolution: 20 m/px Wavelength: 4-6 μm	Spatial Resolution: 10 m/px Wavelength: Mid-IR Filter: 4-6 μm	Howett et al., 2011 [LD14] Ingersoll et al., 2010 [LD15]	Domagal-Goldman and Wright et al., 2016 [LD1] Lewis et al., 2016 [LD10]

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Science Traceability Matrix: Biotic Processes

Decadal Survey	Science Objectives	Science Questions	Science Requirements	Measurements	Instruments	Measurement Requirements	Instrument Performance	Measurement References	Instrument References
"Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?" [LD1]	B. Search for evidence of life on Enceladus	3. Is there evidence of ongoing prebiotic or biotic processes in Enceladus' subsurface ocean?	3.a. Determine the extent that relevant species are produced from abiotic, prebiotic, or biotic processes	Measure abundance of C,H,N,O,P,S elements in organic molecules in plume vapor from 20 to 50 km altitude	Mass Spectrometer for Planetary Exploration (MASPEX)	Mass Resolution: 3000 m/Δm	Mass Resolution: 25,000 m/Δm	Mitri et al., 2018 [LD2] Bouquet et al., 2015 [LD11]	Mitri et al., 2018 [LD2] Brockwell et al., 2016 [LD3]
				Measure abundance of complex organics molecules (e.g. amino acids & amines, carboxylic acid, PAHs) from 20 to 50 km altitude	Enceladus Icy Jet Analyzer (ENIJA) Enceladus Organic Analyzer (EOA)	Sensitivity: 10 ppm	Sensitivity (ENIJA): 10 ppm - 1 ppb Sensitivity (EOA): 1 ppb	Mitri et al., 2018 [LD2] Tobie et al., 2014 [LD29]	Mathies et al., 2017 [LD6] Srama et al., 2015 [LD7]
			3.b. Constrain evidence of chemical disequilibrium as a potential biosignature (i.e. metabolic processes)	Measure isotopic ratios of carbon (^{12}C/ ^{13}C) and hydrogen (D/H) in hydrocarbons in plume vapor from 20 to 50 km altitude	Mass Spectrometer for Planetary Exploration (MASPEX)	Mass Resolution: 5830 m/Δm	Mass Resolution: 25,000 m/Δm	Mitri et al., 2018 [LD2] Horita et al., 1999 [LD17] McKay et al., 2012 [LD26]	Mitri et al., 2018 [LD2] Brockwell et al., 2016 [LD3]
				Measure deviations from abiotic distribution (co-location of reductant and oxidant species such as H_2, O_2, H_2O) from 20 to 50 km altitude	Mass Spectrometer for Planetary Exploration (MASPEX)	Mass Resolution: 6948 m/Δm	Mass Resolution: 25,000 m/Δm	Mitri et al., 2018 [LD2] Tobie et al., 2014 [LD29]	Mitri et al., 2018 [LD2] Brockwell et al., 2016 [LD3]
			3.c. Detect structural preferencers conferring function of organic molecules	Measure chirality of amino acids in plume grains from 20 to 50 km altitude	Enceladus Organic Analyzer (EOA)	Sensitivity: 1 ppm	Sensitivity: 1 ppb	Sherwood, 2016 [LD27]	Mathies et al., 2017 [LD6]

Complete Instruments List

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Instrument	Type
ENceladus Icy Jet Analyzer (ENIJA)	*In-situ*
MAss Spectrometer for Planetary EXploration (MASPEX)	
Enceladus Organics Analyzer (EOA)	
Magnetometers (2)	
Enceladus Imaging Subsystem (EIS): IR, UV, VIS filters - Wide Angle Camera (WAC) - Narrow Angle Camera (NAC)	Remote sensing
Submillimeter Enceladus Life Fundamentals Instrument (SELFI)	
Mercury Laser Altimeter (MLA)	
Communications Radio	

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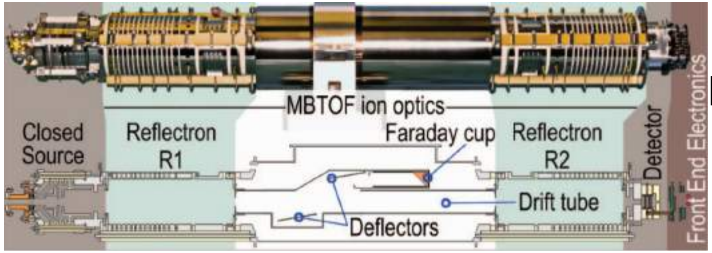
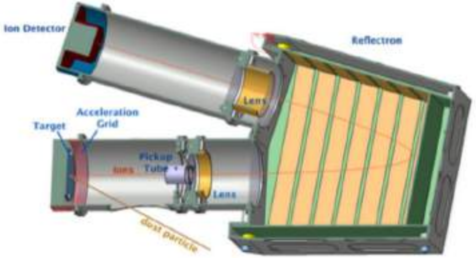
Instruments: *in-situ*

	MASPEX Time of Flight (ToF) mass spectrometer [LD2], [LD3]	**Enceladus Icy Jet Analyzer (ENIJA)** ToF mass spectrometer (impact ionization) [LD2], [LD7]
Purpose	Determine composition and abundance of plume gases	Determine the makeup of solid particles in the plumes
Main Science Question	All	All
Resolution (m/Δm)	25,000	>970
Analyte	Plume gas	Plume dust particles and ice grains



[LD3]



[LD2]

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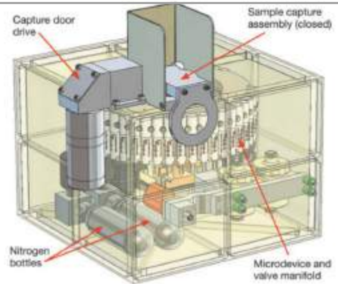
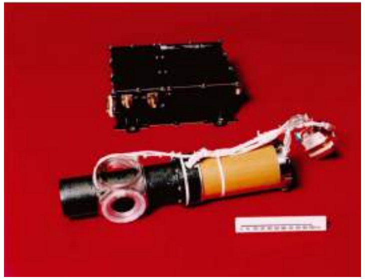
Instruments: *in-situ*

	Enceladus Organics Analyzer (EOA) [LD6]	**Magnetometers (2)** Magnetic field measurement [LD4]
Purpose	Detect presence of organic compounds in plume particles (amines, amino acids, carboxylic acids), determine chirality	Measure magnetic field, implies size of subsurface ocean
Science Question	*Is there evidence of ongoing prebiotic or biotic processes in Enceladus' subsurface ocean?*	*What are the conditions of the subsurface ocean?*
Sensitivity	0.1 ppb	0.1 nT
Analyte	Plume material	Enceladus magnetic field



[LD6]



[LD32]

Instruments: remote sensing

	Submillimeter Enceladus Life Fundamentals Instrument (SELFI) Remote plume and surface characterization [LD5]	**Wide angle camera (WAC) + Narrow Angle Camera (NAC)** IR, Vis, UV Characterization [LD8], [LD10], [LD33]
Purpose	Holistic view of plume composition and surface, more global perspective than *in-situ*	Characterize physical and thermal properties of Enceladus, surface mapping
Main Science Question	*What are the conditions of the subsurface ocean?*	*What is the nature of the energy source sustaining Enceladus' oceans?*
Resolution	Radiometric Temperature: 0.1 K	NAC: 18.6 μrad/px WAC: 101 μrad/px
Analyte	(remotely) plumes, Enceladus surface	(remotely) plumes, Enceladus surface

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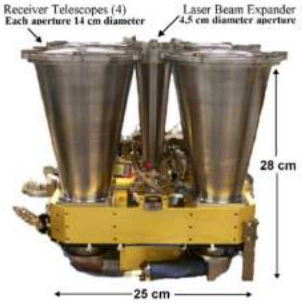
Instruments: remote sensing

	Communications Radio [LD4], [LD16]	**Mercury Laser Altimeter (MLA)** Altitude measurement [LD30]
Purpose	Communications and gravity field measurement	Topographical mapping of Enceladus Surface
Main Science Question	*What is the nature of the energy source sustaining Enceladus' oceans?*	*What is the nature of the energy source sustaining Enceladus' oceans?*
Range	X and Ka Bands	<1500 km
Analyte	Gravity field (via doppler effect)	Enceladus surface



[LD30]

Science Measurement Ranking

NASA Life Detection Ladder		
NASA's working definition of life is a "self-sustaining chemical system capable of Darwinian evolution"		
Priority	Features of Life	Metrics
1	Metabolism	Deviation from abiotic fractionation controlled by thermodynamic equilibrium and/or kinetics
		Deviation from abiotic distribution controlled by thermodynamic equilibrium and/or kinetics (co-located reduction and oxidation species)
2	Molecular Structure conferring Function	Polymers that support information storage and transfer for terran life (DNA, RNA)
		Structural preferences in organic molecules (non-random and enhancing function)
3	Potential biomolecules	Complex organics (e.g. nucleic acid oligomers, peptides, PAH)
		Monomeric units of biopolymers (nucleobases, amino acids, lipids for compartmentalization)
4	Potential metabolic byproducts	Distribution of metals e.g. V in oil of Fe, Ni, Mo/W, Co S, Se, P
		Patterns of complex organics: Deviation from equilibrium (P(Poisson distribution of pathway complexity), 0.01) or abiotic kinetic distribution
5	Habitability	liquid water, pH, energy source

Neuvue, M. et al., 2018 [LD35]

Astrobiology Primer				
Priority	Biomarker	Metrics	Availability	Importance
1	Biogenic organic molecules	Biomarkers (lipids, amino acids, nucleic acids)	10^-12 ppm - 0.75 ppm	0.6
2/3	Isotopic ratios/ isotopic fractionation indicative of metabolism	Deviations from abiotic fractionation	2 per million - 200 per million	0.08
2/3	Biogenic gases	Concentrations that are in disequilibrium (CH4)	10^-12 - 10^-6	0.08
4	Spatial chemical patterns	Concentrations (> microM)	0.01 ppm - 1 ppm	0.03
5	Biomineralization	Mineral concentration	0.1 µm - 100 µm	0.02 - 0.03

Domagal-Goldman, S.D. et al., 2016 [LD36]

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Science Measurement Ranking

Science Measurements	Science Score	MASPEX	ENIJA	EOA	SELFI	Imagining Sub-system	Magnet-ometer	Radio Science	Laser Altimeter
Measure isotopic ratios of carbon (12C/ 13C) and hydrogen (D/H) from hydrocarbons in ice grains and plume vapor	AP - 1 LDL - 1	■							
Measure chirality of amino acids	AP - 1 LDL - 2			■					
Measure abundance of complex organics molecules (e.g. amino acids & amines, carboxyclic acid, PAHs)	AP - 2 LDL - 1		■	■					
Measure deviations from abiotic distribution as a potential sign of microbial metabolism (co-location of reductant and oxidatant species such as H2, O2, H20)	AP - 2/3 LDL - 1	■	■		■				
Measure abundance of C,H,N,O,P,S elements in organic molecules in plume vapor	AP - 2/3 LDL - 3	■							
Quantify the ice/vapor ratio of plume material	AP - 4 LDL - 5				■	■			
Measure the mass flux and velocity of ice grains out of plume vents	AP - 4 LDL - 5				■	■			
Measure spatial distribution of ice grains in plumes	AP - 4 LDL - 5				■	■			
Measure H2 abundance in plume vapor	AP - 5 LDL-5	■							
Characterize abundance of salts and other minerals in ice grains	AP - 5 LDL-5		■	■					
Measure conductivity of Enceladus' subsurface ocean	AP - 5 LDL-5						■		
Measure temperature of the plumes and fissures of Enceladus	AP - 5 LDL-5				■	■			
Measure CO2 abundance in plume vapor	AP - 5 LDL-5	■							
Measure abundance of nitrates (N2, NH3) in the plume as measure of freezing point of ocean	AP - 5 LDL-5					■			
Measure oxygen (16O/18O) isotopic ratios in plume water vapor	AP - 5 LDL-5	■			■				
Measure gravity field (hydrostatic equilibrium, moment of inertia) of Enceladus to ≥4th degree via Doppler shift tracking	AP - N/A LDL- 5							■	■
Map the topography of at least 70% of Enceladus' surface	AP - N/A LDL-5								■
Map at least 70% ice shell fractures on Enceladus' surface	AP - N/A LDL- 5					■			
Thermally map at least 70% Enceladus's surface to measure heat flux of ice shell	AP - N/A LDL- 5				■	■			
Measure abundances of nobles gases (e.g. Ar, Ne, He) that have leached from Enceladus' rock-core	AP - N/A LDL- 5	■							
Measure magnetic field of Enceladus	AP - N/A LDL- 5						■		

Design to Meet Requirements - Suite Comparison

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Instrument	Baseline Suite	Threshold Suite
Enceladus Organics Analyzer (EOA)		
ENceladus Icy Jet Analyzer (ENIJA)		
MAss Spectrometer for Planetary EXploration (MASPEX)		
Imaging Subsystem		
Submillimeter Enceladus Life Fundamentals Instrument (SELFI)		
Radio		
Magnetometers (2)		
Mercury Laser Altimeter (MLA)		

Agenda

- Mission & CONOPS
- Science & Instrumentation
- **Enceladus Operations**
- Spacecraft Design: Main Stage
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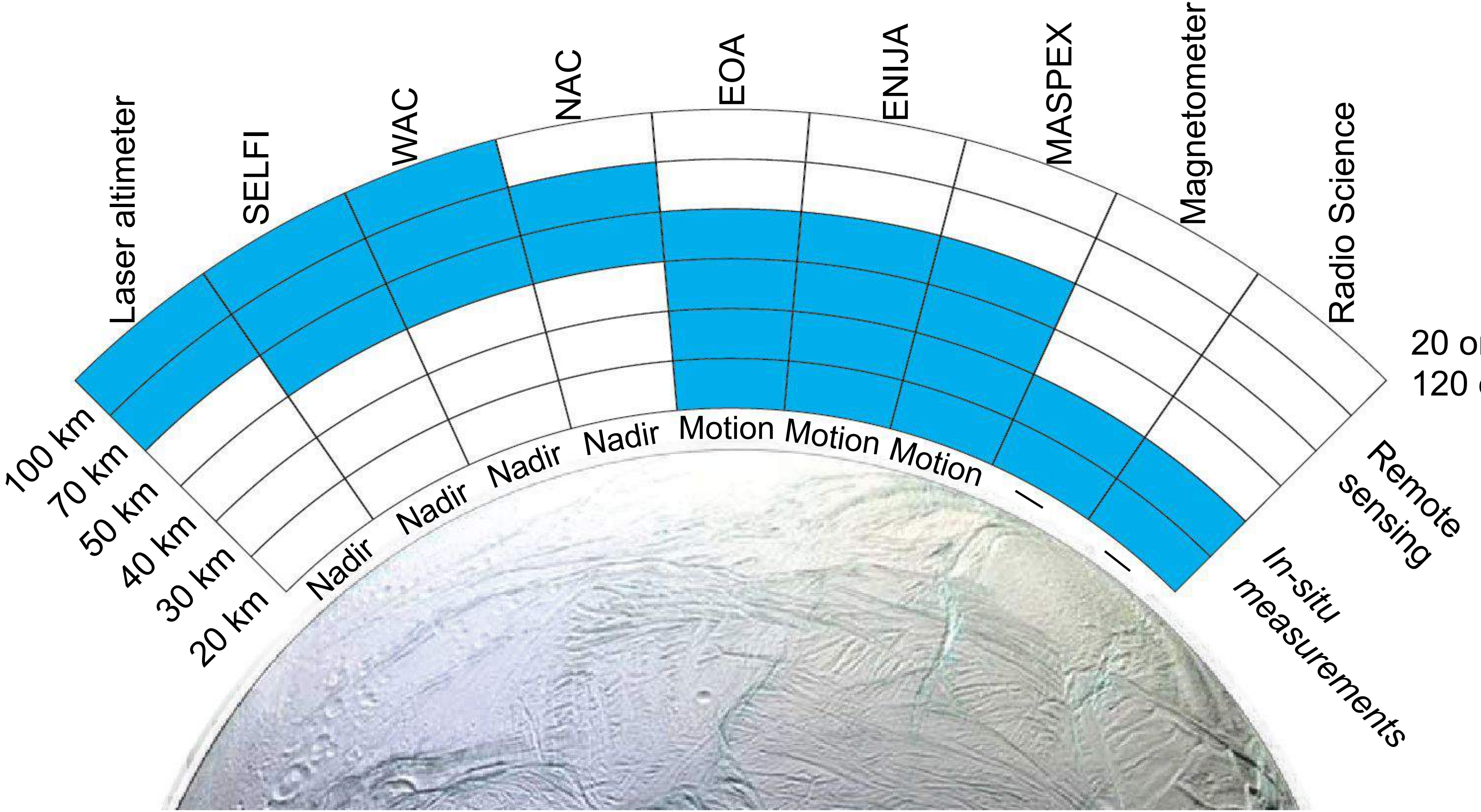
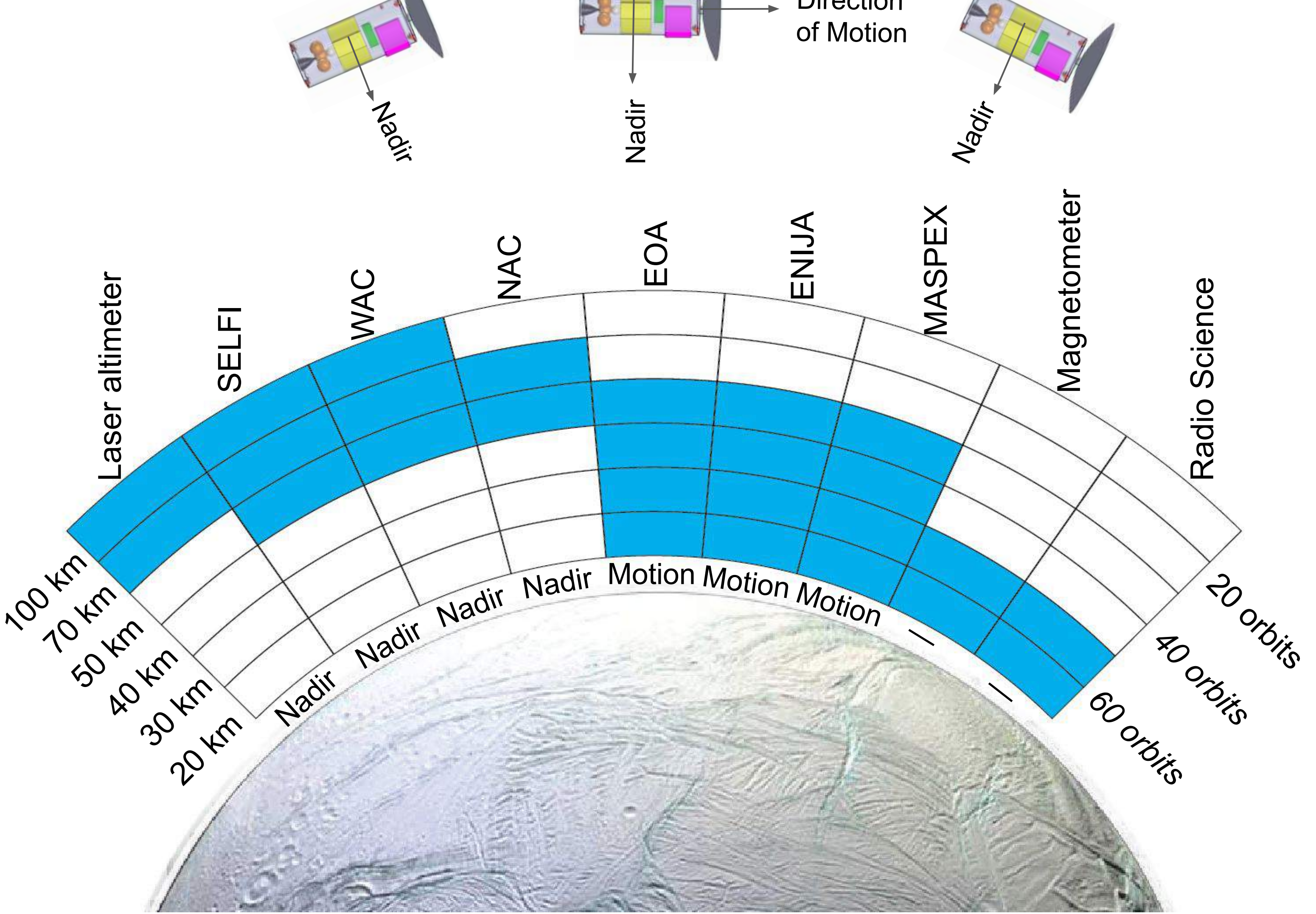
Science operations at each altitude



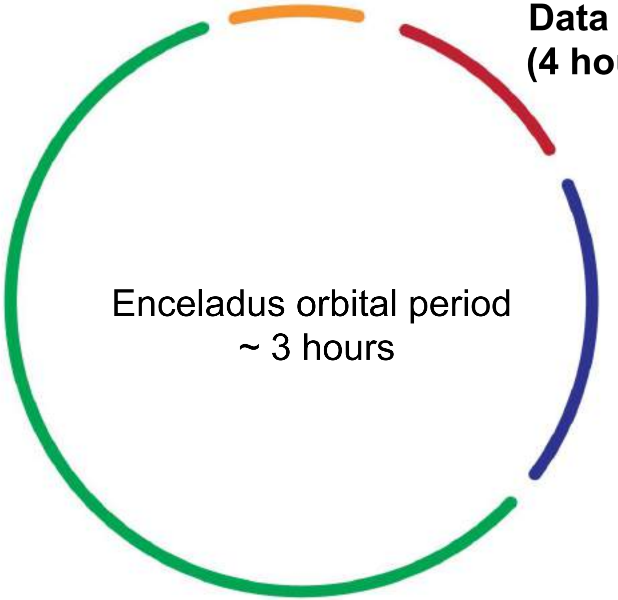
20 orbits per altitude
120 orbits in mission


Direction of Motion
Nadir
Nadir
Nadir
Laser altimeter
SELFI
WAC
NAC
EOA
ENIJA
MASPEX
Magnetometer
Radio Science
Nadir
Nadir
Nadir
Nadir
Motion
Motion
Motion
—
—
100 km
70 km
50 km
40 km
30 km
20 km
20 orbits
40 orbits
60 orbits

Enceladus Operational Modes

Course Adjustment
(<1 hour/week)

Data Downlink
(4 hours/week)



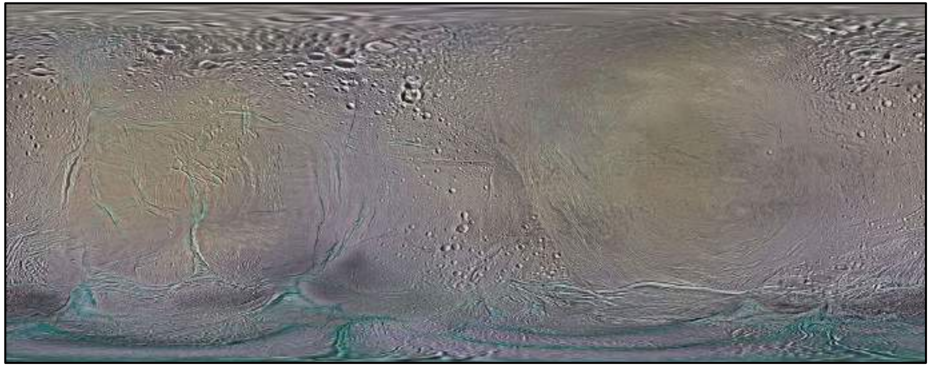
Coasting,
Charging Batteries,
Surface Mapping
(156 hours/week)
Using batteries to provide peak power reduces the number of ASRGs needed from 6 to 3

Data Intensive Mode
(7 hours/week)
Data collection hours limited by downlink bandwidth and plume flyover time
Cassini had 22 encounters with Enceladus

(Not to scale)

Surface Mapping using Image Stitching

- Produce high-resolution maps of the Enceladus surface
  - Maximum resolution of Cassini images is 100 m/px
  - Elder is capable of 10m/px (WAC) and 0.5m/px (NAC)
- Supplement analysis of surface morphology and geography
  - Geographic feature distribution informs plate tectonics
- Public outreach and education
- Constructed from images captured periodically from orbit



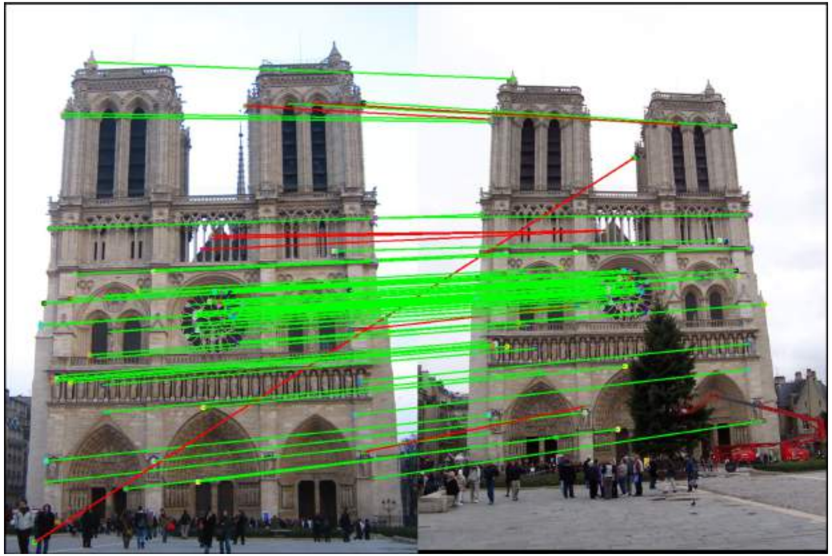
Surface map of Enceladus as taken during the Cassini mission.
[AUTO1]

Image Stitching Algorithm

- SIFT-RANSAC: a two-step procedure
  - Identify identical features between a set of disparate images
  - Compute and apply homography matrices
- Transformed images overlaid, post-processed to form a map
- ***Challenge***: Enceladus is feature-sparse

$$\begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix} = H \begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} = \begin{bmatrix} h_{00} & h_{01} & h_{02} \\ h_{10} & h_{11} & h_{12} \\ h_{20} & h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix}$$

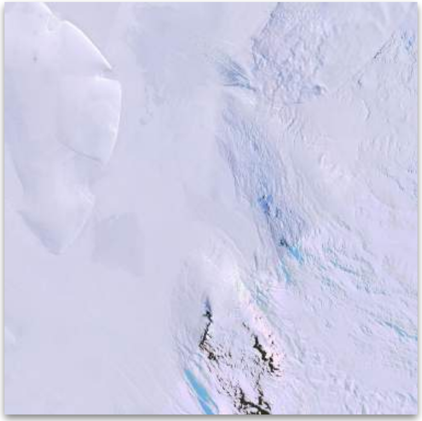
Once the homography matrix H *is computed, any point can be projected onto the new coordinate frame.* [AUTO3]



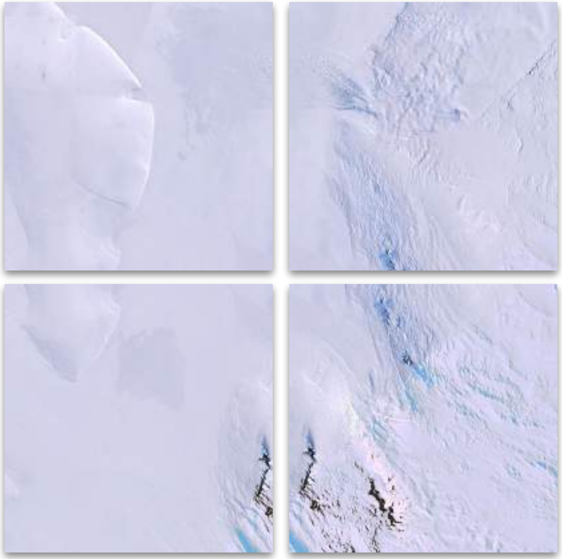
Identified features across two separate images. Once these points are correlated, the homography matrix can be computed. [AUTO2]

Surface Image Stitching Algorithm

- How do we evaluate expected performance at Enceladus?
  - Use best-case analogue: satellite images of Antarctica
- Algorithm tested with a set of randomly offset subimages
  - Original image divided up into sections with some amount of overlap, other corruptions
- Algorithm is fed the set of images, expected output is a reconstructed original



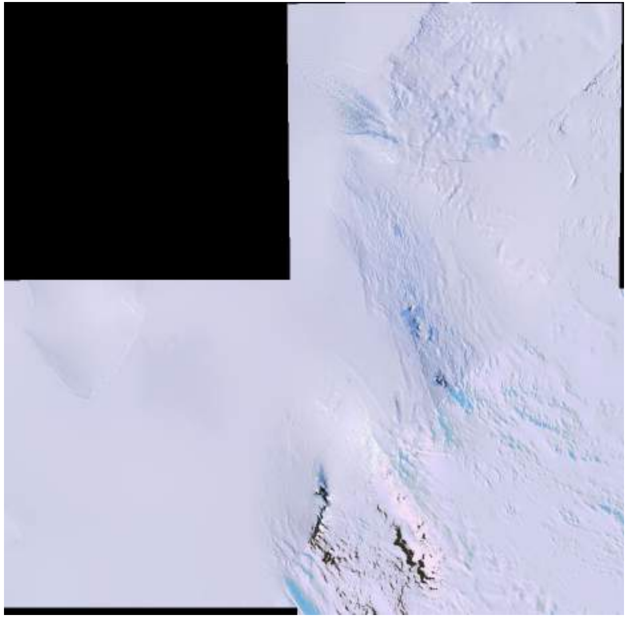
Original, unaltered test image. [AUTO4]



Set of randomly partitioned subimages

Surface Image Stitching Algorithm

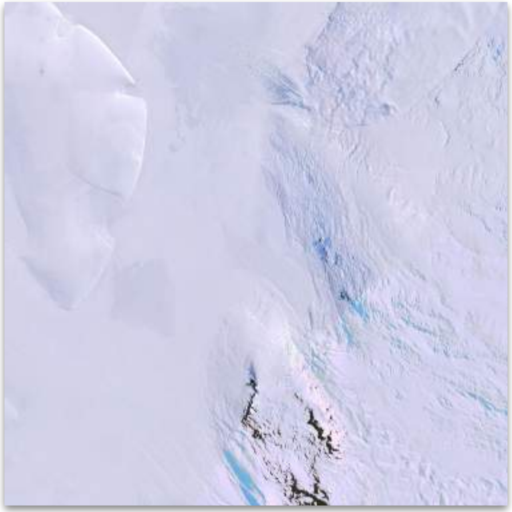
- Mapping algorithm consistently fails to identify features across original images
  - Lacking distinct contours, patterns
- ***Solution***: apply image filters to aid in feature extraction
- Canny edge detection, a multi-step image processing technique
  - Gaussian smoothing: eliminates noise
  - Gradient computation : "typical" edge detection step
  - Edge thinning: removes false, weak edges



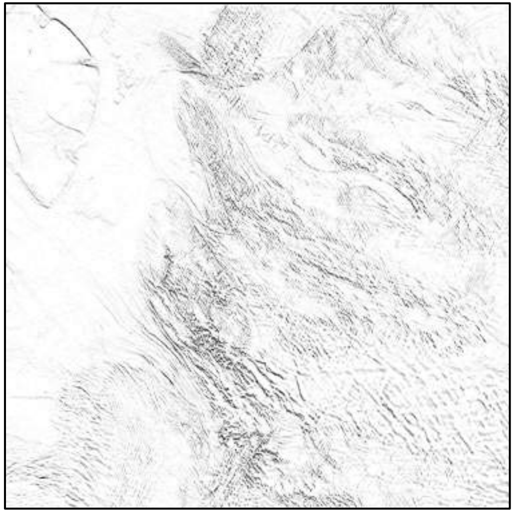
Output when operating on unaltered test images. Note the failure to match the upper-left image to its neighbors.

Surface Image Stitching Algorithm

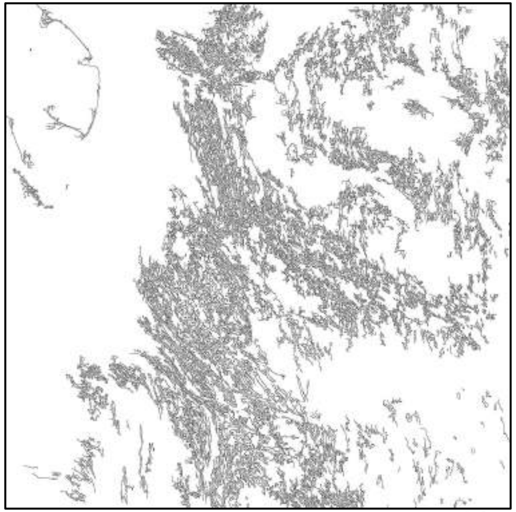
Canny Edge Detection:



Original, unprocessed image



Gradient (edge) detection filter applied, no edge thinning

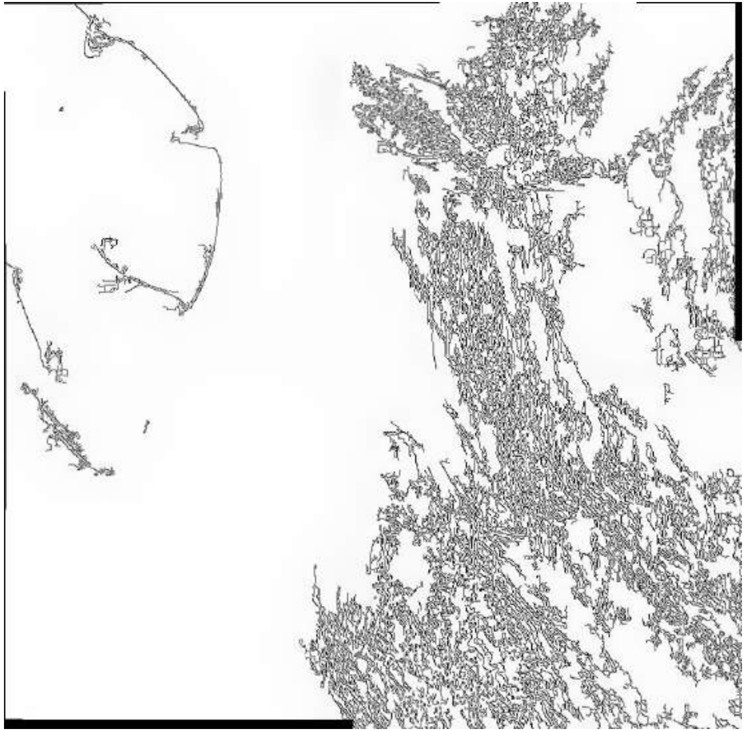


Final output image

Dave Bambrick

Surface Image Stitching Algorithm

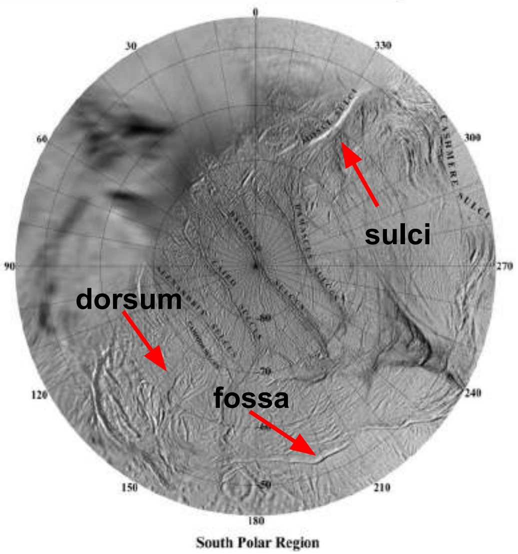
- After processing via the Canny edge detection method, the image is able to be fully reconstructed as shown
  - Matched coordinates can be taken from filtered image and used to reconstruct the original
- Further improvements
  - Tweaking of parameters to minimize information loss
  - Preprocessing steps to more fully capture object edges

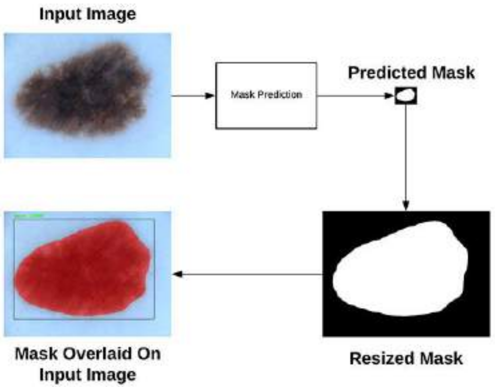


Output when operating on processed test images.

Target Selection Algorithm

- *Semantic segmentation*: process of associating each pixel of an image with a class label
- **Mask RCNN** (region convolutional neural network)
    - Developed by Facebook AI research, used for facial recognition
    - More efficient than other techniques (RCNN, Fast-RCNN)
- Train network with existing images of Enceladus with features labelled manually

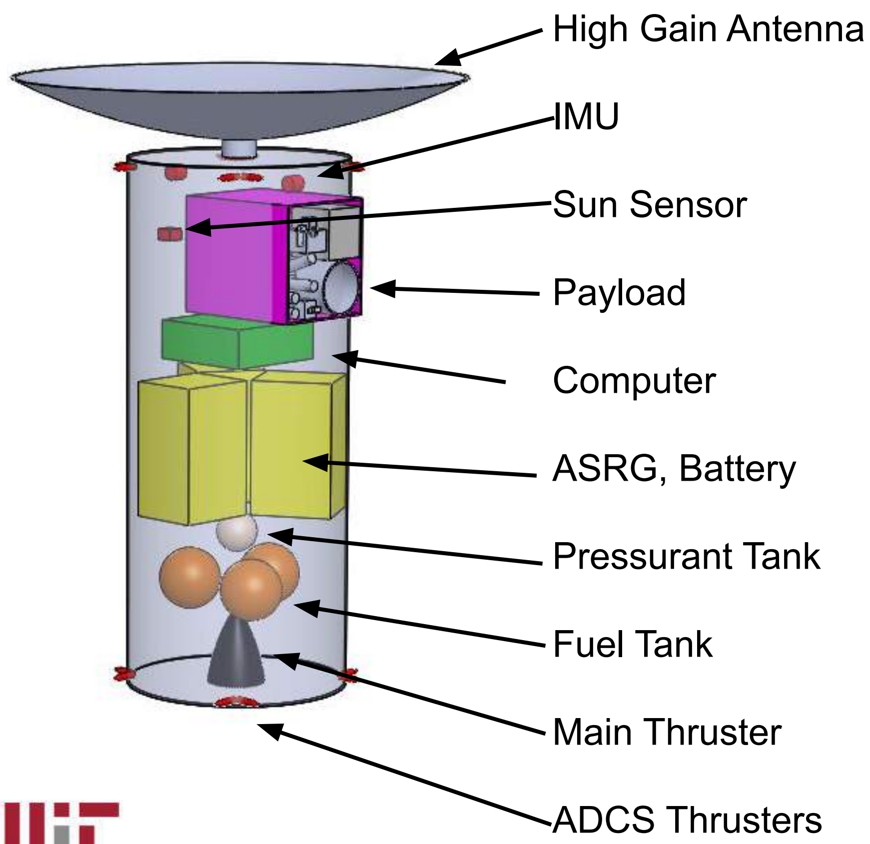


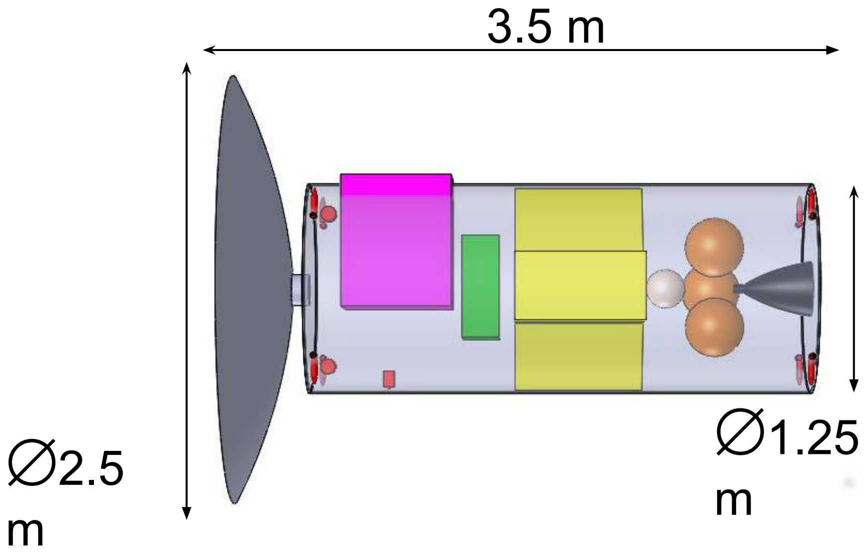


Agenda

- Mission & CONOPS
- Science & Instrumentation
- Enceladus Operations
- **Spacecraft Design: Main Stage**
- Trajectory
- Spacecraft Design: Solar Electric Propulsion Stage
- System Health
- Risks
- Possible Mission Extensions
- Budgets

Main Stage Design Overview





Juan Salazar

Propulsion

Required ΔV at Saturn is 2 km/s

Selected Engine	Aerojet HiPAT
I_{sp}	326 s
Max Thrust	445 N
Quantity	1
Total Mass of MMH/NTO/He	533 kg
Power	46 W

Juan Salazar

Payload

Component	Mass (kg)	Power (W)
Total	**117**	**184**
MASPEX	20	46
ENIJA	4	14
EOA	2	3
SELFI	20	43
Camera	58	56
Magnetometer	6	6
Laser Altimeter	7	16
Radio	(included in comms allocation)	

ADCS

Actuator	Aerojet MR-103
Number Required	16
Mass of Propellant Required	0.04 kg
Total Mass of Actuators	5.28 kg

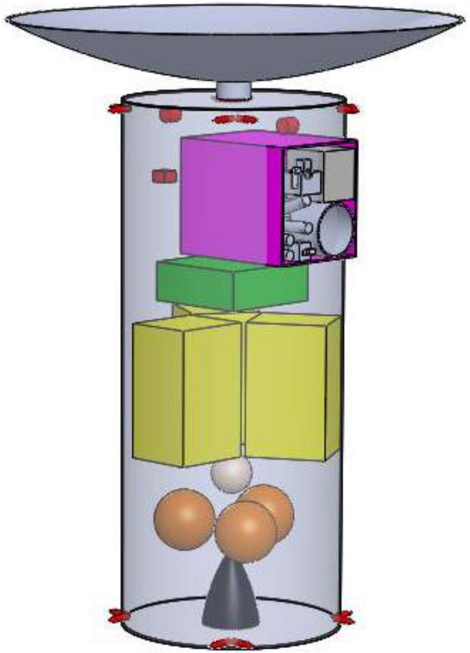
Sensor	Inertial Measurement Unit
Number Required	2
Mass	0.015 kg

Sensor	Sun Tracker
Number Required	1
Mass	0.5 kg

Miguel Wagner

Communication

Antenna Classification	High Gain
Diameter	2.5 m
Mass	51 kg
Power	120 W
Frequency	34 GHz, K_a- Band
Data to Transmit	120 orbits of 500 MBytes each and 30 minutes of video in one year (25 GB)
Data rate	164 kilobits/second



High Gain Antenna

DSN Compatibility

- Transmission Schedule: 4 hour bursts on weekly intervals requiring a data rate of 164 kbps
- Will communicate with 34m Antenna with G_r = 78.9 dB
- In order to achieve a 5 dB Energy per bit to Noise ratio with Free Space Path Loss from 10 AU and System Noise, 73.7 dB of Signal Strength needed from Spacecraft

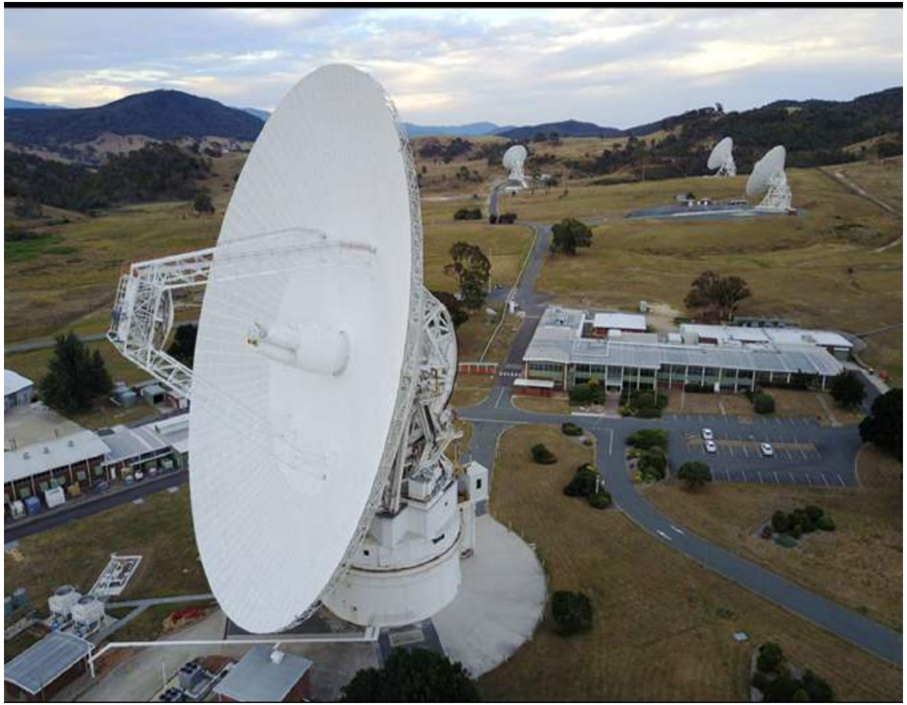


Image from nasa.gov

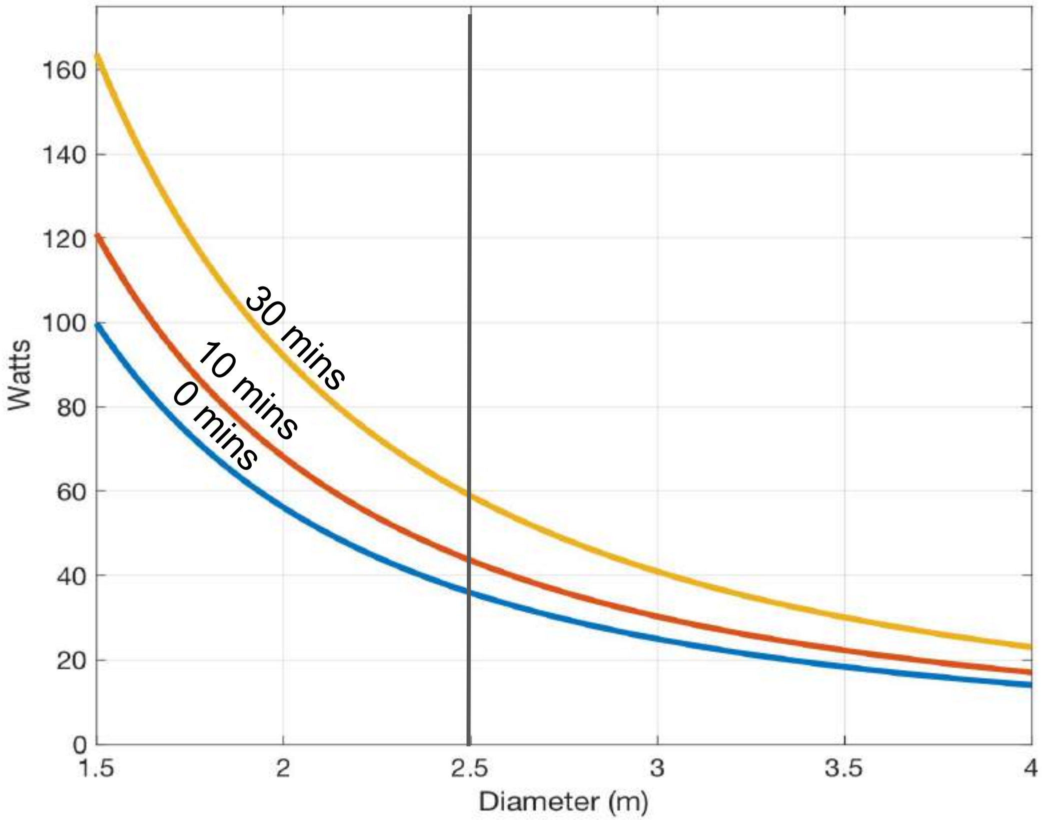
Miguel Wagner

Antenna Sizing and Link Budget Analysis

Antenna Diameter of 2.5 m with transmission power of 58.9 W produces required Signal Strength

Assuming a 50% efficiency factor in hardware components, 117.8 W are used during transmission mode

Accomplished with 3 Traveling Wave Tube Amplifiers (TWTA) each supplying 40 W

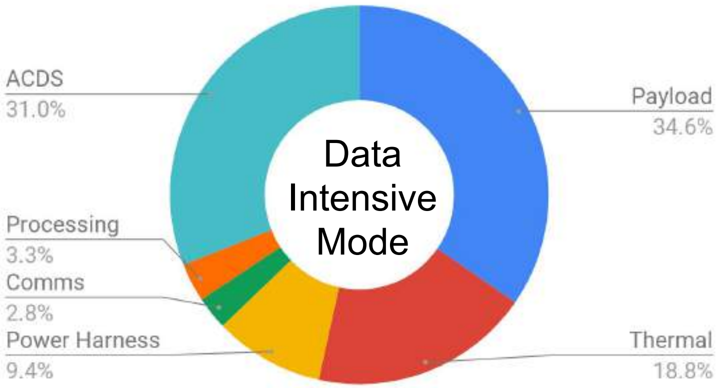


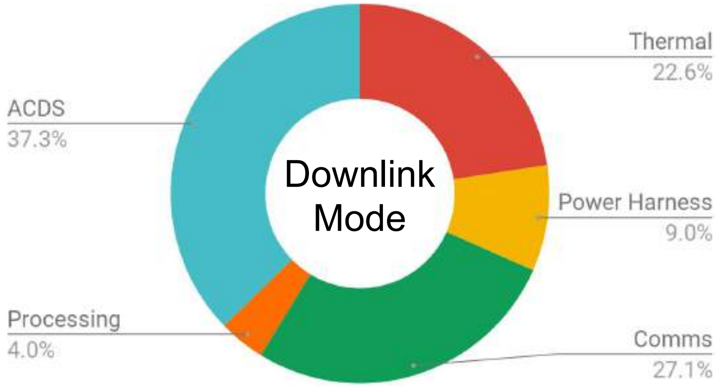
Juan Salazar

Power Budget (Main Stage)

System		Data Intensive Mode (7h)	Downlink Mode (4h)	Trajectory Correction Mode (<1h)	Charging, Surface Mapping (156h)
	Payload	184	0	20	50
	Thermal	100	100	100	100
	Power Harness	50	40	40	25
	Comms	15	120	15	15
	Processing	18	18	18	35
	ACDS	165	165	165	0
	Propulsion	0	0	46	0
Estimated Power Draw (W)		**532**	**443**	**404**	**225**
Margin		30%	30%	30%	30%
Estimate + Margin (W)		**691**	**575**	**525**	**293**

	BOL:	EOL:	
Power Required from ASRGs	394	**317**	W
Power Delivered by 3 ASRGs	420	338	W
Required Battery Capacity (allows 2 weeks of operation without charging)		7658	Wt-hours



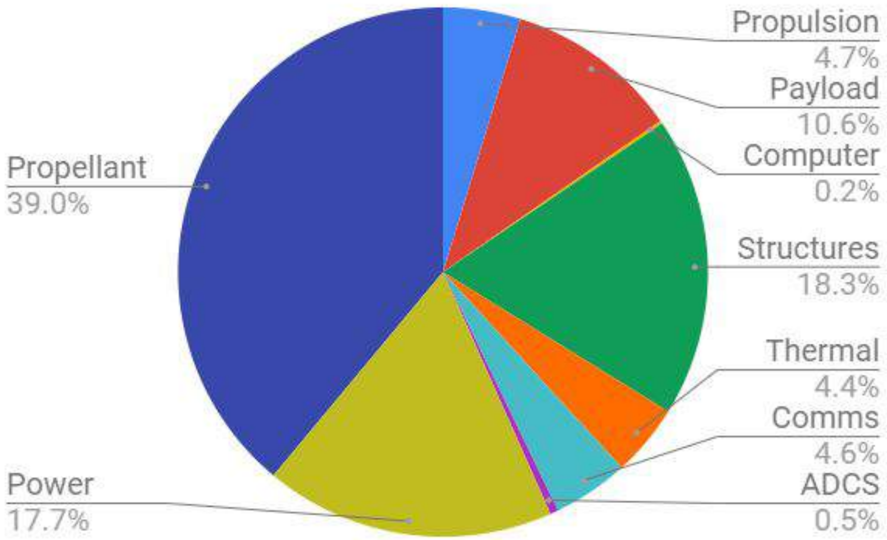


Average weekly power = **317 W**

Juan Salazar

Mass Budget (Main Stage)

System		Estimate (kg)	Margin	Estimate + Margin (kg)
	Propulsion	51	33%	68
	Payload	117	29%	152
	Computer	2	30%	3
	Structures	219	20%	263
	Thermal	53	20%	63
	Communications	51	30%	66
	ADCS	6	21%	7
	Power	195	30%	254
Main Dry Sum		**694**	**26%**	**876**
Propellant		**559**	*	**559**
Main Wet Sum		**1253**	**14%**	**1434**



Main Stage Wet Mass Breakdown

* Propellant mass accounts for worst case dry mass

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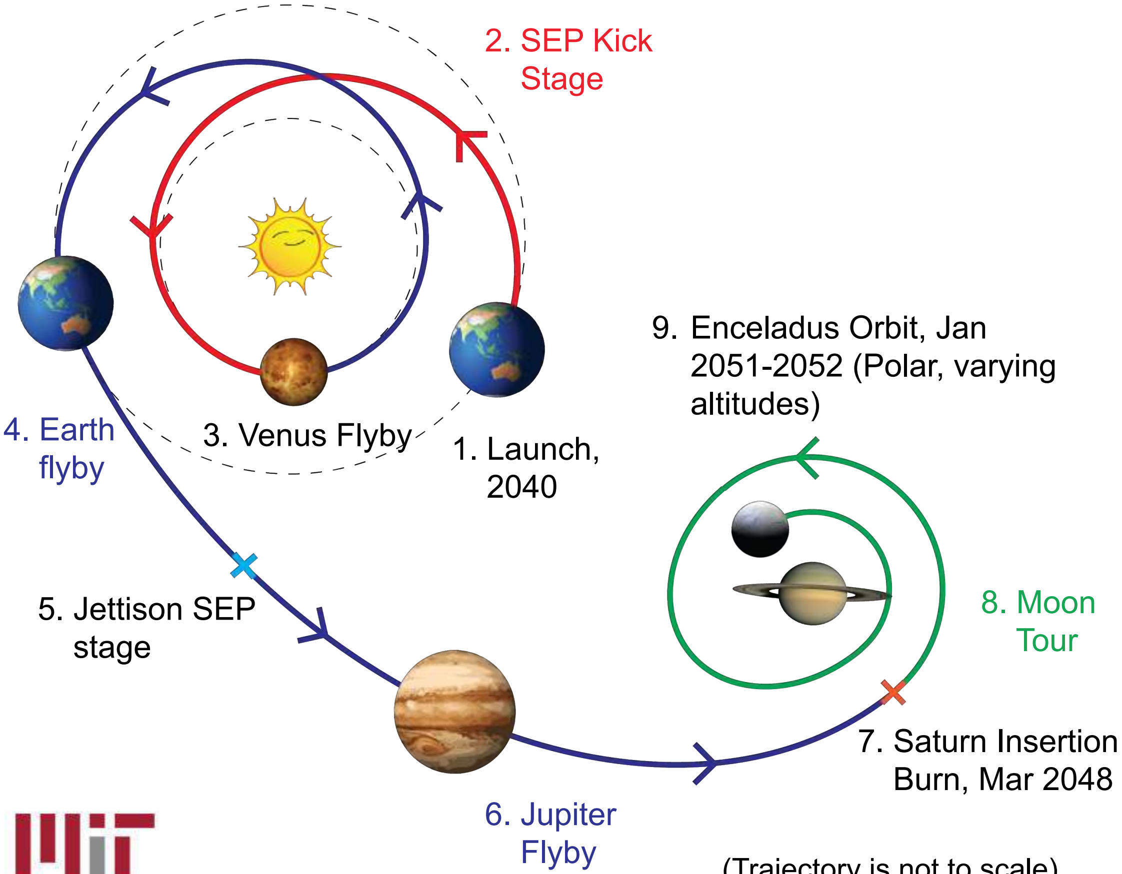
Lucy Halperin

Trajectory Overview & Mission Timeline



(Trajectory is not to scale)

#	Description	Duration
1	January 2040 Launch on Atlas V 551	
2	SEP kick stage to adjust orbit for Venus rendezvous	1 yr
3-6	Venus-Earth-Jupiter gravity assist, jettison SEP stage	6 yr
7	Braking burn to arrive at Saturn	
8	Maneuver within Saturnian system to Enceladus orbit via moon tour	2.7 yr
9	Polar orbit at Enceladus	1 yr
10	Spacecraft disposal	3 yr

Delta V Budget

Maneuver	DeltaV (m/s)
SEP Kick Stage	5757
Total (SEP)	**5757**
Venus-Earth-Jupiter Gravity Assist Trajectory	0
Saturn Capture	470
Saturn->Enceladus (Moon Tour)	806
Orbit at Enceladus	128
Spacecraft Disposal	400
Margin for Trajectory Correction Maneuvers	150
Total (main stage)	**1954**

Spacecraft SEP stage fuel system sized for **7,000 m/s**

Spacecraft main stage fuel system sized for **2,000 m/s**

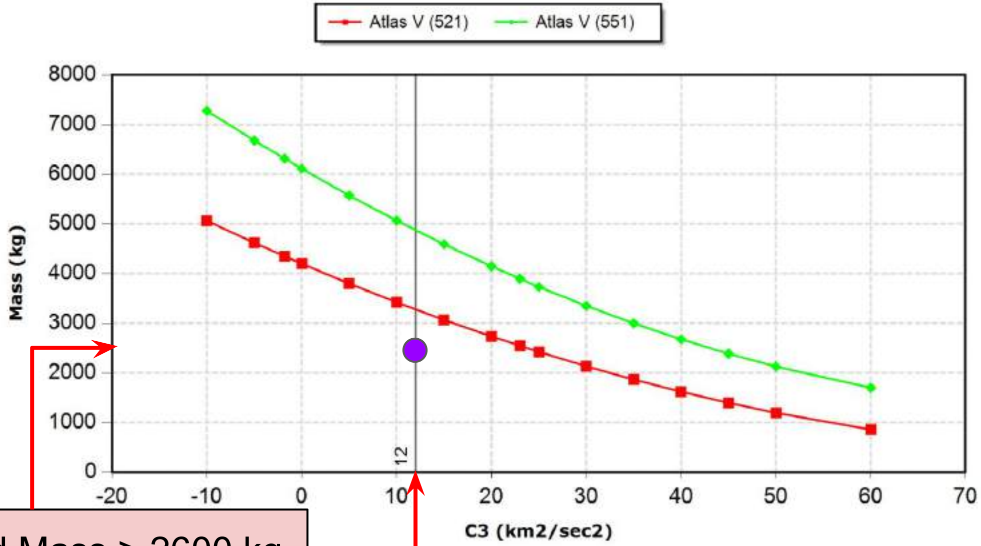
David Mueller

Launching January 2040 on an Atlas V

Launch Vehicle Options	
Launch Vehicle	Estimated Launch Cost ($ millions, 2019)
Atlas V 521	154
Atlas V 551	179

Source: [1]

Maximum Payload Mass vs C3 For Alternative Launch Vehicles



Max. Payload Mass > 2600 kg

C3 > 12 for high-energy escape

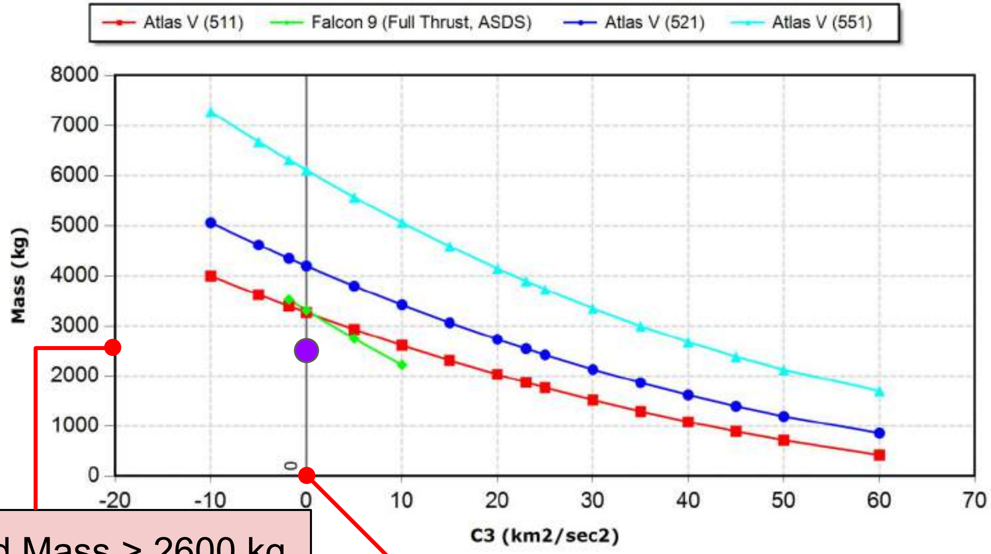
Launch date based on best <u>known</u> flyby tour. Search for earlier opportunities is ongoing.

Alternative Low-Energy Launch

Launch Vehicle Alternatives	
Launch Vehicle	Estimated Launch Cost ($ millions, 2019)
Atlas V 511	137
Falcon 9	62
Atlas V 521	154
Atlas V 551	179

Source: [1]

Maximum Payload Mass vs C3 For Alternative Launch Vehicles



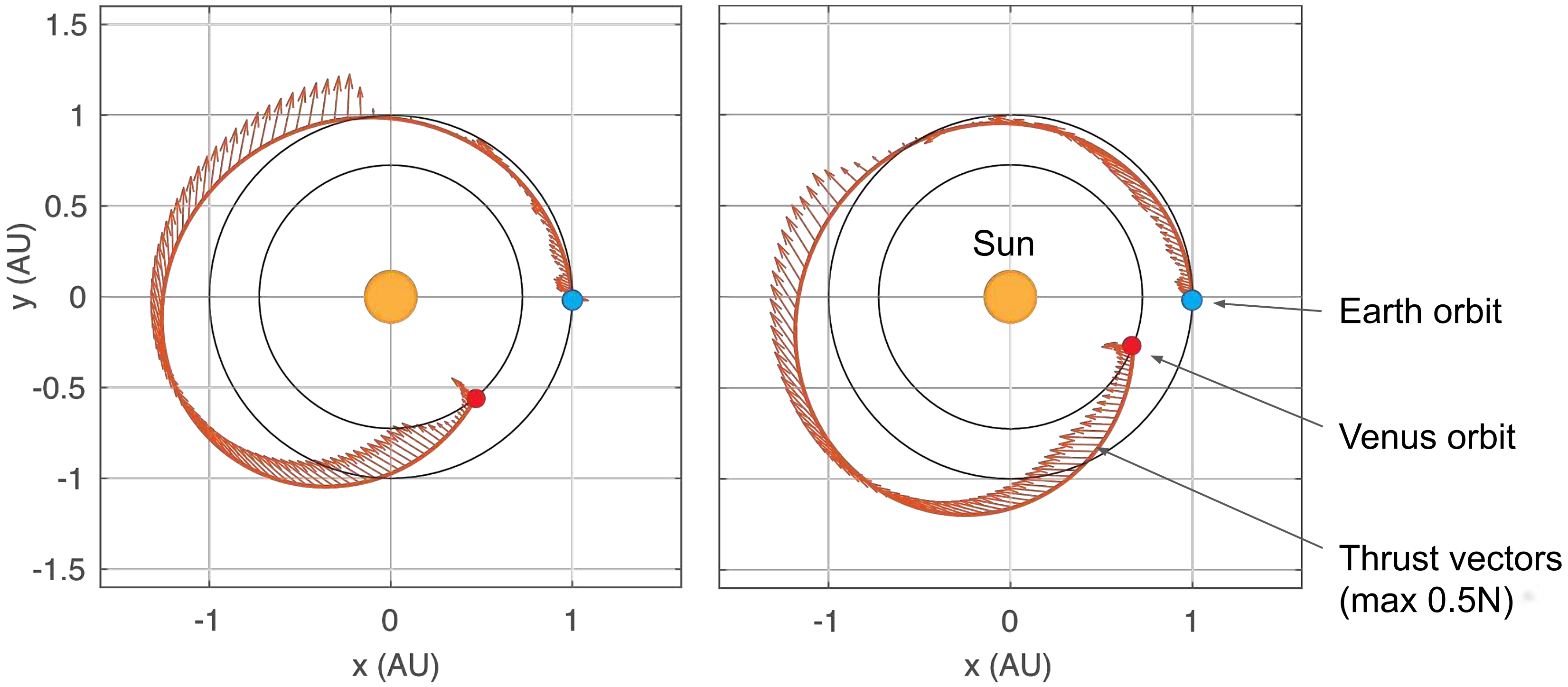
Max. Payload Mass > 2600 kg

C3 > 0 for low-energy escape

Lower launch energy allows smaller launch vehicles; slower overall transit to Saturn

Devansh Agrawal

Earth-Venus: Solar Electric Propulsion



Launch C3: 12 km^2/s^2
Required ΔV = 5.756 km/s
Transit Time: 1.0 years

Launch C3: 6 km^2/s^2
Required ΔV = 6.307 km/s
Transit Time: 1.1 years

Simulation of Venus-Earth-Jupiter-Saturn Tour

Key
ELDER Trajectory
Sun
Earth
Venus
Jupiter
Saturn

Bradley Jomard

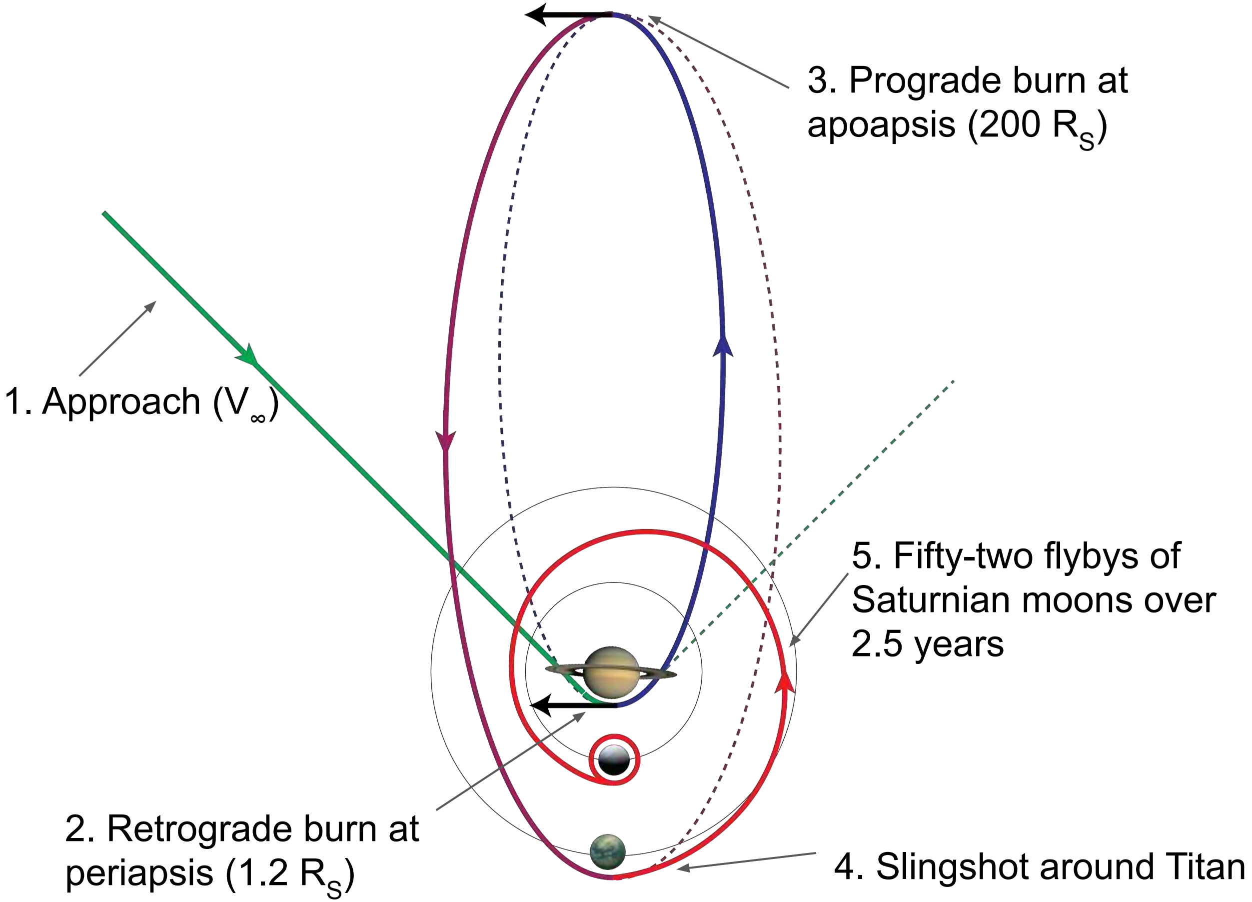
Saturn to Enceladus Breakdown

Direct capture requires 4-5 km/s, but the allocation is only 2 km/s.

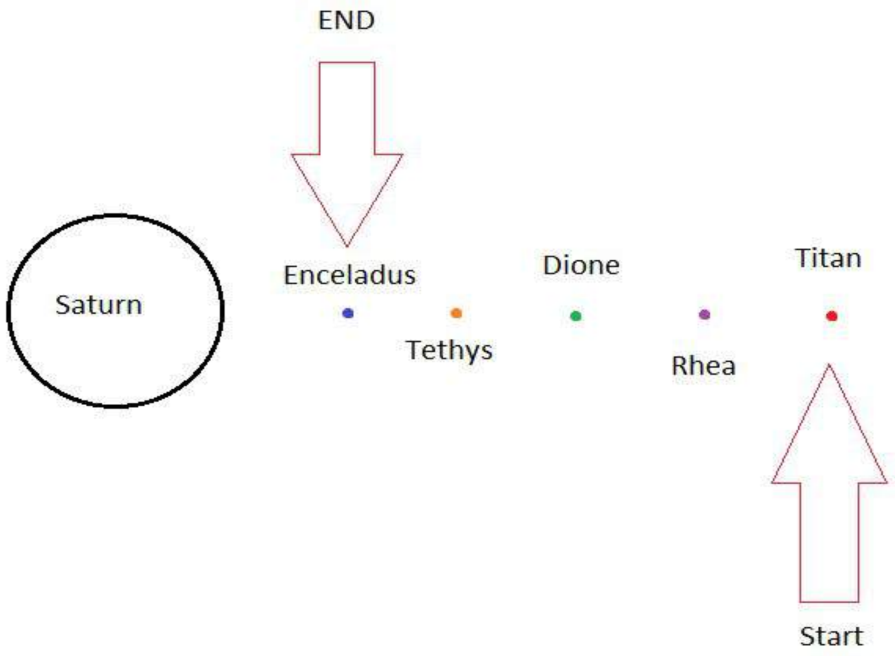
Using moon tours the velocity can be reduced and fuel can be saved.

1. Braking burn to arrive at Saturn → 2. Burn to target Titan from capture orbit → 3. Maneuver within Saturnian system to Enceladus orbit via moon tour → 4. Capture into polar orbit at Enceladus

Saturn: System Entry/Capture



Moon Tour: Gravity Assist Moons



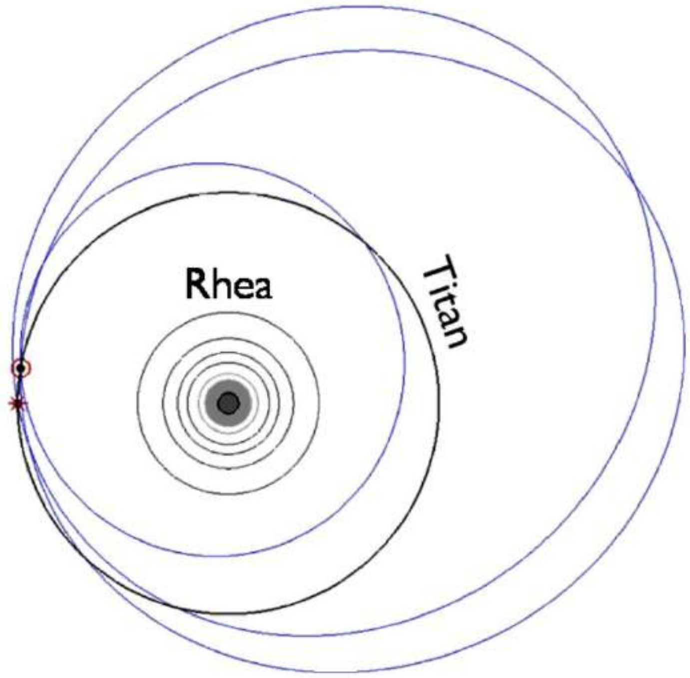
- Start : Titan
- Target : Enceladus
- Using 5 moons total for orbit lowering

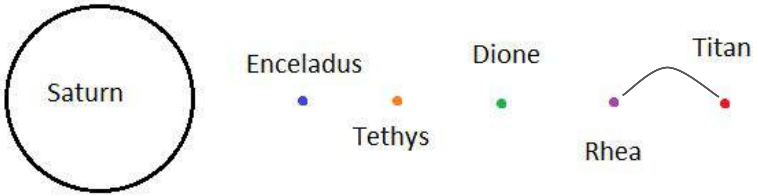
Moon Tour: Budget

Moon	Time of Flight (days)	# of Flybys	TCM DeltaV (m/s)
1. Titan	53	3	29
2. Rhea	363	15	146
3. Dione	190	10	26
4. Tethys	108	12	12
5. Enceladus	233	12	102
Total	**997 (2.7 years)**	**52**	**316**

Bradley Jomard

Moon Tour: Titan Orbit Tightening





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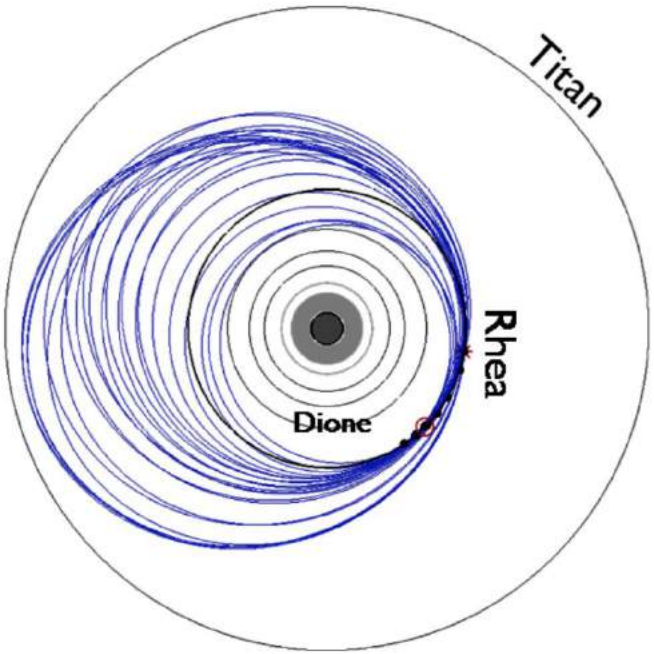
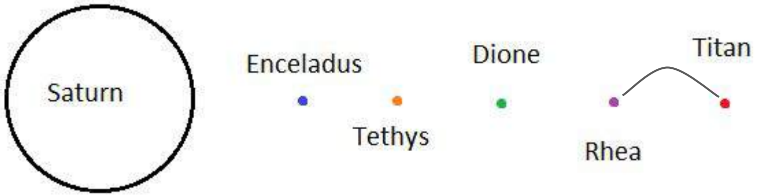
Bradley Jomard

Moon Tour: Titan to Rhea Gravity Assists





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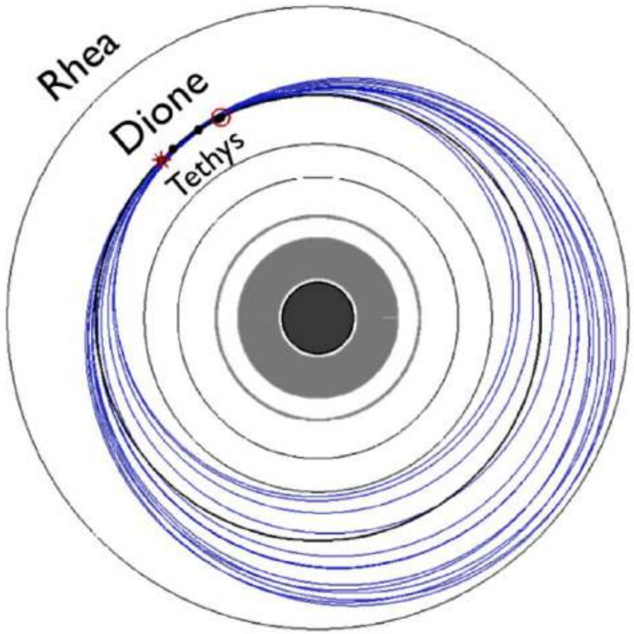
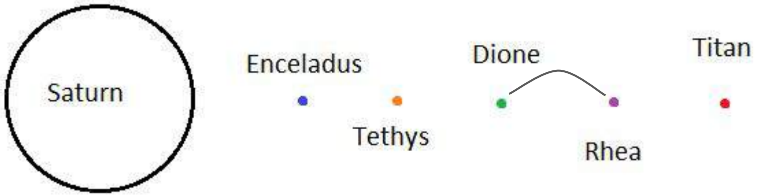
Bradley Jomard

Moon Tour: Rhea to Dione Gravity Assists





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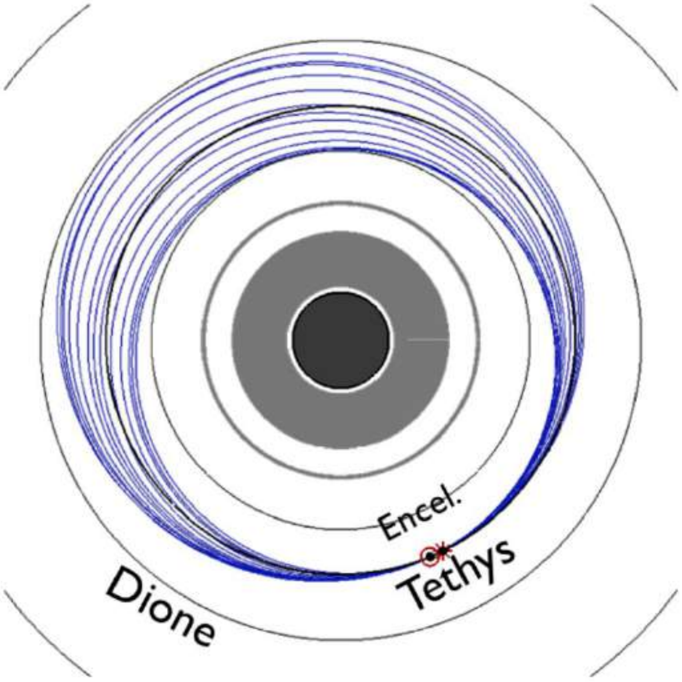
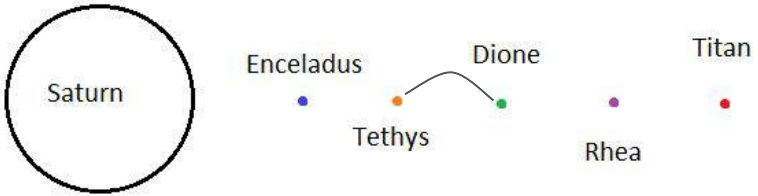
Bradley Jomard

Moon Tour: Dione to Tethys Gravity Assists





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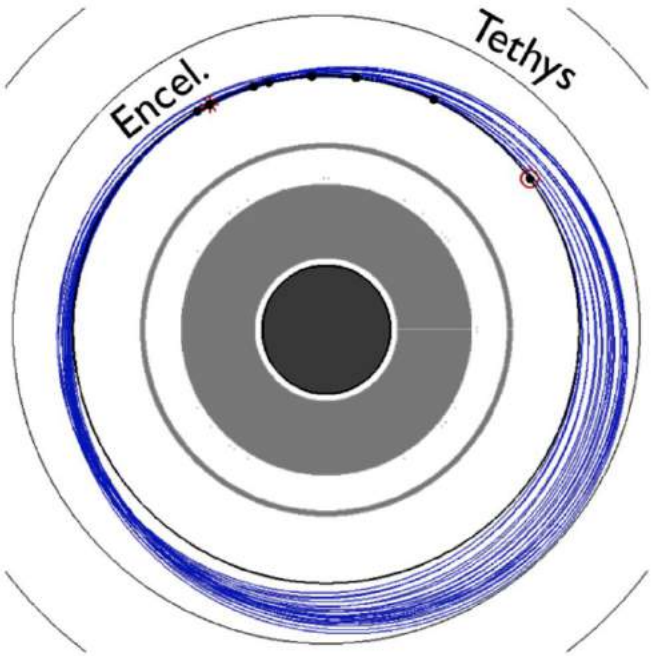
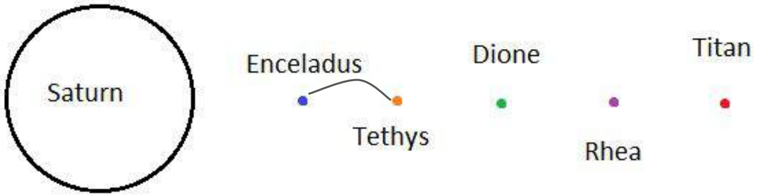
Moon Tour: Tethys to Enceladus Gravity Assists





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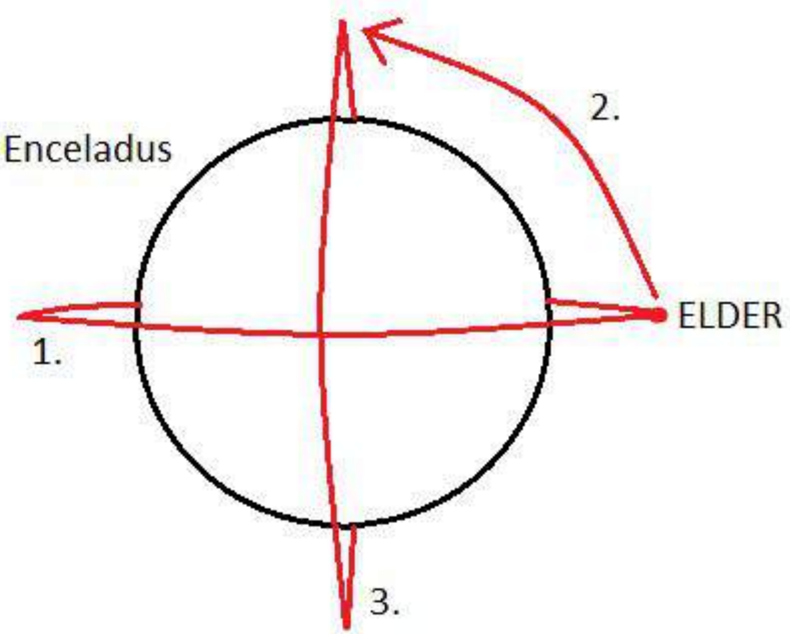
Bradley Jomard

Enceladus Orbit Correction

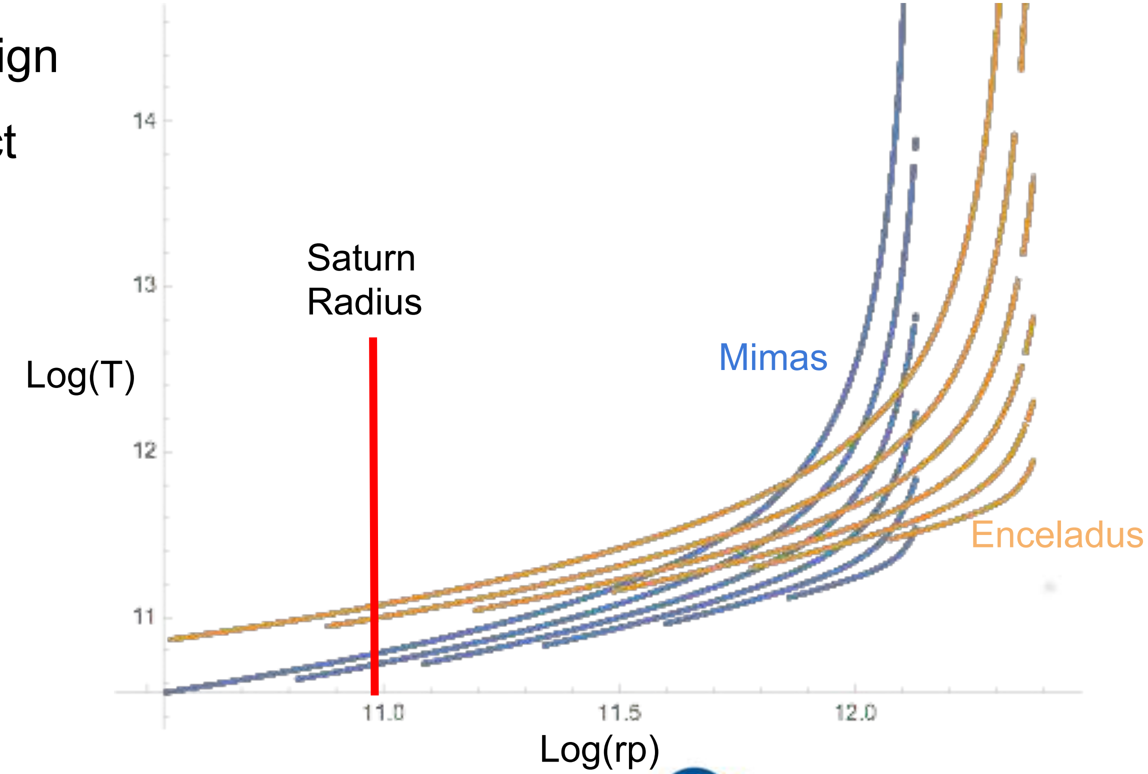


1. Capture Orbit : braking burn of 128 m/s
2. Inclination change : burn of 250 m/s
3. Desired Polar orbit : 100km radius
4. Varying altitude between 100km-20km for science team

End-of-Life

Bradley Jomard

- Use similar moon tour design
- Continue inwards to impact Saturn
- Tour duration and deltaV budget can vary by design



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AEROASTRO

Dev Agrawal

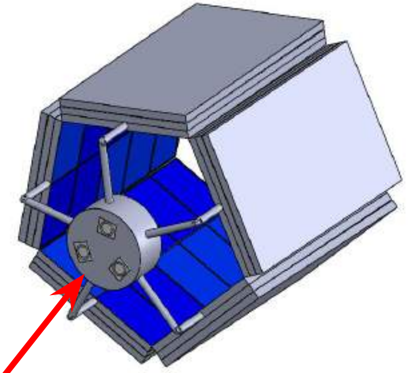
Solar Electric Propulsion (SEP) Kickstage

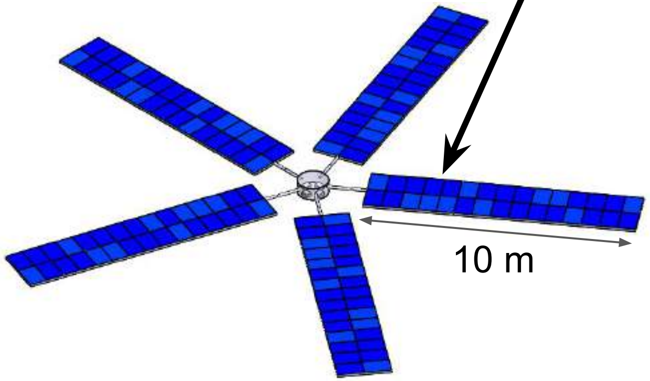
Propellant
- Xenon
- Mass: 776 kg

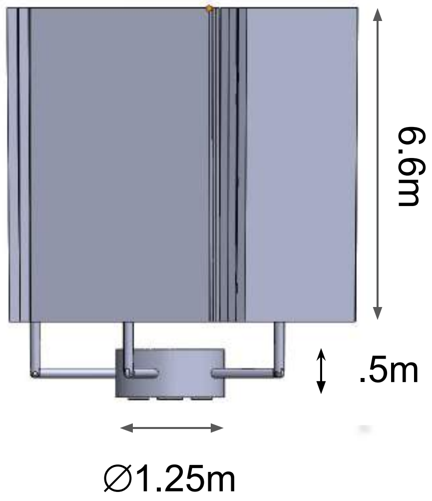
Hall thrusters (3x)
- 1 Redundant

Gallium Arsenide (GaAs) Solar Arrays
- Deployable
- Area: 100 m^2
- Power (1.6AU): 10830 W

Interstage Mechanism



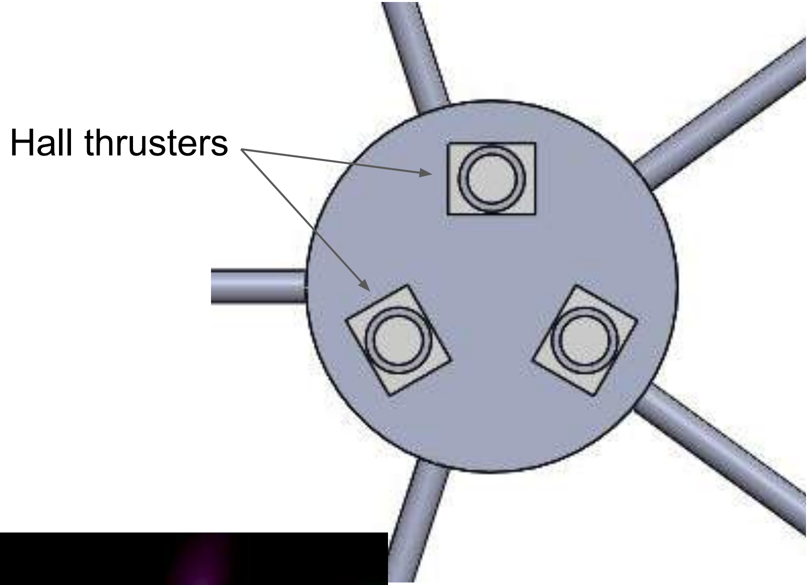




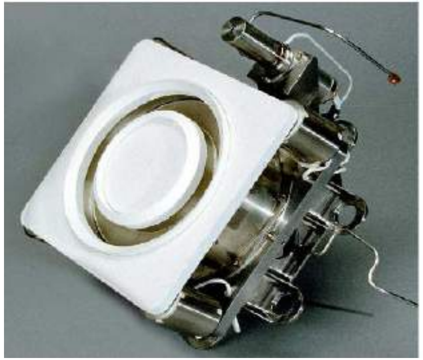
Hall Effect Thruster

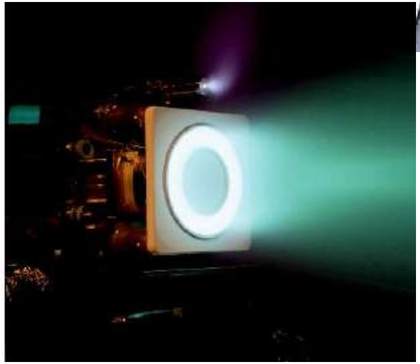
Dev Agrawal

Selected Engine	Aerojet BPT-4000
I_{sp}	2020 s
Max Thrust (each)	270 mN
Quantity	3 (1 redundant)
Mass of Xenon	776 kg
Power (each)	4.5 kW



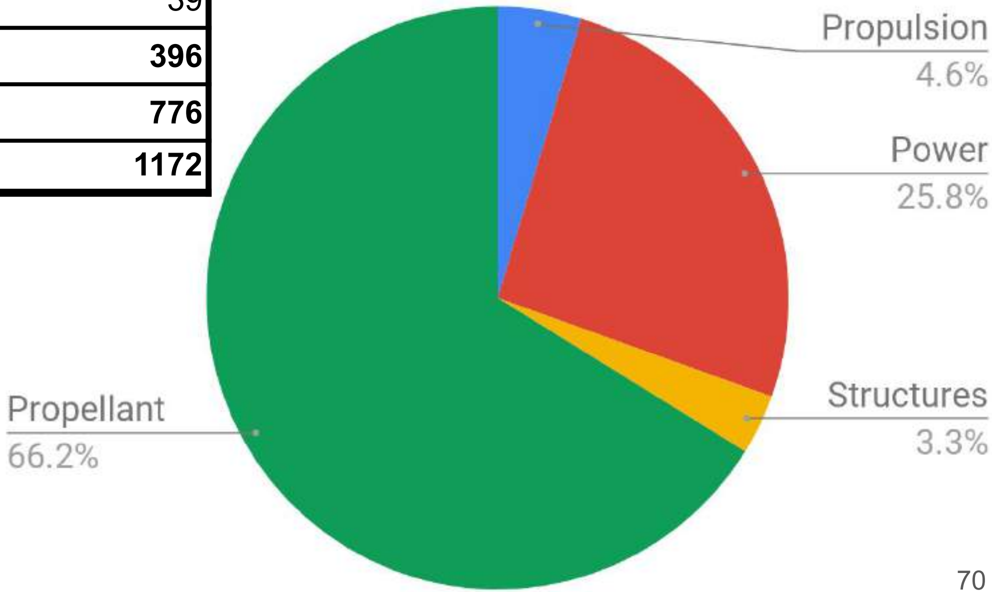
(Bottom view)





Mass Budget (Kickstage)

System	Estimate (kg)	Margin	Estimate + Margin (kg)
Propulsion	45	20%	54
Power	227	33%	303
Structural	30	30%	39
SEP Dry Sum	**302**	**31%**	**396**
Propellant	**776**	*	**776**
Kickstage Wet Sum	**1078**	**9%**	**1172**



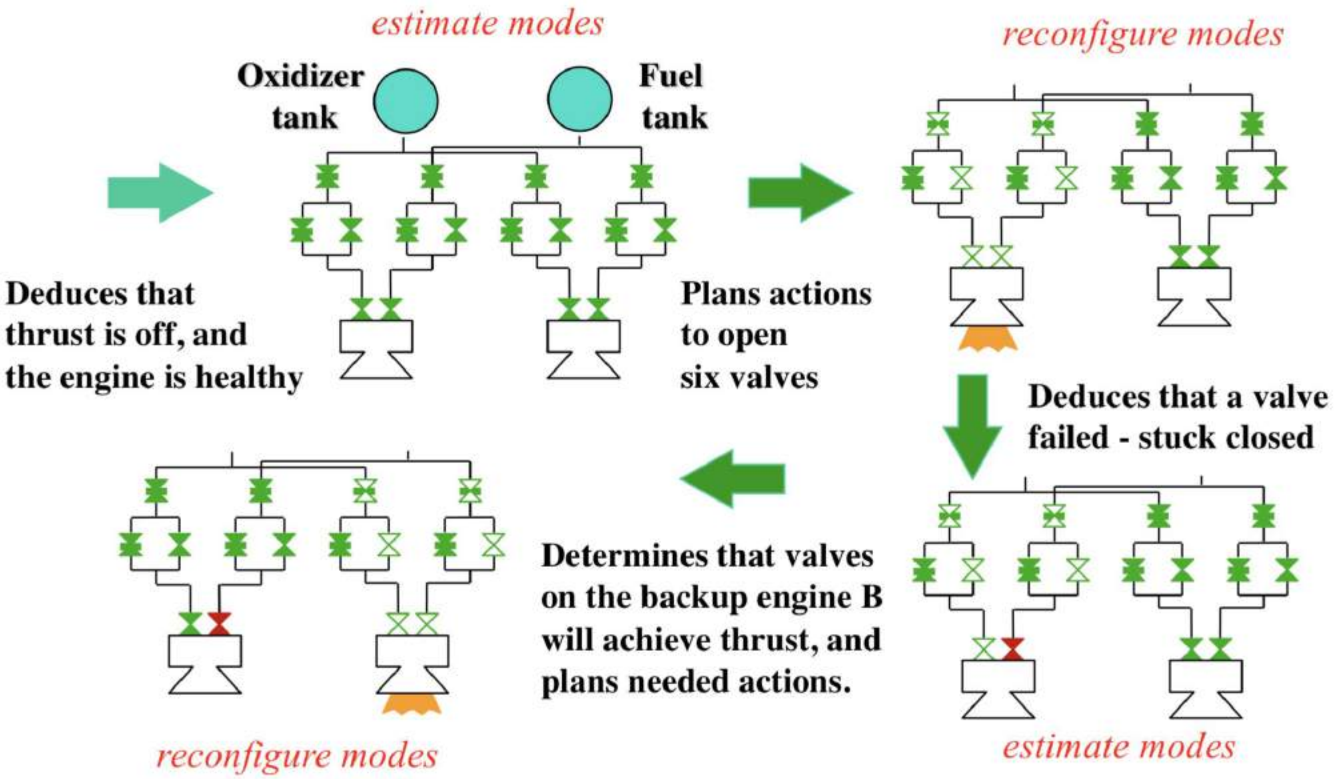
* Propellant mass accounts for worst case dry mass

Agenda

- Mission & CONOPS
- Science & Instrumentation
- Enceladus Operations
- Spacecraft Design: Main Stage
- Trajectory
- Spacecraft Design: Solar Electric Propulsion Stage
- **System Health**
- Risks
- Possible Mission Extensions
- Budgets

Hailey Nichols

System Health Management Design



Challenges of Self-Diagnosing Systems

Issue: Diagnosing hidden failures requires reasoning from a model.
Solution: Generate candidate solutions → test if candidates account for all symptoms

Issue: Failures are often novel.
Solution: For novel faults, make no presumption about faulty component behavior.

Issue: Multiple faults occur.
Solution: Identify all combinations of “consistent” unknown modes → diagnoses are consistent with the model and observations

Fault Diagnoses Response

Health management system will only REPORT to ground suggested diagnoses of the failure state(s) for human validation and verification

→ NO action for self-repair will be taken until approved

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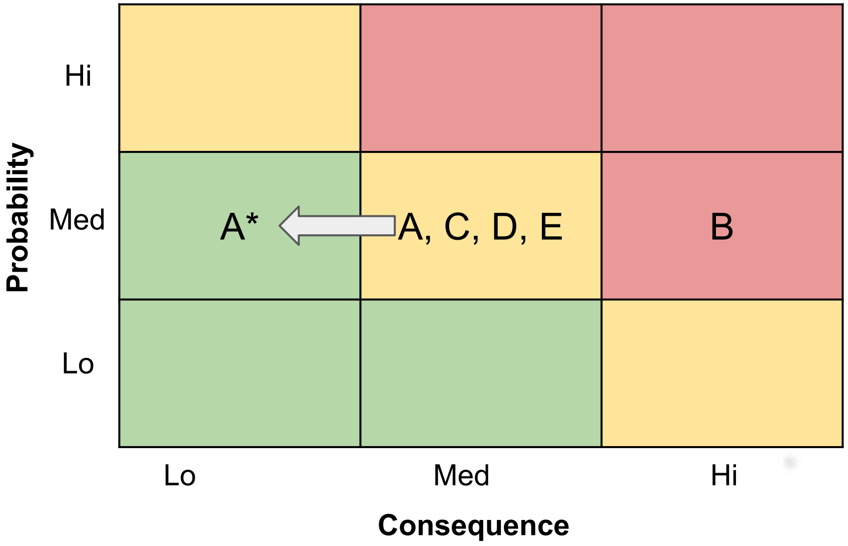
Systems: Risk Mitigation - Launch

Quint Hester

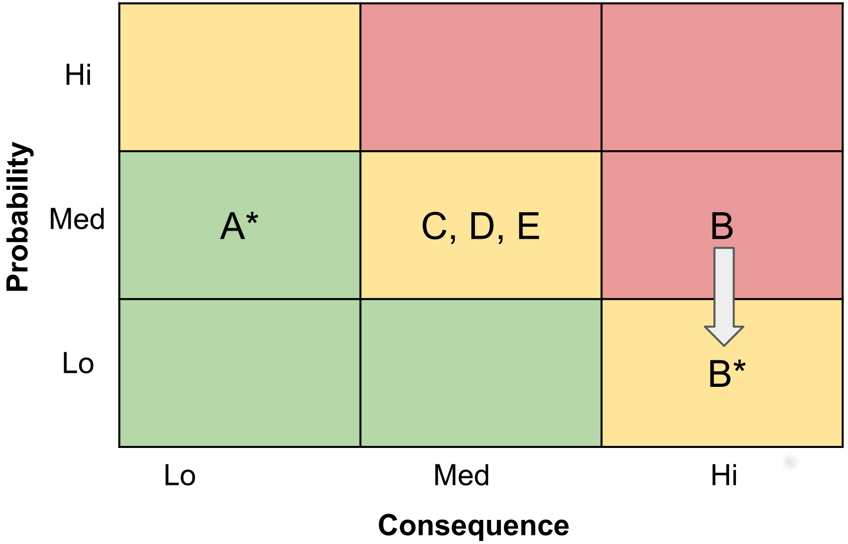
ID	Description
A	**Launch** Delays in development could cause system to miss its launch date, jeopardizing critical Venus flyby
A*	**Launch** at a higher C3 in order to catch up to Venus



Quint Hester

Systems: Risk Mitigation - Separation

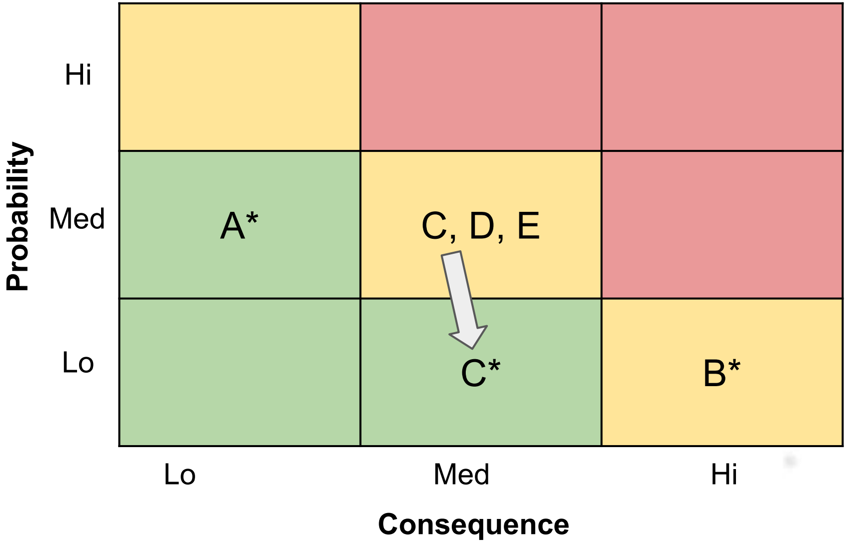
ID	Description
B	**Separation** Separating the kick stage from the main stage could fail due to a hardware malfunction, preventing operation of main engine
B*	**Separation** Incorporate redundant separation systems and heritage hardware in the design, and conduct extensive ground tests



Quint Hester

Systems: Risk Mitigation - Data

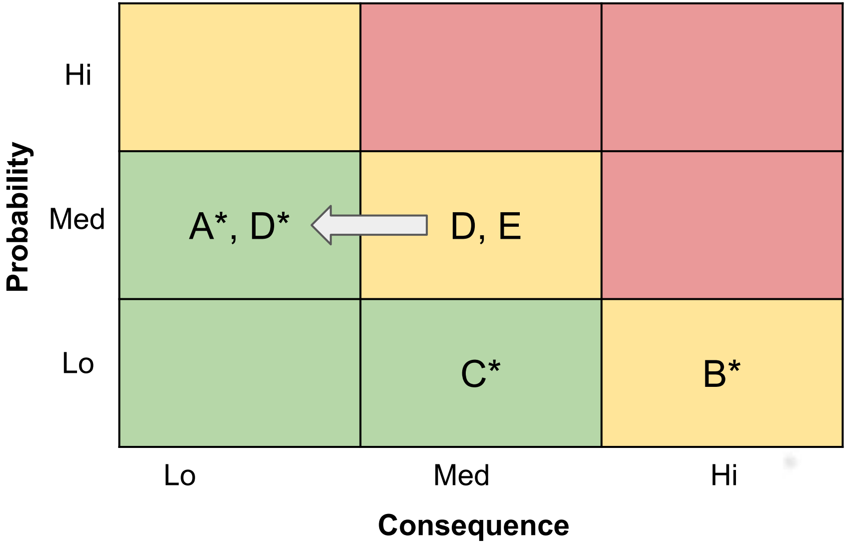
ID	Description
C	**Data Collection/Transmission** Radiation exposure along trajectory could degrade instruments, decreasing possible science
C*	**Data Collection/Transmission** Ensure instrumentation suite protected by sufficient radiation shielding



Systems: Risk Mitigation - Plumes

Quint Hester

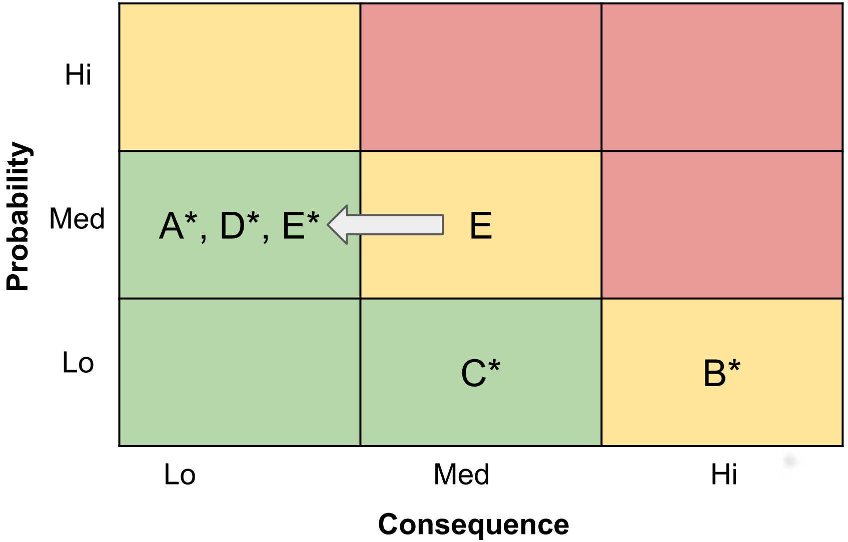
ID	Description
D	**Flying through Plumes** Instruments could be damaged as spacecraft collides with ice grains and dust particles
D*	**Flying through Plumes** Gradually increase risk by lowering altitude as data gathered and science goals accomplished



Quint Hester

Systems: Risk Mitigation - Disposal

ID	Description
E	**End of Life** Spacecraft may not have enough fuel at end of mission to reach Saturn for disposal
E*	**End of Life** Shorten mission to ensure successful disposal at Saturn



Agenda

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- Budgets

Mission Extensions - Science Objectives

Extended Mission

Identify Biotic Markers in Samples

- Lower plume orbits for higher quantity of sample material at greater risk

Determine Habitability

- Increase surface mapping from 70% to 90% of Enceladus' surface

Enceladus Seasonal Variation

- Build an enhanced understanding of Enceladus' climate across Saturnian seasons.

Science through Disposal

Additional budget will allow for science instruments to be operated through EOL disposal. EOL trajectory will involve several more fly-bys of various other Saturnian Moons.

Mission Extensions - Consumables

Charlie Garcia

	End of Phase	ΔV Remaining	Additional Budget
Enceladus Arrival	January 2050	410 m/s	N/A
End of Prime Mission	April 2051	344.5 m/s (-65.5 m/s)	N/A
End of First Extension	April 2052	298.5 m/s (-46 m/s)	$6.5 million
End of Disposal	October 2055	18 m/s	$13.8 million

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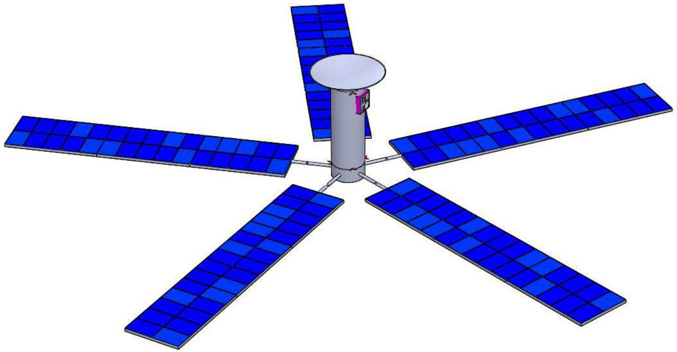
- **Budgets**

Amanda Roberts

Total Mass Budget



System	Estimate (kg)	Margin	Estimate + Margin (kg)
Main Dry Sum	694	26%	876
Main Propellant	559	*	559
Main Wet Mass	**1253**	**14%**	**1434**
Kickstage Dry Sum	303	31%	396
Kickstage propellant	776	*	776
Kickstage wet mass	**1079**	**9%**	**1172**
Total Launch Mass	**2331**	**12%**	**2606**

Estimate: Bottom Up Current Best Estimate,
Margin: is component specific, 20-30%. Propellant margins applied in Delta-v calc

Mission Cost Budget Allocation

Cost Component	Estimated Cost ($M)	Margin ($M)
Instrumentation	74	32
Spacecraft Design	164	70
Autonomy	32	14
Mission Level	80	34
Totals:	350	150

Instrumentation
Payload

Spacecraft Design
Spacecraft

Autonomy
Safety & Mission Assurance
Science/Technology

Mission Level
Systems Engineering
Mission Operations
Ground Systems
System Integration & Testing

*Cost budget data extrapolated from SMAD 2011.[Sys1]

Bret Heaslet

Mission Cost Budget Actual

Cost Component	Estimated Cost ($M)	Margin ($M)
Instrumentation	60	9
Spacecraft Design	250	37
Autonomy	10	2
Mission Level	115	17
Totals:	435	65

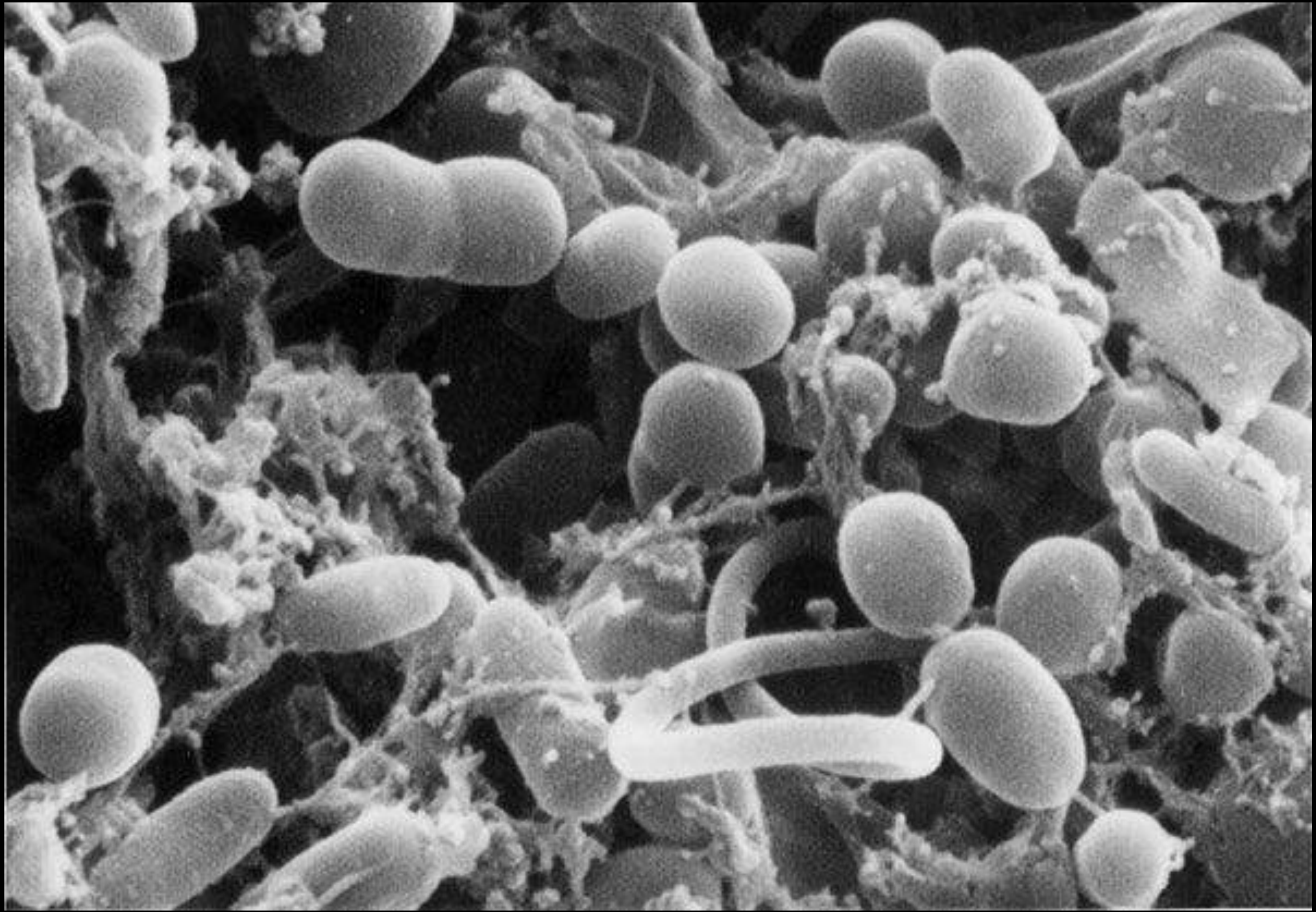
Instrumentation	Cost ($M)
Payload	60

Spacecraft Design	Cost ($M)
Spacecraft	250

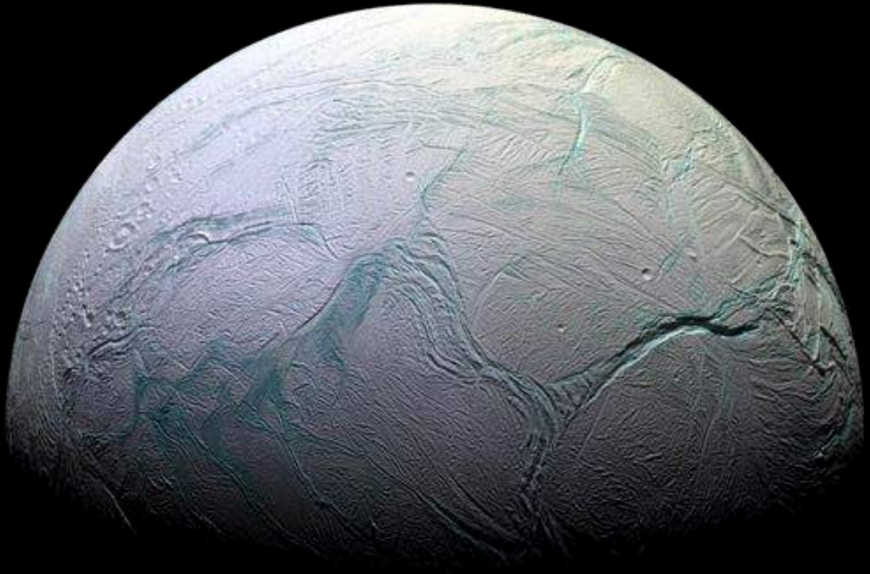
Autonomy	Cost ($M)
Safety & Mission Assurance	5
Science & Technology	5

Mission Level	Cost ($M)
Project Management	10
Mission Operations	65
Ground Systems	20
System Integration & Testing	20

- Biggest cost:
  - 3 ASRGs - $200 million
- Total Estimated Cost:
  - $435 milli



ELDER seeks to explore the existence of life beyond our little blue marble.



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Erisa Hines, JPL	Ben Solish, JPL
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Prof. Richard Linares, MIT	Dr. Catherine Walker, WHOI
Prof. Paolo Lozano, MIT	Prof. Brian Williams, MIT

Backup

Mission Objectives

ID	Statement
M.O.1	Search for signs of life in the plumes of Enceladus.
M.O.2	Communicate to the general public the possibilities and importance of detecting life on ocean worlds and provide scientists with new forms of data to analyze.
M.O.3	Constrain the habitability of Enceladus' subsurface oceans.

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[AUTO3] "Homography Matrix Transformation." https://i.stack.imgur.com/FT1K8.png.

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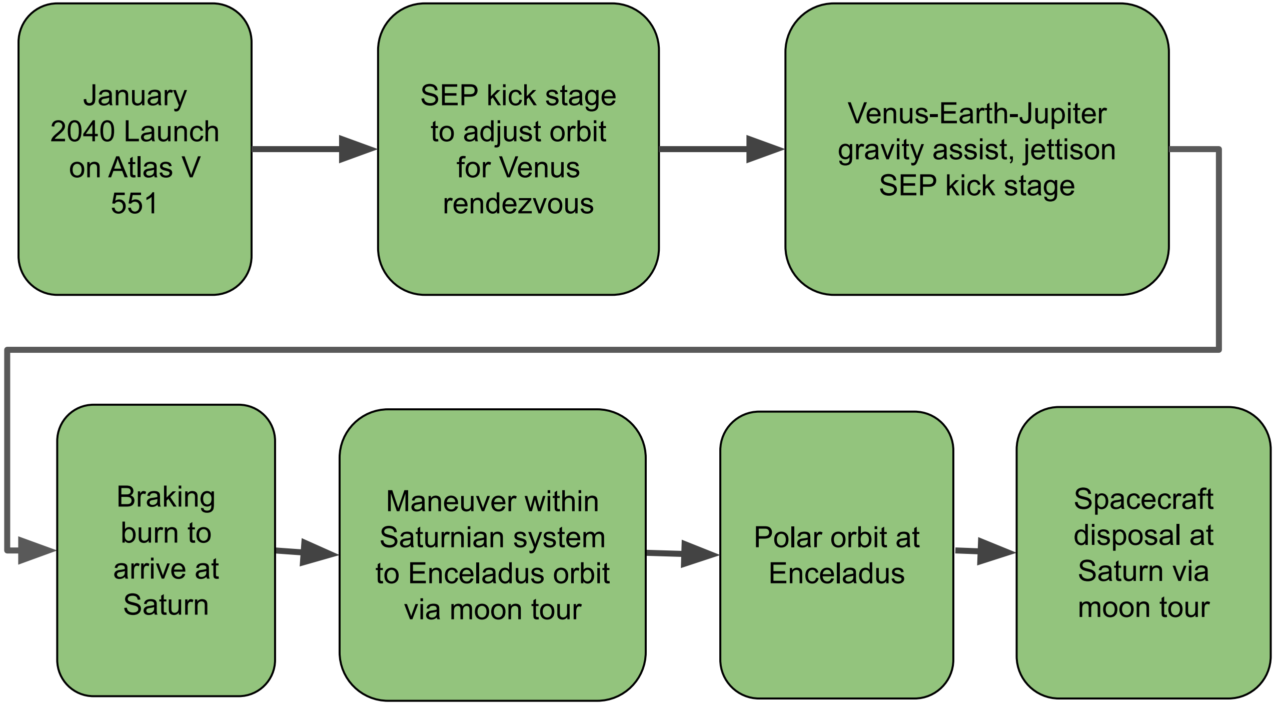
[4] N.J. Strange, T.R. Spilker, D.F. Landau, T. Lam, D.T. Lyons, and J.J. Guzman, "Mission Design for the Titan Saturn System Mission Concept," AAA Paper 09-356, AAS/AIAA Astrodynamics Conference, Pittsburgh, PA, Aug. 2009.

Lucy Halperin

Trajectory Overview & Mission Timeline

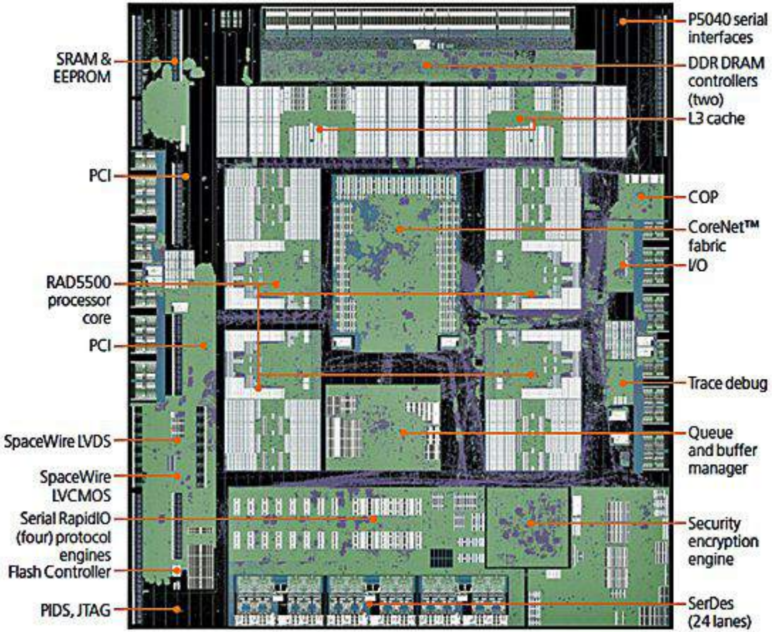


Mission Stage	Duration
Launch->Venus (SEP)	1 year
VEJS Tour	6 years
Saturn Moon Tour	2.7 years
Enceladus Orbit	1 year
Spacecraft Disposal	TBD

Flight Computer

Components selected: BAE RAD5545, DDC 192 Gbit NAND flash memory

RAD5545 Specification	Notes
Processor Throughput	Up to 5.6 GOPS/3.7 GFLOPS
Memory Bandwidth	Up to 102 Gb/s
Memory	Up to 16 GB RAM
Operating Temperature	-55 to +125 degrees Celsius
Power Supply	35W



GOPS = giga operations per second
GFLOPS = giga floating point operations per second

Science operations for a given pass through plumes

Instrument	Day In the Life Pass		
	Approaching Plumes	In Plumes	Departing Plumes
MASPEX	Inactive	Sample Collection	Sample Analysis
EOA	Inactive	Sample Collection	Sample Analysis
ENIJA	Inactive	Sample Collection	Sample Analysis
Imaging Subsystem	Imagining plumes	Imaging surface	Imagining plumes
SELFI	Active	Inactive	Inactive
Magnetometer	Inactive	Inactive	Sometimes Active
Radio	Inactive	Inactive	Active if Enceladus occulting with DSN
Laser Altimeter	Active if mapping topography	Active if mapping fissures	Active if mapping topography

Science operations at each altitude

Orbit Altitude (km)	Number of Orbits	Instruments									Science
		MASPEX	ENIJA	EOA	SELFI	Wide Angle Camera	Narrow Angle Camera	Magnetometer	Radio Science	Laser Altimeter	
20											*in-situ* sample collection & analysis, magnetic sensing, radio science
30											
40											*in-situ* sample collection & analysis
50											*in-situ* sample collection & analysis, Imaging Spectroscopy, VIS/IR surface mapping,
70											Imaging Spectroscopy, VIS/IR surface mapping Topographical surface mapping
100											
Pointing		Direction of Motion	Direction of Motion	Direction of Motion	Nadir	Nadir	Nadir	-	Deep Space Network	Nadir	

Amanda Roberts

Power Budget

Mode	Data Collection	Data Transmission	Trajectory Correction	Coast/Charging
Payload	168	20	20	20
Thermal*	100	100	100	100
Power Harness*	40	40	40	50
Communications	50	275	50	50
Processing	35	35	35	35
ACDS	165	165	165	0
Propulsion	0	0	46	0
Estimated Power Draw	558	635	456	255
Margin	30%	30%	30%	30%
Allocated Power Draw (W)	**725**	**826**	**593**	**332**

Hours/Week	1.7	4	1	161
Energy Used/Week (Wt-hr/week)	1255	3302	593	53,452
Provided by Batteries (Wt-hr/week)	651	1907	244	-

Power required from ASRG	349 W (EOL) 433 W (BOL)
Battery Capacity (2 weeks of operation without charging)	5603 Wt-hrs

* : bounding values. Needs further analysis

Power Supply

Source	ASRG (Advanced Stirling Radioisotope Generator)
Number used	3
Total Mass	128 kg
Total Power	420 W (BoL) 338 W (EoL)

Source	Li-ion Battery
Number used	1
Total Mass	45 kg
Capacity	7658 Wt-hours

System Health Management Verification

- Simulate a component-based model of the spacecraft system
- Over some number of trials, randomly select components to fail
  - Spacecraft system in some hidden failure state
- The algorithm is only given the symptoms of failure and must correctly determine the hidden failure state up to **95%** of the time - defined by requirement AUTO.7

Verifying Target Selection Algorithm

- Simulate Enceladus surface with arbitrarily placed features
  - Geological features–fissures, canyons, geysers
- Design a camera model to replicate hardware performance constraints
- Mapping and target selection algorithms can be fed simulated images via camera model
- Perform algorithms and assess using standard metrics

Charlie Garcia

Mission Extensions - Science Objectives

Primary Mission

Attempt to Detect Life

- In-Situ plume sampling

Determine Habitability

- 70% Surface Mapping
- Subsurface environment estimation

Extended Mission

Attempt to Detect Life

- Lower plume orbits for higher quantity of sample material at greater risk

Determine Habitability

- 90% Surface mapping

Enceladus Seasonal Variation

- Build an enhanced understanding of Enceladus' climente across Saturnian seasons.

Science through Disposal

Additional budget will allow for science instruments to be operated through EOL disposal. EOL trajectory will involve several more fly-bys of various other Saturnian Moons.